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Sustainable manufacturing and industry 4.0: what we know and what we don't

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Abstract

Purpose – The emergence the fourth industrial revolution, known as well as industry 4.0, and its applications in the manufacturing sector ushered a new era for the business entities. It not only promises enhancement in operational efficiency but also magnify sustainable operations practices. This current paper provides a thorough bibliometric and network analysis of more than 600 articles highlighting the benefits in favor of the sustainability dimension in the industry 4.0 paradigm.

Design/methodology/approach – The analysis begins by identifying over 1,000 published articles in Scopus, which were then refined to works of proven influence and those authored by influential researchers. Using rigorous bibliometric software, established and emergent research clusters were identified for intellectual network analysis, identification of key research topics, interrelations and collaboration patterns.

Findings – This bibliometric analysis of the field helps graphically to illustrate the publications evolution over time and identify areas of current research interests and potential directions for future research. The findings provide a robust roadmap for mapping the research territory in the field of industry 4.0 and sustainability.

Originality/value – As the literature on sustainability and industry 4.0 expands, reviews capable of systematizing the main trends and topics of this research field are relevant.

Keywords Sustainability, Fourth industrial revolution, Smart manufacturing, Sustainable operations, Sustainable supply chain

Paper type Literature review

1. Introduction

Two major pressing issues of the current society are the emergence of industry 4.0 technologies and how to achieve a more sustainable society. A number of high-quality works in these fields have been produced; however, studies capable of systematizing the body of knowledge integrating industry 4.0 and sustainability can be useful for end-users trying to understand the characteristics and trends of this field. Originally, this current paper provides a thorough bibliometric and network analysis of more than 600 articles highlighting the benefits in favor of the sustainability dimension in the industry 4.0 paradigm.

Industry 4.0 has brought a new paradigm shift in manufacturing by amalgamating new technologies for delivering maximum output with effective resource utilization (Kamble *et al.*, 2018). The core of industry 4.0 lies in the emergence of digital manufacturing or "smart factory", which allow networking between industry units for creating mobility in processes and leads to flexibility of industrial operations through their interoperability (Jazdi, 2014). Industry 4.0 amalgamates the digital and physical realms through the cyber physical system (CPS) technology, leading the way for further industrial developments which allow productivity and efficiency improvement among various organizations that are implementing this novel manufacturing model (Pereira and Romero, 2017). Industry 4.0 assimilates big data, Internet of things (IoT) and Artificial Intelligence (AI) via smart factories for leveraging manufacturing operations (Tjahjono *et al.*, 2017).

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It is believed that industry 4.0 will enhance economic and social opportunities through the paradigm shift relating to work organization, business models and production technologies (Kagermann, 2013). Industry 4.0 has a remarkable potential for accomplishing sustainable industrial value creation across social, economic and environmental dimensions, improving the resource efficiency.

The definitions of sustainability have a broad spectrum and the characterizations range from survival of human race (Brown *et al.*, 1987), resource consumption (Mieg, 2012) and human impact on the environment (Hansmann *et al.*, 2012). Sustainability aims at meeting the resource needs of the current and the future generations without hampering the environment and it consists of three dimensions, viz. economic, social and environmental, i.e. the triple bottom line (TBL) (Elkington, 1994). It is a normative concept that represents the way society and business interact and react with the environment (Strandhagen *et al.*, 2017). Industry 4.0 holds massive prospects for comprehending sustainable industrial value creation along the TBL (Stock and Seliger, 2016).

Despite the probable advantages of industry 4.0 in paving the way for sustainable manufacturing practices, there are few reviews that have explored industry 4.0 from a sustainability perspective (de Sousa Jabbour *et al.*, 2018a, b; Kamble *et al.*, 2018; Okorie *et al.*, 2018; Fisher *et al.*, 2018; Song *et al.*, 2017). de Sousa Jabbour *et al.* (2018a, b) highlighted the critical success factors for environmentally sustainable manufacturing. Kamble *et al.* (2018) developed a framework on sustainable industry 4.0. Okorie *et al.* (2018) highlighted the digitization and circular economy. Fisher *et al.* (2018) highlighted how cloud manufacturing could be used an alternative for sustainable manufacturing. Song and Moon (2017) focused on deriving sustainability benefits from cybermanufacturing systems.

Taking into account the emergent connections in the literature on the themes sustainability and industry 4.0, the current study aims to investigate the significance of sustainability in industry 4.0 paradigm. Bibliometrics is a well-defined that is used in library science for identifying the information progress and growth in a specific knowledge field utilizing data such as author activities, publication trends, country collaborations to name a few (Firdaus *et al.*, 2019). Bibliometric analysis contributes to an effective association of organizing publication data assets, which are critical from the data management point of view (Wu *et al.*, 2015). The prominent advantages of carrying out a bibliometric analysis include the assessment of the growth in body of knowledge pertaining to a specific field, author's validation of centrality and exploration for their research, and for measuring the impact and quality of research studies (Firdaus *et al.*, 2019). This is followed by a network analysis which is a powerful tool for identifying the established and emerging research areas in a specific field of study. It further helps in identifying the clusters of theory development, past and present of research and researchers based on institutional and author emergent characteristics. Identification of influential researchers within the clusters sets the tone for determining the current trend topics under study.

This paper presents a comprehensive evaluation of the field, focusing on sustainability in industry 4.0, starting from a collection of over 1,000 published articles in Scopus and segregating this pool to more influential works and researchers. Through the usage of rigorous bibliometric tools, a comprehensive network analysis (e.g. citation and co-citation analyses) is completed and five major clusters of research are identified. These algorithmically identified clusters set the stage for topical classification of the published models and further investigation of the evolution of these clusters over years. From these results additional insights are also gained on the current research interests and potential directions for future research.

As industry 4.0 can enable sustainable business models of production and consumption by adding value to CE, the bibliometric analysis was carried out with following research questions in mind.

RQ1. What are the current trends of publication pertaining to sustainability domain in industry 4.0?

RQ2. What information is uncovered from this trend and what are the future directions of sustainability in industry 4.0?

Following this introduction, the rest of the paper is discussed as follows. Section 2 highlights the bibliometrics methodology. Descriptive findings are presented in Section 3. Discussions from the review are presented in Section 4. Based upon the findings from the review, the network analysis presented in Section 5. The study concludes by providing limitations and future research directions in Section 6.

2. Sustainability in industry 4.0 paradigm

This section discusses the various aspects underlying the sustainability dimension in industry 4.0 such as strategy, design, maintenance, purchasing, manufacturing, distribution, supply chain performance and closed-loop supply chains.

2.1 Manufacturing strategy

Manufacturing organizations world over are facing difficulties in embracing the challenges brought about by recent societal, technological and economic innovations. In order to tackle the challenges brought about by sudden technological disruptions, organizations need to have a clear strategic vision with their capabilities for reorganizing their value chains in a responsive manner (Schumacher *et al.*, 2016). Organizations can gain competitive advantage by utilizing sustainable manufacturing techniques for products and operations that are environment friendly (Jensen and Remmen, 2017). For environmentally sustainable decision-making in manufacturing, digital technologies form a fundamental component as they help in optimizing the resource usage, which in turn reduces the harmful impact on the environment (de Sousa Jabbour *et al.*, 2018a, b; Dubey *et al.*, 2019). To incorporate sustainability in manufacturing operations, collective success in areas such as manufacturing planning and control, workforce capability and performance measurement are required (Ngai *et al.*, 2013). As reported by Awan *et al.* (2018) based upon a survey of 239 manufacturing firms, enhanced supplier–buyer relationship helps in building cultural intelligence. This enhances inter-firm commitment to sustainability which improves the organizations social sustainability performance. Digitalization of production plays an important role for sustainable development. As reported by Beier *et al.* (2018) and Beier *et al.* (2017), transparency in the processes created by enabling digitalization across platforms can lead to effective environmental management in organizations. Environmentally sustainable manufacturing decision-making comprises effective system design and system operations for designing green products and processes (Gunasekaran *et al.*, 2014).

Previous studies have highlighted how servitization strategy (Rymaszewska *et al.*, 2017; Helo *et al.*, 2017), enabled by the industry 4.0 digital technologies, helps in the implementation of CE by embedding usage-focused business models (Bressanelli *et al.*, 2018) thereby leading to effective business strategies for sustainable operations. ur Rehman *et al.* (2016) and Song *et al.* (2017) discuss how big data predictive analytics in decision-making can lead to effective environmental strategies thereby minimizing costs and enhancing organizational resource efficiency. Gružauskas *et al.* (2018) present a competitive strategy based upon usage of autonomous vehicles contributing to optimal costs and sustainable distribution management. Fisher *et al.* (2018) investigate cloud manufacturing strategy adoption from an SME perspective and highlight the sustainability benefits associated with cloud manufacturing. Kusiak (2018) and Sjödin *et al.* (2018) argue how the implementation and adoption of smart manufacturing technologies and smart factory can lead to sustainable benefits through data-driven decision-making. Gupta *et al.* (2018) discuss the implementation of green strategies across Indian manufacturing organizations for assessing their sustainable manufacturing practices. Shim *et al.* (2017) investigate a flexible scheduling in a smart factory setup to enhance customer satisfaction leading to firm sustainability. Müller *et al.* (2018) report industry 4.0 has many implications for creating innovative and sustainable business models. Their study highlights data-driven value creation, system offerings instead of product offerings, enhanced customization as the prominent strategies in the industry 4.0 business models. Rauch *et al.* (2017) highlight the usage of industry 4.0 technologies leading to sustainable and transparent production strategies. Müller and Voigt (2018) discuss industrial value creation brought by the Industrial Internet of Things (IIoT) and draw a comparison between the sustainable strategies of industry 4.0 and Made in China 2025 initiatives. Kopacz *et al.* (2017) assess the sustainable mapping strategy of mining industry in Poland through software simulation and modeling. Prause and Atari (2017) highlight the relationship between organizational development and networking in the context of industry 4.0. Siemieniuch *et al.* (2015) highlight the importance of human factor in devising effective sustainable manufacturing strategies in industry 4.0.

The definitive objective of integrating sustainable manufacturing strategies and digital technologies is for progressing toward world-class sustainable manufacturing (Dubey *et al.*, 2015, 2016).

2.2 Sustainable design in manufacturing

Since the early 1970s, design has often been quoted as a foundation for sustainable development (Papanek, 1995). Sustainable design and manufacturing are garnering a lot of attention from the academia and the practitioners (Liu *et al.*, 2020). There is a rise in the number of environmental policies and regulations for controlling the harmful impacts of industrial production on the environment. As the demand for sustainable products is on the rise these days (Ottman, 2017), manufacturing organizations must consider the TBL parameters while designing and developing products (Eastwood and Haapala, 2015). Design for environment (Fiksel and Fiskel, 1996) is defined as the product design process that aims to reduce the harmful environmental impacts of the product throughout its lifecycle. It is an environmentally conscious decision which promotes product recycling and reusing (Hsu *et al.*, 2013; Jackson *et al.*, 2016). Design for sustainability is defined as the product design process that considers environmental and social aspects as the key elements in product design (Küçüksayraç, 2015; Crul *et al.*, 2006). As innovation is perceived to be the key element in industry 4.0, eco-innovation in industry 4.0 paradigm promotes environmental sustainability through sustainable economic models (Bonilla *et al.*, 2018).

Beier *et al.* (2017) highlight the concept of manufacturing for design (Chu *et al.*, 2016) based on hybrid manufacturing technologies for sustainable design of products. Li *et al.* (2018) discuss flexible layout design for enhancing ergonomics and resource efficiency. Tao *et al.* (2018) highlight the usage of CPS for product design for enhancing sustainability in the industry 4.0 paradigm. Bonilla *et al.* (2018) discuss the advantages of additive manufacturing in effectively improving and optimizing material design and selection. This creates a positive impact in the product use phase and allows for recycling and remanufacturing throughout the product lifecycle. Bressanelli *et al.* (2018) report how IoT and big data analytics (Kumar *et al.*, 2018a) help in improving product design based upon product data and effect CE practices. For incorporating sustainability in product design, products should be designed for recycling, remanufacturing and refurbishment to ensure multiple lifecycles for the product (Go *et al.*, 2015). Several product design strategies such as eco-design (Mont, 2008), design for product life extension (Bakker *et al.*, 2014), design for modularization (Nobre and Tavares, 2017) and design for remanufacturing (van Loon and Van Wassenhove, 2018; Okorie *et al.*,

2018) for integrating sustainability in product design. Fisher *et al.* (2018) discuss how cloud manufacturing enables sustainable product design and simulation and enhances provision for manufacturing as a service. Ding (2018) reports on design for eco-friendly medicines for ensuring longer shelf lives (Xie and Breen, 2012). Ekeh *et al.* (2014) discuss about sustainable production design for charcoal operations. Kamble *et al.* (2018) through their review, highlight the role of design in additive manufacturing. Kiel *et al.* (2017) discuss the collaborating role of suppliers and manufacturers in IIoT platforms for effective product and service design and engineering to enhance customer satisfaction and organization performance (Porter and Heppelmann, 2014).

2.3 Purchasing

Certain practices in the supply chain management address environmentally sustainable decision-making such as green supply chain management initiatives (green purchasing) and logistics practices (packaging, etc.) for reducing harmful environmental impacts (de Sousa Jabbour *et al.*, 2018a, b; González-Benito and González-Benito, 2006). For an organization, the role of purchasing in the supply chain is critical as it translates sustainability commitment into performance (Luzzini *et al.*, 2015). Beier *et al.* (2018) highlight how IIoT brings about transparency in the supply chain processes and enhances sustainability through effective environmental management and reporting. Purchasing decisions driven by data-driven decision-making in the CE enhance the resource efficiency by extending the product lifespan and closing the loop (Bressanelli *et al.*, 2018; Jensen and Remmen, 2017). This helps in efficiently carrying out the product end-of-life activities such as refurbishment, recycling and remanufacturing. Fu *et al.* (2018) discuss how a strategic carbon purchasing and trade based on blockchain technology can lead to sustainability in the apparel manufacturing industry. The blockchain technology provides transparency in the carbon trade process throughout the value chain. It also provides automation capability in manufacturing, decentralization and immutability to the environmental management system in consideration.

2.4 Smart manufacturing

The phenomena describing the production in industry 4.0 paradigm is referred to as smart manufacturing (Kusiak, 2018). Of late, many researchers have carried out studies pertaining to smart manufacturing trends (Cui *et al.*, 2020; Ghobakhloo, 2019). Thoben *et al.* (2017) discussed the CPS characteristics. Kang *et al.* (2016) identified important technologies of importance to smart manufacturing. Helu *et al.* (2016) discussed the requirements of data-driven decision-making in smart manufacturing. Zhong *et al.* (2017) highlighted how wireless technologies enabled interactions with smart manufacturing objects. Kusiak (2018), in their study, highlighted the six pillars of smart manufacturing. The six pillars of smart manufacturing as reported by Kusiak (2018) are materials, data, manufacturing technology and processes, resource sharing and networking, predictive engineering and sustainability. It can be inferred that sustainability holds paramount importance in manufacturing in industry 4.0 paradigm and manufacturing can be vital to sustainability (Siemieniuch *et al.*, 2015). Sustainability in manufacturing and green supply chain management were discussed by Chun and Bidanda (2013). Sjödin *et al.* (2018) highlight the concept of a smart factory (Rauch *et al.*, 2017; Latorre-Biel *et al.*, 2018), which would lead to an increase in the process efficiency, lower the operational costs, increase the quality of the product and enhance safety and sustainability. The sustainability criteria guide the development of manufacturing processes. Sustainable product design and development of sustainable materials are the examples of sustainability criteria which are to be considered in sustainable manufacturing operations.

Watanabe *et al.* (2016a) propose a framework and a new industrial business model (Watanabe *et al.*, 2016b) for a CPS-based production system and monitor its performance based on four sustainability parameters, viz. economic, social, technical and environmental. On a similar note, to tackle the arising sustainability pressure on organizations, Song and Moon (2017) have discussed the sustainability benefits of cybermanufacturing systems over traditional manufacturing systems. Ogu *et al.* (2018) highlight how cognizant computing in industry 4.0 can transform business models through data-driven decision-making (Nagy *et al.*, 2018). Zhang *et al.* (2014) highlighted how cloud computing can assist cloud-based manufacturing with high performance computing and service-oriented solutions. Fisher *et al.* (2018) have discussed cloud manufacturing as a service-based business model for sharing manufacturing capabilities and resources on a cloud platform. Their study describes how cloud manufacturing offers a more sustainable manufacturing option for process manufacturing industries (Thomas *et al.*, 2018). Tao *et al.* (2018) highlight how a digital twin driven, that is connecting physical product data and virtual product data to support product design and service, manufacturing and product design driven by big data analytics (Syafrudin *et al.*, 2017; Kumar *et al.*, 2018) can lead to sustainability in manufacturing operations. Waibel *et al.* (2017) investigate the effects of smart production systems on sustainability parameters in terms of resource efficiency and report on how wastes can be reduced through effective supplier relationships via enhanced network coordination and connected devices.

As reported by Garetti and Taisch (2012), sustainable manufacturing (Haapala *et al.*, 2013) is one of the most critical in the pursuit of sustainable development. Many studies have highlighted the aspect of sustainability in manufacturing through practical applications of industry 4.0 technologies in manufacturing, SMEs, electrical and electronics and heavy engineering industries. Yuan *et al.* (2017) highlight how smart manufacturing practices in oil refining and petrochemical industry can lead to sustainability in the oil and petrochemical value chain. Yazdi *et al.* (2018) highlight how overall equipment effectiveness (OEE) leads to manufacturing sustainability and industrial value creation (Müller and Voigt, 2018; Kiel *et al.*, 2017) based on resource efficiency in SMEs. Tsai and Lu (2018) reported a smart manufacturing model on production control with carbon tax for lower carbon emissions and reduced production costs. The effect of servitization and support of smart logistics on smart manufacturing to support sustainable business models was reported by Strandhagen *et al.* (2017). Stock *et al.* (2018) carried out a review on describing how smart manufacturing acts as an enabler for achieving sustainable development by qualitatively assessing the potential for ecological and social value creation. Based upon a survey of 221 electrical and electronics manufacturers in Brazil, Tumulero *et al.* (2019) report how radical eco-innovations in manufacturing based on digital transformations can enhance the socio-economic performance of an organization. Shim *et al.* (2017) highlight how open innovation and sustainability in operations can lead to greater customer satisfaction through product customization, manufacturing flexibility, delivery speed and ensuring quality of the product. Additive manufacturing is a new technology that has led to the development of new materials and has impacted product design drastically (Kusiak, 2018). Murmura and Bravi (2018) discuss the sustainability impact of 3D printing in the Italian wood and furniture sector organizations. The study highlights the benefits and limitations of adoption of 3D printing through a survey spanning 234 industries. Lugert *et al.* (2018) carried out a survey of 170 respondents from various manufacturing industries and investigated the adoption of lean practices (value stream mapping) in industry 4.0 scenario.

Kamble *et al.* (2018) investigated sustainable industry 4.0 through a review and provided a framework highlighting sustainable outcomes with process integration of industry 4.0 technologies. Industry 4.0 technologies have driven current research in the CE paradigm. Okorie *et al.* (2018) presents a review on how current research on CE is linked with manufacturing in industry 4.0. Jensen and Remmen (2017) investigate how product stewardship support CE in a data-driven manufacturing environment. Garbie (2017) highlight how product design can lead to sustainable manufacturing in industry 4.0. Another point to be considered is the contribution of human aspect in smart manufacturing. As reported by Siemieniuch *et al.* (2015), human factor plays a vital role in sustainable manufacturing (factors such as strategy, design and control). Manufacturing in the industry 4.0 realm will rely on extensive human–machine and human–system (autonomation) interactions (Kagermann, 2013). The increasing degree of automation highlights the importance of condition monitoring and warning systems to be in place for human and machine safety aspects (Kusiak, 2018).

2.5 Smart distribution

There has been an increased trend of deploying sustainable practices along all phases of the supply chain (Seuringand Müller, 2008) because of the stringent environmental requirements established by the climate change agreements (Centobelli *et al.*, 2017a). These have not only impacted the manufacturing practices drastically but, have opened new avenues for sustainable practices in manufacturing, distribution and transportation (Schrettle *et al.*, 2014; Dhakal *et al.*, 2016). The adoption of green initiatives by distributors plays a pivotal role in supporting the manufacturers and consumers working toward implementing sustainable environmental strategies (Centobelli *et al.*, 2017b; Maas *et al.*, 2014; Zailani *et al.*, 2011). Affordable and intelligible information and communication technology (ICT) tools have supported the organizations in the adoption of sustainable environment strategies in a positive manner (Stock and Seliger, 2016; Garrigos-Simon *et al.*, 2012). The extensive implementation of ICT permits new business models for distribution which will enhance the organizations pursuit for value creation through sustainable environmental initiatives (Kagermann, 2015). Digitization is perceived to be a key enabler for a reliable smart distribution system.

Digitalization can lead to many noteworthy effects on the manufacturing industry such as reductions in distribution, inventory handling costs which lead to shorter lead times. Optimizing the distribution and material handling processes also leads to increased economic sustainability (Nagy *et al.*, 2018). Yazdi *et al.* (2018) investigate and study the operation of a sustainable smart distribution system for improving the overall equipment effectiveness. For reducing the impact on the environment, distribution organizations are taking help of technologies such as emission control systems, GPS based real-time location systems to name a few (Centobelli *et al.*, 2017; Kang *et al.*, 2013). Beier *et al.* (2018) investigate the reduction of inventory through the usage of IIoT. Their study highlights the availability of digital customer information in reducing overproduction of products thereby enhancing inventory optimization. Bressanelli *et al.* (2018) highlight how data analytics and digital technologies help in optimizing distribution of products during the mid-phase of the product life cycle thereby acting as value drivers for CE. Ding (2018) highlights how the distribution process in pharma supply chains can be benefit from smart distribution. Technologies such as CPS, IoT and cloud computing enable connectivity and traceability for flow of information and materials thereby enhancing transparency and coordination along the supply chain. Emamisaleh and Rahmani (2017) highlight how optimized inventory levels lead to sustainability in the food supply chain industries. Majority of the studies have demonstrated how distribution efficiency can be increased through smart manufacturing (Kusiak, 2018) thereby closing the material loops within the economic dimension and enabling sustainability (Strandhagen *et al.*, 2017).

2.6 Supply chain performance

There has been a surge in the number of organizations striving to make sustainability a vital component of their business strategy (Yadav *et al.*, 2020; Gunasekaran and Spalanzani, 2012).

For sustainability commitment leading to supply chain performance improvement, it should be operationalized effectively throughout the supply chain network (Luthra *et al.*, 2020; Luzzini *et al.*, 2015; Wu *et al.*, 2015; Sarkis, 2012). Suppliers in the supply chain network can manage and measure their performance from parameters such as production planning, quality control and delivery reliability. Organizations can achieve effective environmental compliance through green supply chain initiatives across the supply chain (de Sousa Jabbour *et al.*, 2018a, b; Hofmann and Rüsch, 2017). Ding (2018) suggests that suppliers accredited with ISO14000 will reduce environmental risks (Low *et al.*, 2016) and enhance the environmental performance in the supply chain. Organizations can improve supply chain social responsibility performance through capacity development of suppliers on sustainable business practices (Ding, 2018; Mahapatra *et al.*, 2012). Branke *et al.* (2016), Wang *et al.* (2016) and Waibel *et al.* (2017) highlight how big data analytics applications improves process monitoring throughout the supply chain and enhance environmental performance by minimizing energy consumption and wastes. By implementing sustainable practices in the supply chains, CSR performance can be enhanced which adds intangible benefits to the organizations (Zhang *et al.*, 2017).

Of the many performance indicators, human performance in the supply chains is also perceived as a key enabler to sustainable operations (Luthra and Mangla, 2018; McLeod, 2017). Industry 4.0 enhances business performance by improvising product design, optimizing machine and material requirements in the supply chain management (Gilchrist, 2016; Lin *et al.*, 2017). Fisher *et al.* (2018) highlight how cloud manufacturing enhances process manufacturing performance through effective waste management practices. Studies have also shown how implementation of lean practices in the supply chain can lead to sustainable practices and enhanced environmental performance (Martínez-Juradoand Moyano-Fuentes, 2014; Vinodh *et al.*, 2011). For sustainable management of supply chains, Beske and Seuring (2014) identified five key categories which organizations should achieve in order to enhance sustainability performance of the organization. The five categories identified are organizations orientation toward sustainability (Seuringand Müller, 2008; Carter and Easton, 2011), continuity (Seuringand Müller, 2008; Molenkopf *et al.*, 2010), collaborations (Sarkis *et al.*, 2011; Harms *et al.*, 2013), effective risk management practices (Srivastava, 2007; Seuringand Müller, 2008; Gold *et al.*, 2010) and proactiveness (Miemczyk *et al.*, 2012).

2.7 Closed-loop supply chains

Organizations nowadays are paying a lot of attention toward their environmental and social footprint of business operations (Devika *et al.*, 2014). Globally, the supply chains are shifting toward sustainable supply chain management practices. As reported by Seuring and Müller (2008), a sustainable supply chain takes into consideration the social, environmental and economic impact of the supply chain operations throughout the value chain. In a sustainable supply chain, the product recovery management plays a very important role. Implementing a sustainable supply chain enables the organizations to reduce their undesirable environmental impacts and enhances the economic and social benefits (Zailani *et al.*, 2012; Soleimani *et al.*, 2017). The manufacturer can reuse, recover, and in some cases, even remanufacture some of the used parts of the product in a closed-loop supply chain (Huynh *et al.*, 2016).

A closed-loop supply chain is a combination of forward and reverse supply chain activities in a unique system for improving the environmental and economic performance (Krikke *et al.*, 2004). This unique system is designed, controlled and operated in order to maximize the value creation throughout the life cycle of a product. This ensures the dynamic recovery of value from different types and volumes of returns over time (Govindan *et al.*, 2015). Bressanelli *et al.* (2018) report on how digital technologies act as drivers for enabling CE in usage-focused business models. Their study elaborates on the fact that CE should be taken into consideration by implementing reverse logistics and closed-loop supply chains as CE decouples the economic growth from environmental losses and enables many closed-loop cycles of recycling, reuse and remanufacturing (Kumar and Putnam, 2008). The usage of digital manufacturing technologies enhances the product renovation and end-of-life events by furnishing remanufacturing, recycling and refurbishing details (Pagoropoulos *et al.*, 2017; Bressanelli *et al.*, 2018; Baines and Lightfoot, 2014). Jensen and Remmen (2017), taking case examples from the shipping, aircraft and automobile manufacturing, discuss how product stewardship and product end-of-life strategies relate with CE for resource efficient sustainable manufacturing. Martín-Gómez *et al.* (2019) drafted a holonic framework as an organizational enabler for integrating sustainable supply chain management practices in CE for mitigating the metabolic rift between natural and social capital. Various products, through their sustainable supply chain based on circularity, were validated by this holonic framework. Okorie *et al.* (2018), through their review on digitization and the CE, proposed a synergistic and integrative framework for assessing sustainability practices in digital manufacturing. Closed-loop supply chains create value for the organization (Schenkel *et al.*, 2015) and promote the transition toward sustainable manufacturing practices in the CE.

2.8 Maintenance

Maintenance processes ensure the safety, reliability and availability of the equipment and play a key role in sustainable operations. Industry 4.0 has the capability to offer modularized products that are interconnected with the IoT. With features such as interchangeability and upgrading, modularized products reduce the disposal rate of materials thereby transitioning to a shift from the traditional "seek and identify problem" scenario to smart and preventive maintenance (de Man and Strandahagen, 2017). As data would be collected from all the machines, digital manufacturing technologies will allow for predictive maintenance solutions based upon real-time data of machine health (de Sousa Jabbour *et al.*, 2018a, b; MacArthur and Waughray, 2016). Industry 4.0 technologies deploy sensors and actuators for real-time data collection (Yu *et al.*, 2015), and this data can be used for performance monitoring of products. In this way, depending upon product and service design, maintenance can be monitored and quality service solutions can be given to customers (Rymaszewska *et al.*, 2017).

Bressanelli *et al.* (2018) highlight the importance of preventive and predictive maintenance as enablers of CE within usage-focused business models. Sénéchal (2018) proposed a preliminary framework for integrating sustainability in maintenance dashboard in organizations. Franciosi *et al.* (2018) presented a scoping literature review to highlight sustainability in manufacturing in industry 4.0. Fisher *et al.* (2018) highlight how the implementation of additive manufacturing techniques such as cloud manufacturing can optimize maintenance costs. Cloud manufacturing also allows for adaptive-scheduling and condition-based monitoring based on real-time data (Mourtzis and Vlachou, 2018). With industry 4.0 technologies, fault occurrences will become predictive in nature because of real-time data modeling and simulation (Kusiak, 2018) thereby preventing major faults from occurring. Kumar *et al.* (2018b) classified maintenance into four categories, viz. corrective maintenance (Goyal *et al.*, 2016), preventive maintenance (Singh *et al.*, 2015), planned maintenance and condition-based maintenance and developed a framework for condition-based maintenance which minimizes economic losses by lifetime prognosis thereby addressing the sustainability concerns. The framework enhances customer-service quality by optimizing maintenance planning. Maintenance plays an important role in reducing the harmful environmental impact created by the industries (Afrinaldi *et al.*, 2017).

Sustainable maintenance is a topic less explored because of the real-time data constraints (Franciosi *et al.*, 2018). But, with the advent of industry 4.0 technologies, sensor networks (Zhang *et al.*, 2017) and enhanced IT connectivity allow for e-maintenance and condition-based monitoring.

2.9 Smart disposal

Sustainability has become a global concern due to climate change and depleting resources (Clarke, 2002). This has forced the producers and manufacturers to take requisite steps in order to reduce the impact of their product throughout its lifecycle. Design for environment and waste management at product end-of-life are such measures falling under the areas of extended producer responsibility (Gu *et al.*, 2019; McKerlie *et al.*, 2006). Industries can realize design for environment through judicious consumption of resources, minimizing emissions and wastes during the product lifecycle (Gu *et al.*, 2017). As electronic and electrical waste is one of the fastest growing wastes these days, extended producer responsibility is an important legal measure across countries to keep a check on this waste (Wang *et al.*, 2017; Zeng *et al.*, 2016). As reported by Lee *et al.* (2015), implementation of industry 4.0 technologies leads to enhanced productivity through work and waste reduction. Studies (de Man and Strandhagen, 2017; Stock and Seliger, 2016) have also suggested that industry 4.0 will lead to innovative business models which will enhance sustainability, reduce wastes and emissions and maximize reuse and recyclability throughout the supply chain.

3. Research methodology

A literature review forms the core of a research study. Review helps in providing valuable insights for investigating research in emerging fields and help frame directions for research in the future (Govindan *et al.*, 2015; Junior and Godinho Filho, 2010). After a thorough analysis and assessment of the pertinent literature, research gaps are found out which need to be worked upon for strengthening the research study (Tranfield *et al.*, 2003). This research study adopts the review procedure as reported by Saunders *et al.* (2016). The systematic literature review is achieved using an iterative cycle of defining the appropriate search keywords, searching relevant literature and performing the investigation at the end.

For this research study, pertinent sources of publication were identified in the fields of sustainability in industry 4.0 production. Articles were referred from the Scopus database which is one of the largest collections of peer-reviewed literature (Geraldi *et al.*, 2011).

Scopus encompasses research from renowned publishers, including IEEE, Taylor and Francis, Elsevier, Emerald, Springer and Wiley. The review methodology adopted a six-step process as shown by the flowchart in Figure 1 (Sharma *et al.*, 2018; Kamble *et al.*, 2018; Arunachalam *et al.*, 2018).

3.1 Selection of database

The authors devised a search strategy by accessing appropriate data sources. For ensuring the wide scope of the article selection for this review, Scopus was selected as the database. Scopus is one of the most widely used abstract and citation database as it includes many articles and abstracts from refereed journals in the domain of technology, management, medicine and social sciences (Mongeon and Paul-Hus, 2016). These refereed journals are affiliated to reputed publishing houses such as Wiley, Elsevier, Taylor and Francis, IEEE and Springer.

3.2 Keyword selection

As this literature review aims to establish a comprehensive, unbiased and reproducible article search procedure, the authors cited only the most significant and important research articles. Following were the keywords used by the authors "sustainability and industry 4.0", "sustainability and smart manufacturing," "sustainability and cloud manufacturing," "sustainability and cyber manufacturing" and "sustainability and cyber-physical systems". The use of these keywords also set the extent for the bibliometric analysis in the present study (see Table 1).

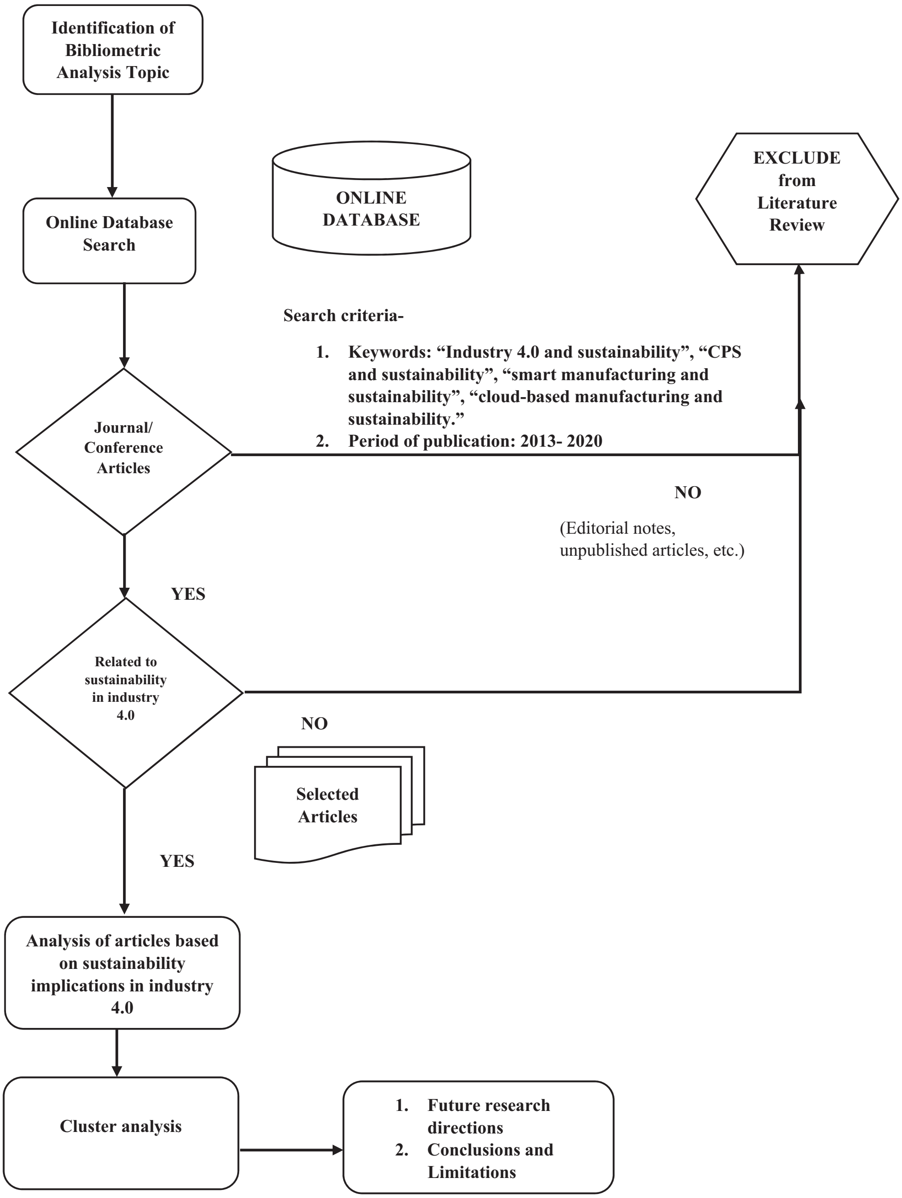

Figure 1.
Review methodology flowchart

3.3 Collection of articles

The time frame involved for the literature review covers the studies published during 2013–2019. The search returned 686 articles. For ensuring the initiation of the research from academic sources (Ramos-Rodríguez and Ruíz-Navarro, 2004; Lamba and Singh, 2017), editorial notes, book chapters and doctoral theses were not included in the search process. A further refinement based on the above criteria led to a drop in the number of articles to 666 as highlighted in Table 2.

3.4 Filtering (inclusion/exclusion of articles)

For further refining, the results, articles with incomplete bibliographic data points were excluded from the review.

3.5 Initial data statistics

Figure 2 highlights the trend in the quantity of articles published. As the topic of sustainability in industry 4.0 is relatively newer (Kagermann *et al.*, 2013) and the publications are increasing YoY at 16.9%. It can be further inferred that there is a geometric growth in the number of publications. The initial statistics show that the top ten journals have contributed to the publication of 188 papers (28%). Table 3 shows the sources in which these articles have appeared. Only the top ten sources are highlighted. For example, Sustainability, Procedia CIRP and Procedia Manufacturing, which occupy top position in this list, have the highest self-citation rates within this given sample. Alternatively, the citation data between the sources show that these sources are most cited by other journals.

3.6 Data analysis

As the study pertains to be a citation analysis study, an inductive approach is followed for the purpose of data analysis (Fahimnia *et al.*, 2015; Seuring and Müller, 2008). The literature

Search keywords	Search results (no. of papers)
Industry 4.0 AND "Sustainability"	309
Smart/intelligent manufacturing AND "Sustainability"	221
Cyber manufacturing AND "Sustainability"	75
Cloud manufacturing AND "Sustainability"	79
Total	684

Table 1.
Initial search results

Search keywords	Search results (no. of papers)
Industry 4.0 AND "Sustainability"	311
Smart/intelligent manufacturing AND "Sustainability"	201
Cyber manufacturing AND "Sustainability"	75
Cloud manufacturing AND "Sustainability"	79
Total	666

Table 2.
The search results after refinement

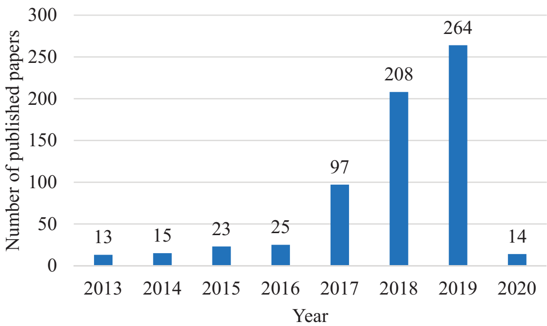

Figure 2.
Publishing trend in the area of sustainability in industry 4.0 paradigm

analysis part of this study has been done using deductive approach prior to actual data analysis. The data analysis is conducted using a bibliometric analysis and a network analysis which is presented in Sections 4 and 5. The bibliometric analysis is carried out using *R* software (bibliometrics package for science mapping). As it is programmed in using *R* software, the proposed tool is flexible and can be rapidly upgraded and integrated with other statistical R-packages. It is therefore, useful in a constantly changing science such as bibliometrics (Aria and Cuccurullo, 2017). For the network analysis part, the study utilized VOS Viewer network analysis software (Van Eck and Waltman, 2010). Both the software were open source and have the capability to work efficiently with large datasets thereby providing a wide range of innovative analysis, visualization and investigation options.

4. Bibliometric analysis

Various studies in the past have used different software with various capabilities and limitations for carrying out bibliometric analysis. Fahimnia *et al.* (2015) used BibExcel and Gephi in their bibliometric analysis on green supply chain management. Kamble *et al.* (2018) used Pajek, Gephi and BibExcel in their literature review on sustainability industry 4.0. Although Gephi and BibExcel are powerful tools for analyzing bibliographic data, they have certain limitations. Therefore, the current study used *R* to perform initial statistical analysis and prepared the data for network analysis using VOS Viewer. The study by Firdaus *et al.* (2019) also utilized *R* for carrying out bibliometric analysis on blockchain technology.

The bibliometric analysis in the current study is divided into four categories which also have multiple sub-categories. The main categories are (1) types of documents, (2) subject area, (3) authors and (4) countries. The sub-categories under authors were: (a) author's dominance factor rankings, (b) author's keywords, (c) total article citations, (d) country-wise total number of publications, (e) country-wise publications, (f) country-wise total citations and (g) collaboration networks (institutional). The findings are vital as they will help in generating the bibliometric information which can be used to unravel high impact research contributing toward new knowledge generation for sustainability in industry 4.0. Table 4 depicts the summary of 666 articles extracted from the Scopus database published between 2013 and 2019 (Nov 2019).

Table 3. Top ten publishing sources in the field of sustainability in industry 4.0

	Publication year								
Source	2013	2014	2015	2016	2017	2018	2019	2020	Total
Sustainability (Switzerland)	0	0	0	0	3	12	23	0	38
Procedia CIRP	1	5	4	2	6	5	6	0	29
Procedia manufacturing	0	0	1	1	8	11	7	0	28
IFIP advances in information and communication technology	1	0	4	2	4	8	7	0	26
Advances in intelligent systems and computing	0	0	0	0	2	2	7	3	14
Studies in computational intelligence	0	1	0	1	0	1	7	2	12
Journal of cleaner production	0	0	0	0	2	4	4	1	11
IOP conference series: materials science and engineering	0	0	0	0	1	2	8	0	11
International journal of production research	0	0	0	0	0	2	8	0	10
Journal of self-governance and management economics	0	0	0	0	0	0	9	0	9
Total	2	6	9	6	26	47	86	6	188

Table 4. Bibliometric analysis summary

Description	Results
Documents	666
Sources (Journals, Books, etc.)	310
Keywords plus (ID)	3,104
Author's keywords (DE)	1769
Period	2013–2020
Average citations per documents	5.932
Authors	1,895
Author appearances	2,267
Authors of single-authored documents	81
Authors of multi-authored documents	1,814
Single-authored documents	122
Documents per Author	0.359
Authors per document	2.79
Co-Authors per documents	3.33
Collaboration index	3.25

As it can be inferred from Table 4, these articles were written in 310 sources consisting of journals, books, conferences and proceedings. The keywords noted in the articles were 3,104. The number of authors identified from the articles was 1895, with 81 single authors in each article and the rest (1814) were articles written by multiple authors. The next sections elaborate further on the bibliometric analysis details.

4.1 Author influence and dominance factor

The author field was extracted from the data file using the *R* software. The frequency of appearance of top ten authors (with single and multiple co-authorships) is highlighted in Table 5. As it can be seen from the table that Trentesaux and Telukdarie dominate the list. Both these authors have collaborated with other authors on many articles. Majority of these researchers have backgrounds in operations research and supply chain management.

Author dominance factor (DF) is a ratio highlighting the fraction of multi-authored articles and the articles wherein the author acts as the first author (Kumar and Kumar, 2008). Studies by Wu *et al.* (2015) and Firdaus *et al.* (2019) have highlighted author dominance factors in their studies. The DF ranking is used in calculating an author's dominance in publishing articles. Mathematically, DF is given by

$$DF = \frac{Nmf}{Nmt}$$

Table 5. Top ten contributing authors and number of published articles

Authors	Number of published articles
Trentesaux, D	9
Telukdarie, A	7
Germani, M	6
Peruzzini, M	6
Taisch, M	6
Papetti, A	5
Romero, D	5
Wuest, T	5
Borangiu, T	4
Fathi, M	4

where *Nmf* is the number of multi-authored documents where the author is first author and *Nmt* is the total number of multi-authored documents by the author. DF ranking is shown in Table 6.

Romero, *D* has a DF of 0.6 and DF rank 1 as they are the first author in three articles out of total five multi-authored documents. DF rank 2 is shared by six authors as they are first authors in two documents out of the multi-authored documents.

4.2 Affiliation statistics

The affiliation statistics were extracted using the *R* software. The method used for assessing the impact of an institution is done by examining the weighted number of articles and weighted citations. Table 7a highlights the affiliation statistics for the overall collection of the documents (conference articles included) and Table 7b highlights the affiliation statistics for only journal articles. It can be inferred from Table 7a that University of Johannesburg, South Africa has the maximum contributions followed by the University of Minho and University of Zilina.

It can be inferred from Table 7a that University of Zilina, Slovakia has the maximum contributions followed by VSTEs School of Expertness and Valuation, Czech Republic and University of Johannesburg, South Africa.

4.3 Geographical region (country-wise) statistics

This section discusses the countries where research on sustainability in industry 4.0 is prominent based on article production, citations and corresponding author country.

Author	Dominance factor	Total articles	Single-authored	Multi-authored	First-authored	Rank by articles	Rank by DF
Romero, D	0.6	5	0	5	3	6	1
Borangiu, T	0.5	4	0	4	2	1	2
Giret, A	0.5	4	0	4	2	1	2
Gregori, F	0.5	4	0	4	2	1	2
May, G	0.5	4	0	4	2	1	2
Mller, J. M	0.5	4	0	4	2	1	2
Peruzzini, M	0.33	6	0	6	2	8	7
Telukdarie, A	0.285	7	0	7	2	9	8
Papetti, A	0.2	5	0	5	1	6	9
Trentesaux, D	0.1	9	0	9	1	10	10

Table 6.
Author dominance factor

Affiliations	Country	Articles
University of Johannesburg	South Africa	14
University of Minho	Portugal	10
University of Zilina	Slovakia	9
Purdue University	USA	8
Chalmers University of Technology	Sweden	7
Technical University of Sofia	Bulgaria	7
Tsinghua University	China	7
University of Modena and Reggio Emilia	Italy	7
Bina Nusantara University	Indonesia	6
Sungkyunkwan University	South Korea	6

Table 7a.
Top ten contributing organizations (with conference articles included)

Figure 3 highlights the country-wise production of articles related to the field of sustainability in industry 4.0. It can be inferred that Germany leads the articles production list with 116 articles, Italy with 115 articles and USA with 110 articles. The widespread outreach of the topic globally shows the importance of sustainability in the manufacturing domain as majority of the universities worldwide are adopting sustainable production and consumption practices.

Affiliations	Country	Articles
University of Zilina	Slovakia	11
The School of Expertness and Valuation	Czech Republic	7
University of Johannesburg	South Africa	6
University of Modena And Reggio Emilia	Italy	6
Tsinghua University	China	5
University of Miskolc	Hungary	5
University of Novi Sad	Serbia	5
Kaunas University of Technology	Lithuania	4
Linköping University	Sweden	4
Luleå University of Technology	Sweden	4

Table 7b. Top ten contributing organizations (only journal articles included)

Country	Articles	Frequency	SCP	MCP	MCP ratio
Italy	48	0.13296	37	11	0.229
Germany	40	0.1108	33	7	0.175
USA	24	0.06648	19	5	0.208
Korea	18	0.04986	18	0	0
United Kingdom	16	0.04432	9	7	0.438
Spain	13	0.03601	11	2	0.154
China	12	0.03324	10	2	0.167
Austria	11	0.03047	8	3	0.273
Brazil	11	0.03047	8	3	0.273
France	11	0.03047	6	5	0.455

Table 8. Corresponding author country

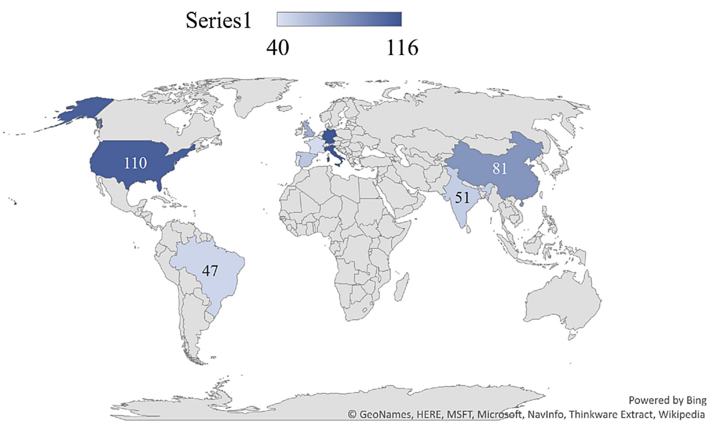

Figure 3. Country-wise article production

Table 8 highlights the corresponding author country based upon the article frequency, single authored documents and multi-authored documents. Most of the corresponding authors have their country as Italy, followed by Germany and the USA.

Table 9 highlights the total citations and average article citations country-wise. It can be inferred that USA leads with 438 citations, followed by Italy with 409 citations and Germany with 341 citations. The country collaboration map (see Figure 4) highlights the joint research initiatives between different institutions of different countries. It can be inferred from Figure 4 that there is a lot of collaboration among countries when it comes to sustainability in industry 4.0 domain (see Table 10) (see Figure 5).

4.4 Keyword statistics

Keyword statistics is an analysis used for identifying the most frequently used keywords/ phrases in the keywords and paper titles. The researchers have used multiple keywords and related it with sustainability in industry 4.0 in their research articles. Keyword analysis is an important part as this helps in analysis of research trends and identifying the possible research gaps in the research domain. The density visualization of author keywords is highlighted in Figure 5 using VOS Viewer. Further, a topic dendrogram is highlighted in Figure 6 which shows the hierarchical relationship between keywords generated from hierarchical clustering. It is used for allocating the objects to clusters by measuring the height of the different objects that are joined together in branches. The dendrogram starts with sustainability and industrial production/ development.

Table 9.
Country-wise citations

Country	Total citations	Average article citations
USA	438	18.25
Italy	409	8.521
Germany	341	8.525
Korea	127	7.056
South Africa	122	20.333
France	107	9.727
United Kingdom	80	5
Ireland	56	8
Czech Republic	54	9
Austria	51	4.636

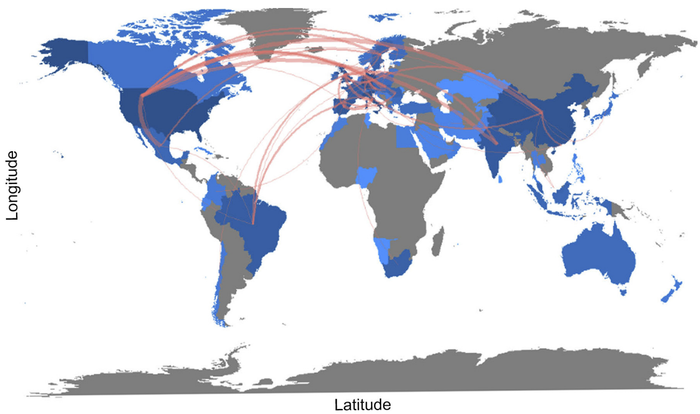

Figure 4.
Country collaboration

Words	Occurrences	Words	Occurrences
Industry 4 0	199	Smart manufacturing	44
Sustainable development	197	Big data	42
Manufacture	126	Flow control	40
Internet of things	69	Life cycle	40
Embedded systems	57	Information management	37
Sustainable manufacturing	56	Sustainability	32
Industrial research	53	Intelligent manufacturing	31
Decision-making	45	Energy efficiency	30
Industrial revolutions	45	Manufacturing	29
Competition	44	Cyber physical system	27

Table 10.
Keyword occurrences

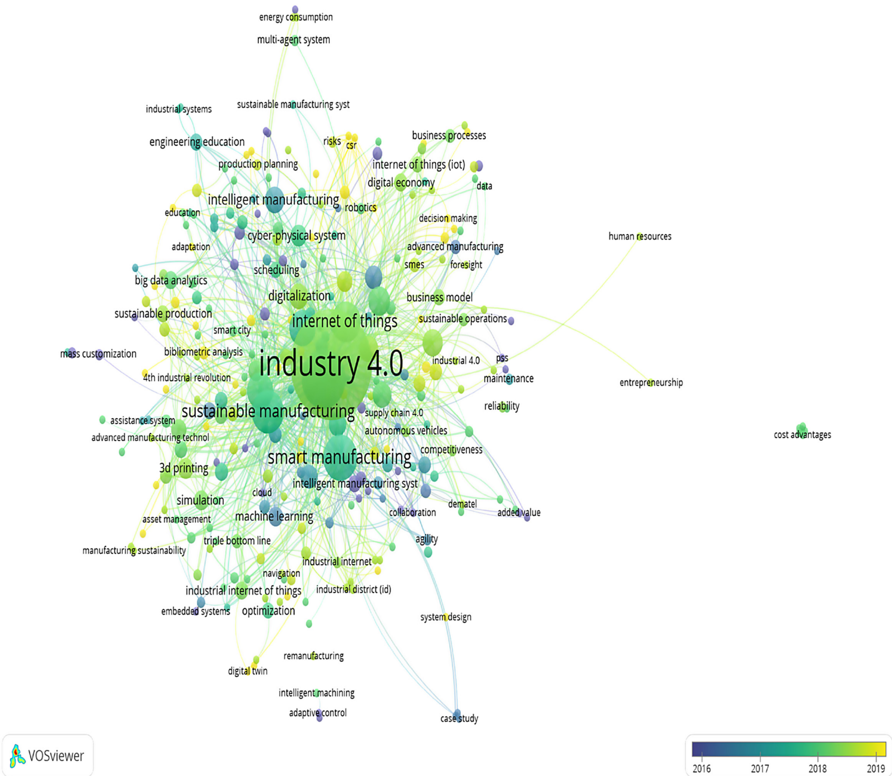

Figure 5.
Density visualization of author keywords

5. Network analysis of publications

In this section, a network analysis and graphical investigation is carried out for the selected sample. The current study has used *R* software and VOS Viewer for network analysis as both are open source. The dataset was saved in CSV format for network analysis and contains bibliographic data. The bibliographic data field is used for carrying out citation analysis.

5.1 Citation analysis

A citation analysis is used for examining the degree of connectivity between the articles. In citation analysis, the current study highlights the most global (Scopus citations) and local

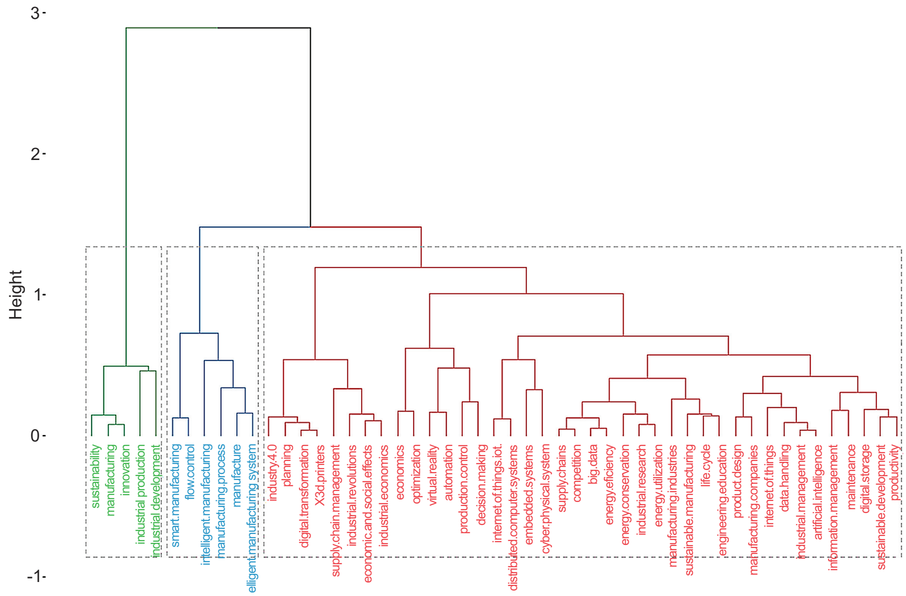

Figure 6.
Topic dendrogram

Author	Total citations	TC per year
Stock and Seliger (2016)	297	74.25
Davis *et al.* (2012)	259	32.375
Shrouf and Miragliotta (2015)	240	40
Kagermann (2015)	141	28.2
Haseeb *et al.* (2019)	110	110
Kusiak (2018)	98	49
Müller *et al.* (2018)	77	38.5
Shin *et al.* (2014)	63	10.5
Romero and Vernadat (2016)	62	15.5
Yue *et al.* (2015)	58	11.6

Table 11.
Global citations

cited (within the 666 selected articles) documents. In terms of global citations, Stock and Seliger (2016) has the maximum number of total citations, that is 297. Davis *et al.* (2012) has second-highest citations, that is 259. The authors are prolific in publications pertaining to sustainability in industry 4.0 and have written influential articles. It can be observed that most of the top global cited documents are from European authors. The total citation per year measure is used for capturing the immediate impact of a recently published article. It can be seen that, four of the top ten papers have received high number of total citations per year. Table 11 depicts the global citations and local citations are depicted in Table 12. The network structure for global citations is highlighted in Figure 7.

In terms of local citations received, Stock and Seliger (2016) have the maximum number of citations, that is 47 followed by Monostori (2014) with 15 citations.

5.2 Co-citation analysis

As reported by Pampel (2004), the co-citation analysis visualization is a form of exploratory data analysis (EDA) which relies on graph theory for exploring the data structure. In a co-

Cited references	Citations
Stock and Seliger (2016)	47
Monostori (2014)	15
Lee *et al.* (2014)	11
Fatorachian *et al.* (2018)	10
Lee *et al.* (2014)	10
Qin *et al.* (2016)	10
Xu *et al.* (2018)	10
Zhong *et al.* (2017)	10
Ivanov *et al.* (2016)	9
Kusiak (2018)	9

Table 12.
Local citations

citation map, the articles represent the nodes and the co-occurrence of the articles is represented by the edges (Leydesdorff and Welbers, 2011). Co-citation of two articles takes place when both articles are cited in a third article. Therefore, co-citation is the counterpart of bibliographic coupling. A co-citation network is obtained using the general formula:

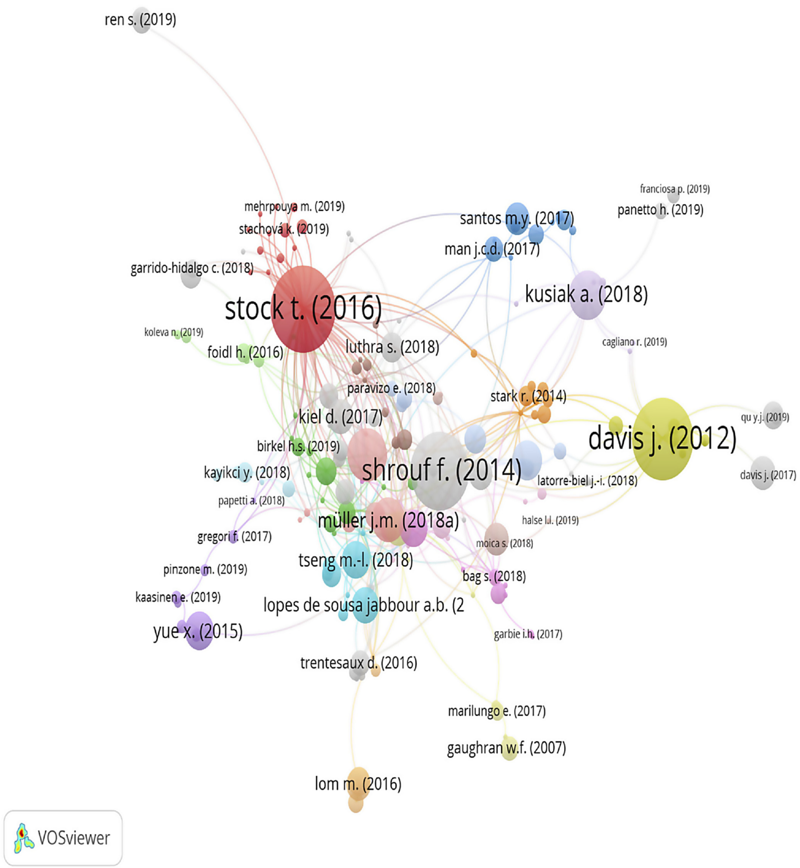

Figure 7.
Global citation network

$$B_{cocit} = A \times A$$

where A is an article × Cited reference matrix.

B_{cocit} is a symmetrical matrix and element b_{ij} indicates how many co-citations exist between articles i and j. The main diagonal of B_{cocit} contains the number of articles where a reference is cited in the study data frame. That is, the diagonal element b_{ij} is the number of local citations of the reference i.

The lead papers of each cluster are highlighted in Table 13.

5.2.1 Cluster analysis. In bibliometric analysis, emphasis is laid on analysis of networks which include authors, keywords or documents (Waltman *et al.*, 2010). Clustering is mostly used for studying such networks as it provides insights into the structure of a network. Hierarchical clustering is the most commonly used clustering technique (McCain, 1990). Usually, clustering and mapping techniques are combinedly used for network analysis. Generally, a map is constructed using the software wherein the individual nodes in the network are highlighted and clustered based on the inputs required. Another approach is to cluster the nodes of the network and construct a map using the software for highlighting node clusters (Waltman *et al.*, 2010; Van Eck and Waltman, 2010).

In cluster analysis, five major research clusters were identified for highlighting their area of research focus. Table 13 highlights the clusters identified based upon the total link strength (TLS).

In cluster 1, the prominent articles identified are by Xu *et al.* (2018) which has a TLS of 49. Their study highlights the various perspectives that industry 4.0 holds for practitioners and researchers. A framework is presented depicting the interoperability and business process management for industries to adopt industry 4.0 technologies. The article by Kamble *et al.* (2018) has a TLS of 47 and portrays the current status of research in industry 4.0. Their study highlights a sustainability framework for industry 4.0. The study by Lee *et al.* (2015) portrays how a CPS can be implemented for realizing smart manufacturing. The study by Kusiak (2018) presents the nine pillars of smart manufacturing. Further, their study reports conjectures for realizing digitization in manufacturing. The study by Moeuf *et al.* (2018) depicts the production planning, process and control functions of industry 4.0 in SMEs. It can be observed that the prime focus of the selected articles was on architecture framework and interoperability of industry 4.0 technologies. The common theme across the selected articles in cluster 1 was designing of frameworks to achieve digitization in manufacturing/ smart manufacturing.

In cluster 2, the study by Stock and Seliger (2016) has a TLS of 123. Their study reports on sustainability and value creation activities in industry 4.0. The study by Lee *et al.* (2014) discusses the concept of predictive maintenance for reducing machine downtime using real-time analytics. Hofmann and Rüsch (2017) highlight how implementation of industry 4.0 technologies in logistics can lead to enhanced flexibility and agility. Overall, cluster two highlights the shift toward sustainability and application of industry 4.0 frameworks in areas such as predictive maintenance, supply chain management and logistics.

In cluster 3, Zhong *et al.* (2017) highlight intelligent manufacturing using cloud computing and IoT suggesting a move toward a product service-based manufacturing ecosystem (servitization). Lu (2017) discusses enterprise architecture for interoperability of machines in a big data environment. The study by de Sousa Jabbour *et al.* (2018a, b) reports on the potential of industry 4.0 for creating sustainable business models. Schumacher *et al.* (2016) highlight the maturity assessment framework for industry 4.0 in a discrete manufacturing industry using maturity model for IT management. It can be observed that the focus of the studies has now shifted toward sustainable business models and toward assessing the IT maturity in industry 4.0 manufacturing ecosystems.

Cluster 1	Total link strength
Xu *et al.* (2018)	49
Kamble *et al.* (2018)	47
Lee *et al.* (2015)	44
Kusiak (2018)	41
Moeuf *et al.* (2018)	40
Cluster 2	**Total link strength**
Stock and Seliger (2016)	123
Lee *et al.* (2014)	46
Hofmann and Rusch (2017)	22
Shrouf and Miragliotta (2015)	21
Lee *et al.* (2014)	20
Cluster 3	**Total Link strength**
Hofmann and Rusch (2017)	37
Zhong *et al.* (2017)	31
Lu (2017)	30
de Man and Strandhagen (2017)	28
Schumacher *et al.* (2016)	23
Cluster 4	**Total Link strength**
Qin *et al.* (2016)	37
Sanders *et al.* (2016)	36
Monostori (2014)	32
Ivanov *et al.* (2016)	28
Teece (1997)	4
Cluster 5	**Total Link strength**
Fatorachian and Kazemi (2018)	39
Telukdarie *et al.* (2018)	27
Oztemel and Gursev (2018)	20
Rauch *et al.* (2020)	18
Wilkesmann and Wilkesmann (2018)	18

Table 13. Lead papers from the cluster

In cluster 4, Qin *et al.* (2016) report on how production can be optimized in an industry 4.0 framework. The study by Sanders *et al.* (2016) discusses the integration of lean management practices and industry 4.0 for business process improvement. Monostori (2014) depict the R&D challenges in incorporating industry 4.0 technologies. The study by Ivanov *et al.* (2016) highlights a dynamic scheduling scenario in a smart factory setting using simulation and optimization. This cluster has cited the work by Teece (1997) on dynamic capabilities and strategic management. Therefore, it can be said that, most of these works consider industry 4.0 technologies as resources that can endow competitive capabilities to organizations. The shift is now toward strategic management concepts in industry 4.0, that is design and planning strategies.

Finally, in cluster 5, the study by Fatorachian and Kazemi (2018) investigate industry 4.0 and its enabling technologies as a new operational approach in manufacturing. The study by Telukdarie *et al.* (2018) highlights the business strategy, system and data integration for facilitating real-time business optimization in industry 4.0. The review presented by Oztemel and Gursev (2018) highlights the holistic development and transition toward smart society using industry 4.0. The study by Rauch *et al.* (2020) highlights the human–machine interaction with and within an industry 4.0 ecosystem. Following the cluster analysis, it can be said that the focus has now shifted toward barriers/enablers in practical implementation (see Figure 8).

Using the *R* software, the current study presents a thematic mapping chart (see Figure 9) which highlights how the themes have evolved for the topic sustainability in industry 4.0.

Table 14 depicts the thematic evolution of topics from early automation to industry 4.0 and toward the adoption of sustainable business models.

6. Conclusion and future research directions

6.1 Final remarks

In this study, a bibliometric analysis of sustainability in industry 4.0 research was conducted analyzing 666 articles identified from the Scopus database. With the help of bibliometric analysis tools and techniques, key journals, influential institutions, impactful and trending articles were identified. Sustainability, Journal of Cleaner Production and International Journal of Production Research are the leading article sources (see Table 3). Among the most influential institutions, are University of Johannesburg, University of Minho and University of Zilina. The top trending articles are Xu *et al.* (2018), Kamble *et al.* (2018) and Lee *et al.* (2015) respectively are found after the co-citation analysis. Themes are identified and future research directions are described.

6.2 Implications for end-users and stakeholders

This work systematizes the body of knowledge on the integration of Industry 4.0 and sustainability. Our findings have the following implications for end-users, managers and policy makers.

First, our work reveals that, indeed, universities and researchers around the world have investigated the interface of Industry 4.0 and sustainability. Thus, there is evidence on the advantages and disadvantages of this process available for end-users and stakeholders in order to them to make evidence-based decision-making.

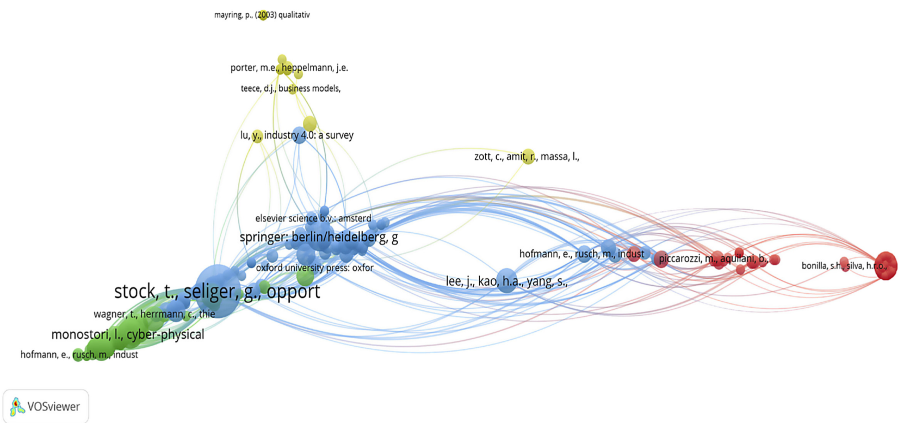

Figure 8.
Co-citation analysis

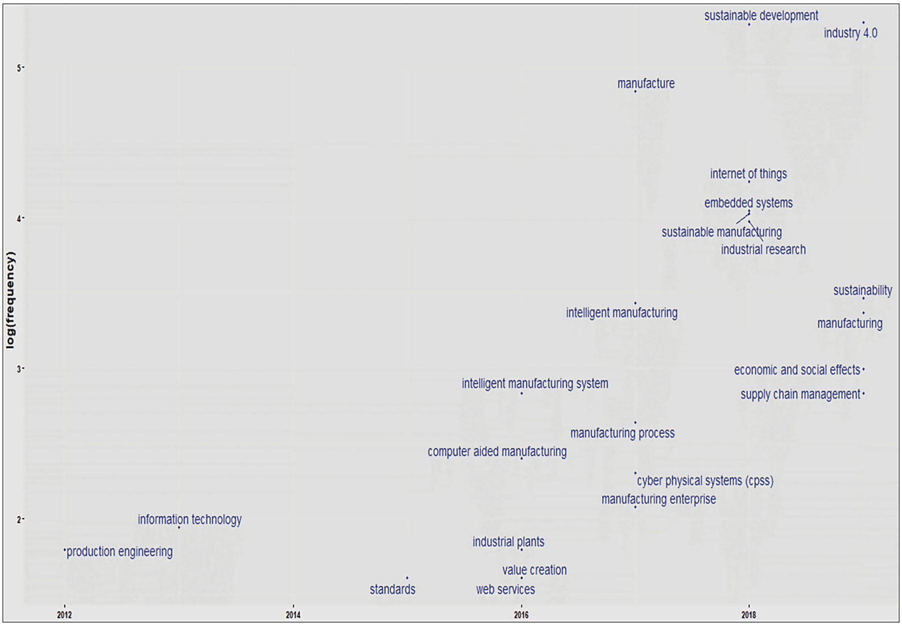

Figure 9.
Trend topics

Second, this work highlights the main technologies and terms used to better understanding the transition to sustainable organizations based on the adoption of Industry 4.0 technologies.

6.3 Future research

As most of the papers have proposed frameworks for industry 4.0 adoption and implementation, the proposed models and frameworks need to be empirically validated using empirical research or simulation (Kamble *et al.*, 2018). The current research on industry 4.0 needs to be replicated in different sectors, industries and geographies (Buer *et al.*, 2018), because there are different barriers to the adoption of industry 4.0 technologies in developed and developing countries (Raj *et al.*, 2019). Figure 10 systematizes the main industry 4.0 technologies and their relationships in order to unlock organizational sustainability.

The social/cultural and economic effects of the presented frameworks need to be further studied in detail. Also, there is a pressing need for research on the sustainability indicators (such as carbon emission evaluation functions, energy, wastes and labor to name a few) (Chaim *et al.*, 2018; Stock *et al.*, 2018; Franciosi *et al.*, 2018). The developed models need to be modified to consider external factors, such as policies or economic trends, as well as behavior of the individual cluster members as their decisions influence the effectiveness of the proposed strategy.

Extensive research on the human–machine interface and interoperability is required to minimize the information asymmetries and enhance the organizational performance (Rauch *et al.*, 2020). The link between the social dimension of sustainability and the use of digital technologies should be developed further.

From	To	Keywords
Automation–1998–2017	Embedded systems–2018–2018	Automation
	Big data–2018–2018	Big data; manufacturing companies; industrial management
	Embedded systems–2018–2018	Embedded systems
	Industry 4.0–2018–2018	Industry 4.0; industrial revolutions; information management
	Sustainable development–2018–2018	Internet of things; life cycle; Internet of things (IoT)
Competition–1998–2017	Decision-making–2018–2018	Energy efficiency
	Industry 4.0–2018–2018	Competition
	Sustainable development–2018–2018	Intelligent manufacturing system
Cyber physical system–1998–2017	Embedded systems–2018–2018	Cyber physical system
Manufacture–1998–2017	Decision-making–2018–2018	Decision-making
	Embedded systems–2018–2018	Flow control; smart manufacturing
	Sustainable development–2018–2018	Sustainable development; manufacture; intelligent manufacturing; manufacturing process; planning; energy utilization; optimization; sustainable manufacturing; industrial research; supply chains; product design
Manufacturing enterprise–1998–2017	Sustainable development–2018–2018	Environmental sustainability; economics
Big data–2018–2018	Industry 4.0–2019–2019	Manufacturing companies
	Manufacture–2019–2019	Maintenance; big data
Decision-making–2018–2018	Industry 4.0–2019–2019	Decision-making
	Manufacture–2019–2019	Energy efficiency
	Sustainability–2019–2019	Manufacturing; sustainability; industrial production; innovation
Embedded systems–2018–2018	Industry 4.0–2019–2019	Cyber physical system; embedded systems
	Manufacture–2019–2019	Flow control; smart manufacturing; automation
Industry 4.0–2018–2018	Industry 4.0–2019–2019	Industry 4.0; industrial revolutions; competition; information management; digital transformation; industrial economics
	Manufacture–2019–2019	Productivity
	Supply chain management–2019–2019	Supply chain management

Table 14.
Thematic evolution of keywords

(*continued*)

Table 14.

From	To	Keywords
Sustainable development–2018–2018	Article–2019–2019	Optimization
	Industry 4.0–2019–2019	Product design; sustainable development; planning; industrial research; supply chains; life cycle; sustainable manufacturing
	Internet of things–2019–2019	Internet of things; Internet of things (IoT)
	Manufacture–2019–2019	Energy utilization; manufacture; energy conservation

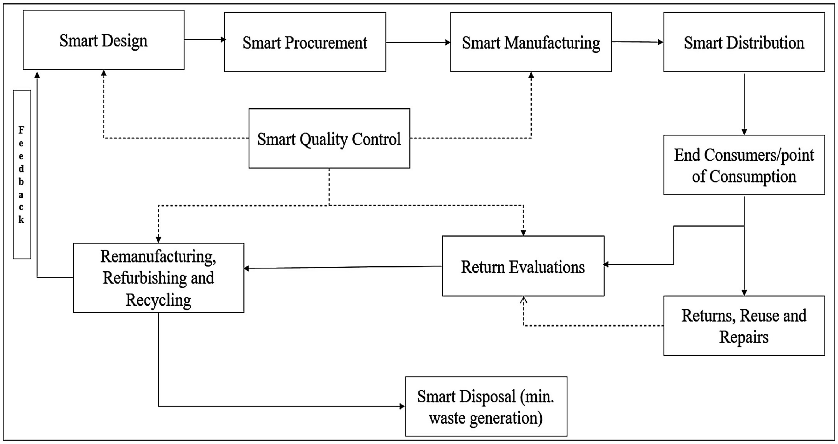

Figure 10. Proposed framework for future research

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