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Exploring industry 4.0 technologies for sustainable development goals: a systematic literature review

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Abstract:

In recent years, Industry 4.0 (I4.0) has emerged as a most significant concept in global manufacturing. Empirical research in the field of I4.0 or Smart Manufacturing (SM) is dominating continuously with great emphasis on conceptual models and case studies. Literature reviews of I4.0 or SM are less portrayed as compared to other manufacturing theories. In the present study, a categorized review of the published literature on I4.0 and SM is lucubrated and precisely visualized. The study examines the research trends in Industry 4.0 (I4.0) from 2011 to 2022, focusing on various parameters like definitions, research methods, journals, and authors to support sustainable development. It analyzed 121 articles, categorizing them by enablers, barriers, and sustainability aspects of I4.0. China, the USA, India, and Germany lead in publishing on I4.0. While conceptual models dominate, there's a growing focus on case studies and mathematical modeling. The study highlights challenges small industries face in adopting I4.0 due to resource constraints and emphasizes the need for government and expert support. It also shows that integrating Lean and Six Sigma with I4.0 can improve efficiency. However, the research lacks clarity on I4.0's long-term impacts, and few studies explore non-manufacturing sectors. The study concludes by identifying opportunities for further research, particularly in mathematical modeling, supply chain management, and linking sustainability with I4.0 technologies.

Key words:

Industry 4.0, smart manufacturing, intelligent manufacturing, flexibility, productivity, sustainability.

1. Introduction

Sustainable development is imperative for manufacturing industries due to its multifaceted benefits. By promoting resource efficiency and minimizing environmental impacts, sustainable practices in manufacturing help conserve raw materials, reduce energy consumption, and mitigate pollution (Egorov et al., 2019). Addressing climate change becomes a priority, with sustainable development aiming to lower carbon emissions and adhere to global climate goals (Aravindaraj and Chinna, 2022). Waste reduction measures not only contribute to environmental well-being but also offer long-term cost savings. Regulatory compliance is crucial in a landscape increasingly governed by environmental standards, while meeting market demands for socially responsible products enhances a company's reputation and consumer appeal. Beyond economic considerations, sustainable development fosters fair labor practices, community engagement, and the well-being of workers. As consumers become more environmentally conscious, businesses embracing

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sustainable practices gain a competitive edge. Overall, sustainable development in manufacturing ensures long-term viability, supply chain resilience, and a positive impact on both the environment and society, aligning with the ethos of meeting present needs without compromising the ability of future generations to meet their own (Nedaei et al., 2020; Ching et al., 2022). The current industries are transforming from analog and centralized concepts to digital and decentralized one. Industries are changing the present scenario of mass production to customized production. The fourth industrial revolution has emerged as new approach which focuses on real-time control and monitoring of production processes. More recently, manufacturing companies are continuously shifting towards technological paradigm shift to ensure economic growth, productivity improvement with sustainable manufacturing. Therefore, Governments in various countries have started smart initiatives namely 'Smart Manufacturing (SM)' in USA, 'Industry 4.0 (I4.0)' in Germany and *'Made in China 2025'* in China (Rosin et al. 2019). Indian government has also started *'Make in India'* and *'Digital India'* mission and provide resources for the industries to shift towards fourth generation of manufacturing. Japan initiates "Society 5.0" for the future that takes full advantage of Industry 4.0 technologies. It as a society focused on people, where economic growth and solving social problems go hand in hand. This is achieved by combining digital technology with the real world in a highly integrated way (Yang and Gu, 2021). The European Union supports research in the area of smart technologies. Its research program, "Horizon 2020," provides funding for projects focused on smart cities and communities. These projects include looking at how smart cities can help solve energy and transportation issues, and exploring how to expand the use of smart city solutions on a larger scale (Roblek et al. 2016).

These initiates will be beneficial for the overall sustainable growth. This building block of advanced technologies enables the production of personalized and customized products (Moeuf et al. 2019). I4.0 is digitization and intelligentization of various processes of entire life cycle of the product. Many disruptive technologies i.e. Cloud Computing (CC), Internet of Things (IoT), Big Data (BD), and Artificial Intelligence (AI) have permeated the manufacturing industries. Kusiak (2017) stated that smart manufacturing is autonomy, evolution, simulation and optimization of the manufacturing enterprise depending on the availability of data and tools. Big data, IoT, cloud computing and AI offers opportunity to transform traditional way of manufacturing to smart manufacturing (Tao et al. 2018).

Rapid advancements in industries, technologies and applications, have emerged with new concept of Industry 4.0 in manufacturing (Qin et al., 2016). Lu (2017) proposed framework to solve critical issues related to interoperability for Industry 4.0 design principles and elaborated that I4.0 was initiated in Germany and combines Cyber-Physical Systems, Internet of Things, Enterprise Architecture (EA), Integration of Enterprises (IoE), Information and Communication Technology (ICT). Industry 4.0 adoption requires high investment and support from top management due to dependent technologies (Akdil et al., 2018).

The German government has considered "Industry 4.0" as a high-tech technology for upcoming years and this term has become a hotspot for global industries. Industry 4.0 concepts will provide great opportunities. Industry 4.0 and lean manufacturing (LM) support each other and both aims to increase productivity and flexibility. The integration of both the domains affects different dimensions of production system (Buer et al., 2018). Small and Medium Scale Enterprises (SMEs) need to map themselves with emerging technologies of I4.0 while practicing existing lean manufacturing philosophies to be competitive in the global market. Manufacturing industries are converging different ICT technologies along with existing manufacturing technologies in order to make real time decisions.

1.1. Summary of the articles based on review of I4.0 or SM

In this review process, first of all it was decided to analyze 16 review articles based on I4.0 or SM (as shown in Table 1) out of total 121 articles which are screened in the study. The objective of doing this was to elucidate the overview of the review method to be adopted in the presented work. The review articles were analyzed based on 'type of review method applied in reviewing' and 'dimensions covered or focused points in the review' to extract the major dimensions to be covered in the present review. After analysis, it was found that most of the articles have covered very limited review parameters on the selected topics. Sharma et al. (2020) and Ejsmont et al. (2020) followed bibliometric with network

Table 1. Analysis of 16 existing review articles.

S. No.	Author	Type of review method	Dimensions covered / focused points
1	Yadav et al. (2022)	Systematic literature review	Reviewed the various technologies of industry 4.0 in agriculture food supply chain
2	Zheng et al. (2021)	Systematic literature review	Discussed the application of I4.0 enabling technologies in manufacturing companies
3	Sharma et al. (2020)	Bibliometric and intellectual network analysis	Outlined Industry 4.0 technologies and sustainability aspects
4	Ejsmont et al. (2020)	Systematic literature review and bibliometric network analysis	Impacts of I4.0 on sustainability
5	Sartal et al. (2020)	Descriptive work	Interpretations about concepts, evolution and opportunities of sustainable manufacturing in Industry 4.0
6	Alcacer and Cruz-Machado (2019)	Architectural review	Review of enabling technologies of Industry 4.0
7	Bonilla et al. (2018)	Concise description	Sustainability implications (impacts and challenges) of I 4.0-deployment, operation and technologies, integration and compliance
8	Gupta et al. (2019)	Systematic literature review and investigation framework	Big data techniques for LSS phases
9	Kusiak (2019)	Comprehensive assessment and multi-thread perspective	Characteristics of smart and sustainable manufacturing
10	Sony and Naik (2018)	Systematic literature review	Examined the essential components for determining an organization's level of Industry 4.0 readiness.
11	Ghobakhloo (2018)	State-of-the-art review	I4.0 design principles and technologies trends
12	Mittal et al. (2018)	Critical review	Review of existing I4.0 and smart manufacturing maturity models for SMEs
13	Ahuett-Garza and Kurfess (2018)	Descriptive review	Review of habilitating technologies of I4.0 and smart manufacturing
14	Kusiak (2017)	Exploratory study	Six pillars and ten conjectures characterizing smart manufacturing
15	Strange and Zucchella (2017)	Descriptive review	Provide assessment of adoption of I4.0
16	Yue et al. (2015)	Architectural review	Development and character of Cyber-Physical Systems

analysis in their review articles and outlined impacts of I4.0 technologies on sustainability. Sartal et al. (2020) in their descriptive work had interpreted about concepts, evolution and opportunities of sustainable manufacturing in I4.0. Alcacer and Cruz-Machado (2019) applied architectural review analysis in reviewing I4.0 technologies and interoperability standards of I4.0. Sustainability implications, impacts and challenges of Industry 4.0 were concisely described by Bonilla et al. (2018). Ghobakhloo (2018) illustrated state-of-the-art review on design principles and technologies of I4.0. It is also clear from Table 1 that I4.0 or SM technologies, challenges and opportunities are elaborated by most of the authors (Alcacer and Cruz-Machado, 2019). Mittal et al. (2018) critically reviewed existing maturity models of I4.0 and SM. Kusiak (2019) explained the characteristics of smart and sustainable manufacturing applying comprehensive assessment and multi-thread perspective method of review. Intelligent manufacturing and smart manufacturing concept, its importance, key features, implications and technologies of I4.0 assessment of adoption of I4.0 (Strange and Zucchella 2017) and standards of smart manufacturing are main dimensions that were reviewed and focused in descriptive studies. Yue et al. (2015) explained characteristics of CPS and IoT based smart factories.

After analysis of the review articles (Table 1) included in this qualitative synthesis, it is concluded that though the authors have covered various dimensions such as technologies, design principles, sustainable manufacturing in perspective of I4.0 or SM. But,

very few or limited studies have critically reviewed the existing articles in I4.0 or SM, and none of the existing reviews categorized the published articles over multiple parameters. Hence, there is need to synthesize the past work in the research domain which elucidate the current trends and vistas of I4.0 or SM. The present study deals with the following two research questions:

Q.1 What is the current scenario of Industry 4.0 technologies to enhance the sustainable manufacturing?

Q.2 What are the critical gaps in the current research on Industry 4.0, and how can future studies address the challenges of sustainability?

Therefore, the present study aims to evaluate and build a conceptual platform within the research domain through categorized review and analysis of articles over different dimensions to discuss the research question in details. The articles on the selected themes came into existence in 2011 when Germany coined the I4.0. Hence, this review study comprised the articles published between 2011 and 2022.

This paper is organized into six sections; Section 1 highlights introductory description about the domain followed by research background in Section 2. In Section 3, methodology used for review is listed followed by the classification of research articles on the basis of different dimensions in Section 4. Section 5 includes discussion about relationships between I4.0, LM, Lean Six Sigma (LSS) and sustainability. This section also describes the articles based on barriers, enablers of I4.0 or SM, whereas Section 6 and 7 deals with the conclusion which combines future research directions and limitations.

2. Industry 4.0 and Sustainable Development

In this section, evolution, concept and definitions of I4.0 or SM are discussed. The evolution of the manufacturing paradigms has gone through three industrial revolutions in the past. It was late 18th century when the first industrial revolution was coined with the development of water and steam power (Zheng et al. 2018; Sartal et al. 2020). Second industrial revolution was started in the beginning of 19th century when mass production was becoming popular through assembly line concept, electrical power and division of labour. Later in early 1970s, the third industrial revolution came in loop with the advent of IT automated production using PLCs. In the beginning of 21st century, the manufacturing paradigm is becoming more digital and intelligent with the emergence of fourth industrial revolution, also termed as I4.0. The term Industry 4.0 was coined in 2011 at the Hannover Fair in Germany (Qin et al. 2016). Serrano et al., 2021 reviewed the potential of Digital Twin (DT) technology and Zero-Defect Manufacturing (ZDM) in automating and optimizing smart manufacturing scheduling (SMS) and suggests future directions for improving autonomous scheduling systems with minimal human intervention.

The current factories are striving to become smart to cope up with the challenges of dynamic demands of customers. Global manufacturing scenario is transforming towards Industry 4.0 with the advent of disrupting technologies such as IoT, cloud computing, big data and AI. It is basically adding IoT and CPS concepts into manufacturing companies. In this transformation, physical objects i.e. machines, work, vehicles etc. are connected with cyber technologies such as RFIDs, microprocessors, sensors, actuators and other embedded systems. Manufacturing organizations in Germany are promoting inclusion of computerization in their processing, monitoring, supply chain, production planning, scheduling etc. Moeuf et al. (2019) described it as real-time synchronization approach for controlling the processes to produce customized products. Smart manufacturing has been defined by different authors (Kusiak, 2017; Moyne and Iskandar, 2017; Lin et al., 2018; Wang, Ma et al., 2018; Ding et al., 2019 and Kang and Lee, 2019). SM is integration of sensors, communication technologies, controlling devices, data intensive modeling, simulation and predictive engineering and reflects the effect of disruptive technologies of I4.0 such as CPS, IoT, cloud computing, service-oriented computing, AI and data science (Kusiak, 2017; Moyne and Iskandar, 2017; Lin et al. 2018).

Sustainable development integrates economic progress with environmental stewardship and social equity to meet current needs without compromising future generations. In the context of energy and the environment, it entails adopting renewable energy sources, minimizing carbon emissions, and promoting energy efficiency (Mitlin, 1992; Dantas et al., 2021). This involves transitioning from fossil fuels to cleaner alternatives, implementing green

technologies, and fostering conservation practices. Sustainable development aims to strike a balance between human activities and the Earth's capacity to support life, ensuring a resilient and harmonious coexistence between society, the economy, and the environment for the benefit of present and future generations (Qandil et al., 2021; Ruggerio, 2021).

Industry 4.0 improves responsiveness and efficiency of a production system by combining advanced technologies (Ahuett-Garza and Kurfess, 2018) and achieves process intelligence through smart factories (Ivanov et al., 2016). Industry 4.0 creates smartness in existing production systems by integrating digital and physical worlds using CPS and IoT (Bag et al., 2018). Saniuk and Grabowska (2020) explored that I4.0 refers to CPS and set new horizon in production and management with sustainable manufacturing. The fourth industrial revolution is the collection of connected and embedded systems that erase the barriers between real and virtual world through CPS and IoT (Machado et al., 2020; Rossit et al., 2018). Bonilla et al. (2018) called I4.0 as revolutionary approach of industrial and production systems. I4.0 has been considered as key enabler of digital transformation of the entire value chain (Oesterreich and Teuteberg, 2016).

Though the author/s has defined I4.0 in their perception, but still there is a need to formulate the concepts of the new paradigm in perspective of business and economic implications. I4.0 could be described with considerations of implementation strategies and expected economic results. The researchers are required to highlight the fundamentals, challenges, design principles and technologies in more fertile way, so that the practitioners could be benefited. From author's perspective, Industry 4.0 can be characterized by the collective application of information and communication technologies in the production systems to shift it to automation. Cyber-Physical Production System is the next step of Industry 4.0 in which production systems, machines, components and people can communicate using internet connection and digital twinning.

Exploring Industry 4.0 technologies for Sustainable Development Goals (SDGs) represents a crucial intersection of innovation and global responsibility. Industry 4.0, characterized by the integration of digital technologies into manufacturing processes, has the potential to revolutionize sustainable development (Bag et al., 2021). By leveraging these technologies, industries can enhance resource efficiency, reduce environmental impact, and optimize production processes. Smart manufacturing systems enable real-time monitoring and analysis, facilitating precise resource allocation and waste reduction. Furthermore, the application of artificial intelligence and data analytics enhances predictive maintenance, minimizing downtime and promoting sustainable consumption patterns (Khan et al., 2021).

In the pursuit of SDGs, Industry 4.0 fosters responsible production practices and supports economic growth while mitigating environmental harm. The use of interconnected devices and intelligent systems contributes to energy efficiency, thereby aligning with the global goals of combating climate change. Collaboration between governments, industries, and technological innovators is paramount to harnessing the full potential of Industry 4.0 for sustainable development (Oláh et al., 2020). Embracing these technologies not only propels industrial evolution but also demonstrates a commitment to building a more sustainable and equitable future, addressing key challenges outlined in the United Nations' SDGs.

3. Research methodology

The systematic literature review is an investigation method. This is typically used to draw out the important insights from the literature about the chosen subject and establishes strong foundation to know future research directions as well as current research trends in emerging fields (Govindan et al., 2015). This categorized review follows transparent steps as shown in Figure 1, to capture the snapshot about the research being done in the area of I4.0. For this study, the articles reported in reputed journals and recognized conferences, containing the word "*Industry 4.0*" and "*Smart Manufacturing*" in the title or in keywords, are included in this review (as per the methodology inputs, shown in Table 2).

This review analysis comprises peer-reviewed journal articles from ScienceDirect, Emerald insights, Taylor & Francis, Springer, MDPI and SAGE. Preliminary search was carried out from Scopus and Google Scholar data bases. The general search query was "Industry 4.0" OR "Smart Manufacturing" OR "Digital Manufacturing" AND "Sustainable Development" OR "Sustainability" OR "Sustainable Manufacturing" for the databases. Total 207 articles were considered at this stage. In the second stage, the articles having 'Industry 4.0' or 'Smart Manufacturing' in title or in keywords were included for the review.

Table 2. Summary of methodology.

Research inputs	Research articles
Literature review methodology	Categorized review of existing literature
Period covered	2011-2022
Databases used and publishers	Scopus, Google Scholar, ScienceDirect (Elsevier) , Emerald insight, Taylor & Francis, Springer, MDPI and SAGE
Keywords and phrases used to search articles from databases	Industry 4.0, Smart Manufacturing, Internet of Things, Cyber-Physical Systems, digital twin, barriers in Industry 4.0 implementation, enablers or critical success factors of Industry 4.0, Intelligent Manufacturing, Sustainability in Industry 4.0, Lean and Industry 4.0, Lean Six Sigma and Industry 4.0, Additive Manufacturing, Smart Factory, cloud manufacturing, Industrial Internet of Things
Total number of articles considered	121

Total 169 articles were screened at this stage of the methodology. At the third level of screening, 48 articles out of 169 were found not related to the selected themes. Conference papers, vague and non-english, short survey, editorial notes, news reports, viewpoints, unpublished articles and textbooks were not included in this review paper. Therefore, based on the exclusion criteria mentioned in Figure 1, finally 121 articles were selected for in-depth analysis based on multiple parameters. But, before that, the authors decided to analysis 16 review based research papers of SM/I4.0 (shown in Table 1 and as discussed in section 1.1) to identify the gaps and extract key dimensions to be covered in this analysis.

After analysis, the review or classification method and multiple-parameters were finalized. Then, at the fourth stage, 121 articles were categorized and analyzed based on selected perspectives such as concept or definition, key terms, year of publication, countries, research methods, journals, author's profile, active authors, enablers, barriers and sustainability. At the end of the paper, conclusive remarks and future implications are presented with limitations. Total articles included in this review are from reputed publishers.

Each article shortlisted in this study is deeply reviewed and best efforts were applied to extract conclusive information that can be helpful to understand the smart manufacturing and Industry

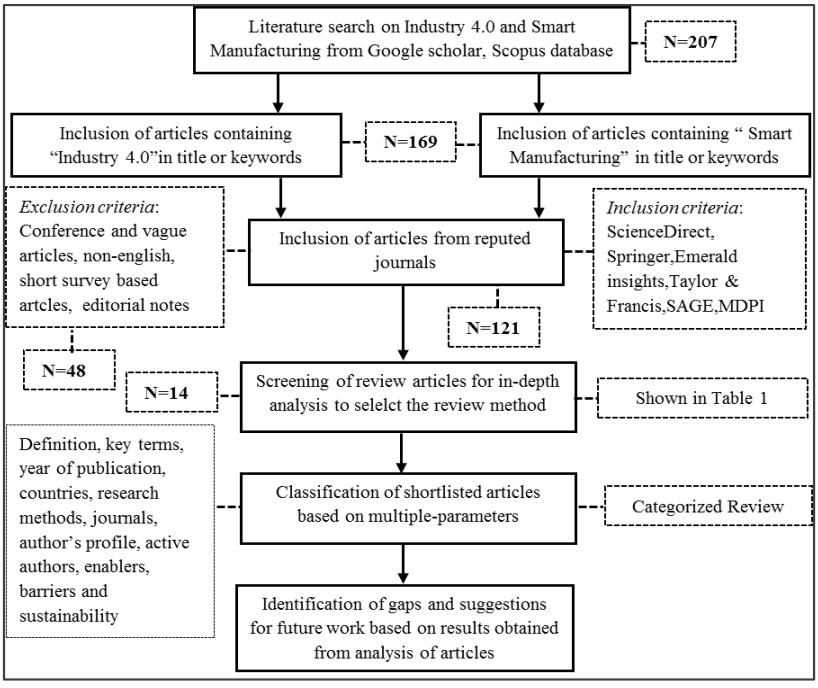

Figure 1. Research Methodology adopted for the study.

4.0. Although the study presented in this review is not exhaustive but, this will be a beneficial tool for practitioners working in this domain.

4. Analysis of classifications

In the present categorized review, rigorous research of the shortlisted articles was pursued to uncover the chronological growth of work in the selected domain. The articles are thoroughly reviewed and classified on various parameters and their analysis is presented in the subsections.

4.1. Categorization of articles based on key terms/synonyms used in existing articles

Due to a proliferation of research in recent years, not only by industry experts but, to a larger extent by academics and consultants, a number of other key terms have been used as synonyms such as SM, IoT, DT, CPS, CPPS, IIoT, AM, IM, SF and CM with a little of misconception among them.

Table 3 shows different industry 4.0 technologies which have illustrated by the different author/s in their research articles. These key terms denote the main stream of Industry 4.0. IoT and Cyber Physical System technologies are frequently floated by the authors in their research work.

It is clear from Table 3 that IoT and Cyber Physical System are the terms which has been used by most of the authors in their research articles, may be due to smartness of the manufacturing and service facilities which is possible by using I4.0 technologies followed by AI and Bigdata.

4.2. Categorization of articles based on publishers/journals

Comprehensive representation of all contributing publishers in terms of number of articles and percentage is shown in Figure 2. Among the prominent publishers, ScienceDirect has contributed major role in publication articles on I4.0 followed by Taylor & Francis, Emeraldinsight, Springer,

Table 3. Different key terms/synonyms used by the authors.

Authors	BD	IoT	DT	CPS	ML	AI	AM	AR/VR	BC	CC
Singh and Bhanot (2019), Zhang et al. (2014), Rajput and Singh (2018), Nagy et al. (2018), Manavalan and Jayakrishna (2018), Lelli (2019), Branger and Pang (2015), Zheng et al. (2021).	x	x		x		x		x	x	
Javaid (2022), Lu et al. (2020), Urbina Coronado et al. (2018), Moreno et al. (2017).			x		x					x
Bodkhe et al. (2020), Wang, Zhang, and Zhong (2020), Ding et al. (2019), Leng, Zhang et al. (2018), Zhuang, Liu, and Xiong (2018)		x	x	x		x				
Qian et al. (2020), Zhang et al. (2019), Kusiak (2019), Lin, Wang, and Sheng (2019), Tao, Qi et al. (2018), Wang, Ma et al. (2018) , Tuptuk and Hailes (2018), Ren et al. (2018), Sharp et al. (2018), Zhou, Lin et al. (2018), Ghobakhloo (2020).	x	x			x	x	x			
Kang and Lee (2019)		x			x	x	x		x	x
Han et al. (2022), Ma et al. (2019), Liu et al. (2018), Helo et al. (2014), Lee, Bagheri, and Kao (2015), Yue et al. (2015)				x						
Cheng, Zhang et al. (2018)	x	x		x						
Wang, Wan et al. (2016), Ivanov et al. (2016), Radziwon et al. (2014).									x	
Cheng, Chen et al. (2018)	x					x				
Kumar (2017)		x					x			
Matthyssens (2019).				x		x				
Xu (2012).										x
Nara (2021), Thomas and Trentesaux (2014).								x		

BG-Big Data, IoT-Internet of Things, DT-Digital Twin, CPS-Cyber-Physical Systems, ML-Machine Learning, AI Artificial Intelligence, AM-Additive Manufacturing, AR/VR- Augmented Reality and Virtual Reality, BC-Block chain, CC-Cloud Computing.

MDPI and SAGE. It is observed from analysis that ScienceDirect, Taylor & Francis, Emeraldinsights and Springer are the key publishers.

Figure 3 shows distribution of articles based on journals and recognized conferences. The authors have assigned coding from J1 to J19 for journals. In this section, the analysis does not include the journals published only one article.

There are various journals from production, manufacturing, engineering, processes, sustainability, quality, business, industrial, chemical science, robotic, computer engineering, supply chain management disciplines that covered articles on I4.0. *International Journal of Production Research* is meticulously focusing to publish research in the domain. *Emeralinsights* is also leading front in publication of articles in this series. Journals from other publishers viz. MDPI, SAGE are also putting efforts to carry out research in this direction. *Sustainability* and *Processes* from MDPI, *The International Journal of Advanced Manufacturing Technology* from Springer and *International Journal of Computer Integrated Manufacturing* from Taylor & Francis, have shared good contributions.

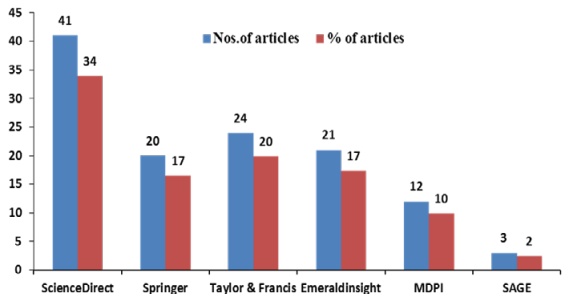

Figure 2. Classification of articles based on publishers.

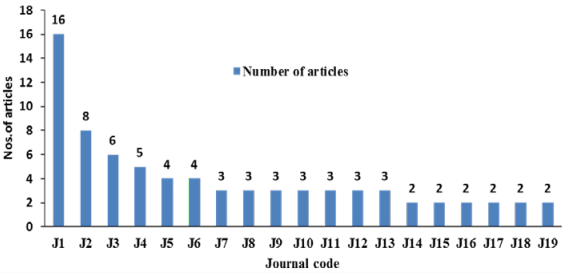

Figure 3. Articles based on journals.

J1- International Journal of Production Research, J2- Journal of Manufacturing Systems, J3-Sustainability, J4- Robotics and Computer Integrated Manufacturing, J5- Computers in Industry, J6- Journal of Cleaner Production, J7- Manufacturing letters, J8- Journal of Manufacturing Technology Management, J9- Industrial Management & Data Systems, J10- Assembly automation, J11- The International Journal of Advanced Manufacturing Technology, J12-Processes, J13- SAGE Published Journals, J14- International Journal of Production Economics, J15- Technological Forecasting & Social Change, J16- Journal of Industrial Information Integration, J17- Computers and Chemical Engineering, J18- Benchmarking: An International Journal, J19- International Journal of Computer Integrated Manufacturing.

4.3. Categorization of articles based on year of publication

Figure 4 shows the categorization of the articles based on the year of publication. This review analysis covers the articles published over the span of last 12 years from 2011 to 2022. There appears very limited research between 2011 and 2013, as the research on I4.0 during this span of time was in initial phase when Germany coined this word.

After 2013, I4.0 research increased significantly with the publications of articles based on *design principles* (Ghobakhloo 2018; Mittal, Khan et al. 2019; Akdil et al., 2018), *technologies* (Nascimento et al., 2018; Moeuf et al., 2019; Machado et al., 2020; Saniuk and Grabowska, 2020; Kamble et al., 2020; Alcacer and Cruz-Machado, 2019; Strange and Zucchella, 2017; Oesterreich and Teuteberg, 2016), *sustainability aspects of I4.0* (Saniuk and Grabowska, 2020; Machado et al., 2020; Hasseb et al., 2019; Muller et al., 2018), *integration of I4.0 with lean manufacturing* (Tortorella and Fettermann, 2017; Rosin et al., 2020; Rafique et al., 2016; Varela et al., 2019; Kaswan et al. 2022).

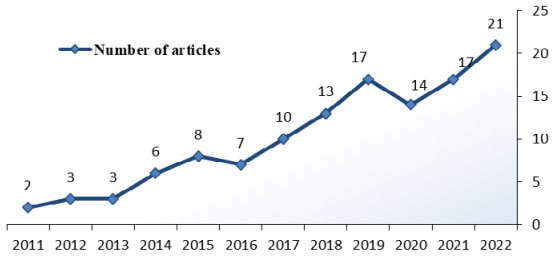

Figure 4. Classification of articles based on year of publication.

As per the analysis, it is found that after 2016, the research trend is blooming continuously and very large number of articles are published on the integrating manufacturing aspects i.e. lean manufacturing and I4.0, sustainable manufacturing and SM. It has been also observed that limited articles are on *integration of I4.0 and Lean Six*

Sigma (Yadav et al., 2020; Zwetsloot et al. 2018). Tremendous growth was observed in year 2018, as technological development was at its highest level in the field of I4.0. Therefore, year 2018 have significant share in publication based on I4.0 and SM disciplines. Since there are very less industries operating during the COVID-19 pandemic and no practical implications can be made, the majority of studies are framework-related. Following the COVID-19 pandemic, research publications increased year over year in 2021 and 2022.

4.4. Categorization of articles based on countries

The findings from research on I4.0 across literature have covered 31 countries around the world. As shown in Figure 5, Out of 121 articles, China has shared the largest number of publications (26 articles) followed by USA (14 articles). Apart from China and USA, the authors from Germany and India have shown marvelous performance in publications in the fields. Other countries like UK, New Zealand, Spain, Italy, Brazil, France, and Korea have contributed significant number of articles. Countries such as Sweden, Portugal, Turkey and Iran are putting good efforts in this direction, but the countries such as Austria, Taiwan, Finland, Romania, Norway, Ireland etc. are the locations where very limited or comparatively less number of publications was seen. This shows that there are ample possibilities in these locations for research and further expand the I4.0 base. Classifications of articles in this section are based on the country of the first author only.

The authors from China (Ding et al., 2019; Wang et al., 2020; Ma et al., 2019; Wang et al., 2018; Leng et al., 2018; Cheng, Zhang et al., 2018, and Zhuang et al., 2018) have focused on publishing the articles on *Digital Twin and Cyber-Physical Systems* to develop the platform for I4.0. *India* has also contributed collectively *with France* (Raj et al., 2019; Sharma et al., 2020) *and USA* (Kamble et al., 2018; Gupta et al., 2019) in developing the *concepts of the domain*. USA has focused on SM design principles and technologies to develop theoretical base to implement fourth generation paradigm. First authors from USA (Davis et al., 2012; Lee et al., 2015; Kumar, 2017; Kusiak, 2017; Mittal et al., 2019; Sharp et al., 2018; Frank et al., 2019) have shown sincere efforts to describe *theories of SM*. Germany also have shared good number of articles (Muller et al., 2018; Khan and Turowski, 2016; Oesterreich and Teuteberg, 2016; Ivanov et al., 2016; Schlechtendahl et al., 2014; Schmidt et al., 2015) on I4.0.

According to the HSRC (https://www.prnewswire.com) report, The U.S. as well as the China started to invest in the development of Industry 4.0 market and technologies to become the largest manufacturers globally. Therefore, researchers from China have shown greater contribution in this direction.

4.5. Co-occurrence network map for author keywords

As seen in Figure 6, the network map of keyword co-occurrences has also been thoroughly examined. The quantity of publications where two keywords appear together in the title, abstract, or keyword list is known as the co-occurrence of two keywords. The bigger the circle size, the more times the keyword appears in the papers that have been published. Industry 4.0, digital transformation, sustainable development, and machine learning are the terms

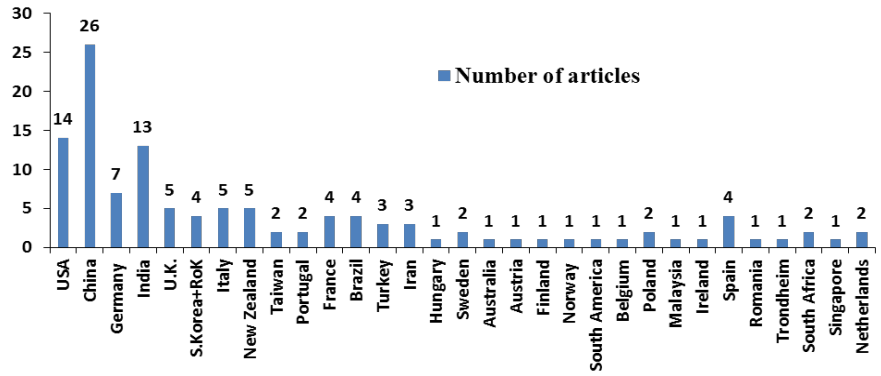

Figure 5. Classification of articles based on countries.

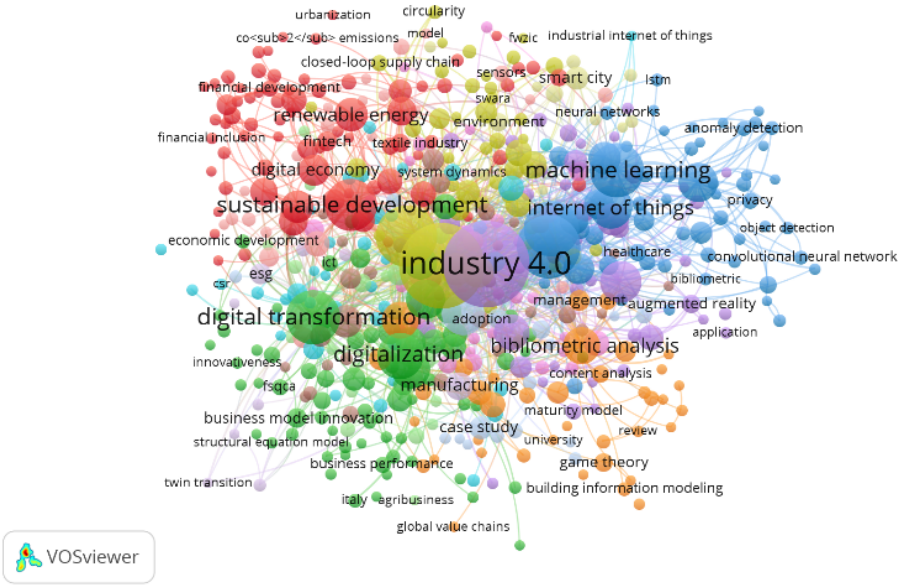

Figure 6. Co-occurrence network map for author keywords.

with the largest linkages with other keywords, as can be seen in the figure. The colour scheme displays the research clusters for the many study domains. The relationship between the terms and the frequency of their combination are depicted by the lines connecting the knots.

4.6. Affiliation wise categorization

Table 4 gives the affiliation wise categorization which helps to identify the leading institutions driving innovation and advancements in smart technologies. This information can guide collaboration opportunities, funding decisions, and recruitment of top talent. It also provides insights into emerging trends and cutting-edge research, helping businesses and policymakers stay ahead in the rapidly evolving field.the ideaaThe data lists the top 20 universities excelling in Industry 4.0, including institutions from China, Italy, Hong Kong, and more, known for their advanced research and innovation.

Table 4. Top 20 author affiliation universities.

S. No.	Author's Affiliation University/Institute
1	Huazhong University of Science and Technology
2	The Hong Kong Polytechnic University
3	University of Johannesburg
4	Ministry of Education of the People's Republic of China
5	Silesian University of Technology
6	Politecnico di Milano
7	Jamia Millia Islamia
8	Universiti Teknologi Malaysia
9	Tecnológico de Monterrey
10	King Saud University
11	Beihang University
12	Cranfield University
13	Nanyang Technological University
14	Universidade de São Paulo
15	Universidade do Minho
16	Universidade Federal de Santa Catarina
17	Shanghai Jiao Tong University
18	Wuhan University of Technology
19	Chongqing University
20	Universitat Politècnica de València

5. Categorization of articles based on proposed classification framework

In this section of the study, the authors have categorized the articles based on a conceptual framework shown in Figure 6. The objective of this classification is to investigate the relationships of I4.0 design principles and technologies with lean and sustainable manufacturing as well as Lean Six Sigma. The framework also represents the articles based on enablers and barriers to explore the different challenges and critical success factors of I4.0 identified in the selected articles.

As per the analysis, highest number of articles (As shown in Figure 7) reported the interlink between sustainable manufacturing and I4.0. Machado et al. (2020); Muller et al. (2018); Sartal et al. (2020) presented a conceptual framework of scope, opportunities of sustainable manufacturing in the development of I4.0 agenda and identified the gap for broader understanding of the relationships between I4.0 technologies and sustainable manufacturing principles. Saniuk and Grabowska (2020) identified the social changes and expectations towards the development and implementation of I4.0 concepts from mass production to customized production. Ejsmont et al. (2020) explored about the contributions of I4.0 design principles in the sustainable development of manufacturing. Leng et al. (2020) conducted survey on blockchain-empowered sustainable manufacturing and product life cycle management in I4.0.

Kamble et al. (2020) have described and investigated the impacts of integrated effects of I4.0 technologies and lean manufacturing practices on sustainable organizational performance in Indian companies. Manavalan and Jayakrishna (2018) formulated a conceptual model exploring the potential opportunities of IoT enabled sustainable supply chain in perspective of I4.0. Varela et al. (2019) evaluated the influences of two production philosophies of lean and I4.0 on three pillars of sustainability. Kamble et al. (2020); Rosin et al. (2019) examined the impacts and contributions of I4.0 technologies

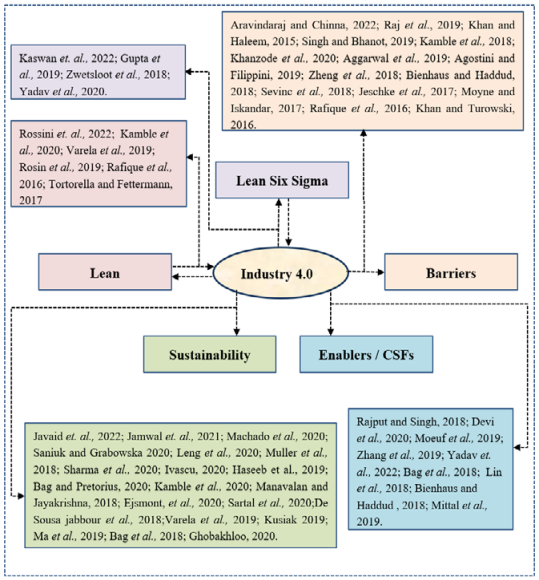

Figure 7. Conceptual framework of interlinking I4.0 with different dimensions.

for enhancement of lean manufacturing practices. Rafique et al. (2016) explained RFID-enabled lean manufacturing to control the barriers affecting manufacturing industries. Tortorella and Fettermann (2017) examined the status of implementation of I4.0 and lean production in Brazilian manufacturing companies.

6. Review Findings and Discussion

The objective of this categorized review is to scrutinize the status of research trends in I4.0 in terms of various parameters such as definition, synonyms, research methods, journals, author's profile etc to support sustainable development. In continuation, classification framework is also designed for categorization of the articles based on enablers, barriers and sustainability aspects of I4.0. A span of online database (2011-2022) was searched to obtain the critical listing of articles for getting better insights about the discipline. The articles were shortlisted after following the certain inclusion criterions using specific keywords and phrases listed in Table 2. Finally, total 121 articles were thoroughly reviewed and information gathered on different classification variables. Based on different dimensions, the articles were classified for better analysis and depiction of what the existing research has covered about I4.0. Research aimed to interpret the information on current trends, issues and future directions of the discipline. All the shortlisted articles were distributed in categories based on various parameters. Across the globe, this manufacturing paradigm is drawing the attention of academicians/practitioners/researchers. China, USA, India and Germany are leading in the publications on fourth industrial revolution which was reported in the literature during the study. The major outcomes depict that the conceptual models have highest credibility and the drift is stirring in the direction of case studies, survey and mathematical modeling. It is evident from the study that despite of plenty amount of research have published on I4.0 among the different publishers; still there exist ample opportunities for future research work on the topic to disclose various hidden aspects.

The discussion on the research questions stated in introduction section is as follows:

Research on Industry 4.0 has been initiated by several countries, with large industries making significant strides to adopt this new phase of manufacturing. However, small-scale industries are struggling to

fully embrace it due to a lack of financial and non-financial resources. Therefore, support from the government and industry experts is essential to help these organizations enhance their capacity to adopt Industry 4.0 technologies. Both management and shop floor workers need to be involved in this process.

The review findings show that manufacturing industries are attempting to incorporate Industry 4.0 technologies to remain competitive in today's fast-changing and highly competitive market. The conceptual framework suggests that existing quality methods like Lean and Six Sigma can be more effective when combined with Industry 4.0 technologies. Although research in this area is limited, there is potential for future studies to explore the integration of sustainability with this new manufacturing paradigm. The authors believe there is still some confusion among researchers about the definition of Industry 4.0, as it is a relatively new and somewhat unclear concept. This study provides a comprehensive overview of the research in this area, offering practitioners a guide to follow when transitioning to Industry 4.0. The authors note that more focus should be placed on using advanced simulations and mathematical models, incorporating insights from industry experts through interviews.

In Section 5 of the study, the articles are categorized based on a classification framework. The analysis shows that the authors covered barriers, enablers, and the integration of lean, Six Sigma, and sustainable manufacturing. While Industry 4.0 offers many benefits, organizations face challenges in adopting these new technologies, such as high investment costs, uncertainty about economic benefits, and a lack of skills, IT facilities, and infrastructure. The authors also identified key drivers for successful implementation, such as management support, Big Data analytics, real-time information, and IT infrastructure. Comprehensive training programs and supportive government policies play a significant role in success. Industry 4.0 technologies offer great potential for enhancing lean and sustainable manufacturing. However, the connection between Lean Six Sigma and Industry 4.0 has been explored in only a few studies.

The study also reviewed how Industry 4.0 (I4.0) technologies can support the United Nations' Sustainable Development Goals (SDGs). It shows that technologies like the Internet of Things (IoT), Artificial Intelligence (AI), and Big Data can significantly improve resource efficiency, reduce environmental impact, and promote clean energy. I4.0 can help industries transition to sustainable production by minimizing waste, cutting energy consumption, and improving supply chains. However, the research also highlights certain challenges. For example, there is limited integration of sustainability into current I4.0 strategies, and small businesses often lack the resources to adopt these technologies. The study suggests that more focus is needed on how I4.0 can be aligned with long-term environmental and economic goals. It concludes that, while I4.0 has great potential to advance sustainability, there is still much work needed to fully leverage its benefits.

Current research on Industry 4.0 (I4.0) reveals several critical gaps, particularly in sustainability. First, many studies rely on conceptual models and case studies, while few employ mathematical models, simulation, or fuzzy logic to support theoretical findings. There is also uncertainty about the long-term environmental and economic impacts of I4.0, and limited research evaluates sustainability over long time horizons. Moreover, most research focuses on the manufacturing sector, with little attention to other industries. A standardized framework for implementing I4.0 in a sustainable way is also lacking. The integration of I4.0 technologies, like blockchain and AI, into supply chain management for improved sustainability remains largely unexplored. Additionally, many studies are academic, without input from industry experts, which may lead to incomplete practical insights.

Future research should address these gaps by developing mathematical models, exploring cross-sector applications, and building frameworks for sustainable I4.0 implementation. Collaboration with industry experts will also help align I4.0 practices with real-world challenges.

7. Conclusion

In conclusion, this review provides a detailed look at the current trends and research on Industry 4.0, focusing on areas like sustainability, challenges, and opportunities for improvement. Although many countries and large companies have embraced Industry 4.0, smaller industries still struggle due to resource constraints. The study highlights the need for more collaboration between governments, industry experts, and businesses to overcome these challenges.

The review also shows that while there has been progress in integrating technologies like IoT, AI, and Big Data into manufacturing, there is still confusion about what Industry 4.0 really means and how it can be applied effectively. Moreover, most research has focused on large industries, and there is a lack of attention on small businesses and sectors outside of manufacturing. Many studies have used conceptual models rather than more rigorous methods like mathematical simulations, and there's a need for more research that looks at the long-term impacts of Industry 4.0 on both the environment and the economy.

The study has covered I4.0 spread in the articles using categorized review of the existing literature during period of last 10 years (2011-2022). The classification based on different parameters in this review analysis opens positive research directions in the area of fourth industrial revolution. The study has focused on the efficacy of I4.0 and has documented various attributes such as definitions proposed by different researchers, contribution in publication across the countries, research methods adopted by the authors. Despite of these, the authors have illustrated the research work interlinking I4.0 with Lean principles, Lean Six Sigma and sustainable manufacturing. Barriers and enablers are also demonstrated to plan the better implementation strategies by the practitioners. The researchers and practitioners can refer this review analysis for getting more insights in this new area of the research. The researchers and practitioners need deeper understanding of the challenges that can hinder the diffusion of I4.0 in current manufacturing organizations. The research presented could be used to develop a strong foundation of I4.0 practices while transforming the current manufacturing facilities towards smart and intelligent one. This may act as reference framework for the researchers as well as practitioners. However, this review paper has compiled various dimensions of I4.0 reflecting the spread of definitions, current research trends in the domain but in future, research can be carried out on studying design principles, technologies and practical applications of this emerging approach of manufacturing. The future research can also be focused on explaining the barriers and enablers of I4.0 in more descriptive way with the development of more conceptualized framework. It is expected that the divergent view of ongoing research presented in this paper would definitely help practitioners to develop plan for implementing I4.0 concepts. The study builds up the knowledge base for practitioners and academicians to get better understanding about the research trends in I4.0 domain.

Though, the authors have carried out this review analysis considering 121 articles from recognized journals. The analysis can be broadened including more articles and journals to get more information. The presented study is covered articles from six publishers such as ScienceDirect, Taylor & Francis, Emerald insights, Springer, MDPI and SAGE. There is scope to include more articles from journals of Inderscience, Wiley and other well-known publishers. In this study all the exertions have been made to apply analysis on various dimensions but this may be possible in future to discover more parameters to provide more comprehensive information on the topic.

References

Ahuett-Garza, H., & Kurfess, T. (2018). A brief discussion on the trends of habilitating technologies for Industry 4.0 and Smart Manufacturing. *Manufacturing Letters, 15*(B), 60-63. https://doi.org/10.1016/j.mfglet.2018.02.011

Akdil, K. Y., Ustundag, A., & Cevikcan, E. (2018). Maturity and readiness model for Industry 4.0 strategy. In A. Ustundag & E. Cevikcan (Eds.), *Industry 4.0: Managing the digital transformation* (pp. 61-94). Springer. https://doi.org/10.1007/978-3-319-57870-5_461-94

Alcacer, V., & Cruz-Machado, V. (2019). Scanning the Industry 4.0: A literature review on technologies for manufacturing systems. *Engineering Science and Technology, an International Journal, 22*, 899-919. https://doi.org/10.1016/j.jestch.2019.01.006

Aravindaraj, K., & Chinna, P. R. (2022). A systematic literature review of integration of industry 4.0 and warehouse management to achieve Sustainable Development Goals (SDGs). *Cleaner Logistics and Supply Chain*, 100072. https://doi.org/10.1016/j.clscn.2022.100072

Bag, S., Telukdarie, A., Pretorius, J. H. C., & Gupta, S. (2018). Industry 4.0 and supply chain sustainability: Framework and future research directions. *Benchmarking: An International Journal*. https://doi.org/10.1108/BIJ-03-2018-0056

Bag, S., Gupta, S., & Kumar, S. (2021). Industry 4.0 adoption and 10R advance manufacturing capabilities for sustainable development. *International Journal of Production Economics*, *231*, 107844. https://doi.org/10.1016/j.ijpe.2020.107844

Bodkhe, U., Tanwar, S., Parekh, K., Khanpara, P., Tyagi, S., Kumar, N., & Alazab, M. (2020). Blockchain for Industry 4.0: A comprehensive review. *IEEE Access*, *8*, 79764-79800. https://doi.org/10.1109/ACCESS.2020.2988579

Bonilla, S. H., Silva, H. R. O., da Silva, M. T., Goncalves, R. F., & Sacomano, J. B. (2018). Industry 4.0 and sustainability implications: A scenario-based analysis of the impacts and challenges. *Sustainability*, *10*, 3740. https://doi.org/10.3390/su10103740

Branger, J., & Pang, Z. (2015). From automated home to sustainable, healthy and manufacturing home: A new story enabled by the Internet-of-Things and Industry 4.0. *Journal of Management Analytics*, *2*(4), 314-332. https://doi.org/10.1080/23270012.2015.1115379

Buer, S. V., Strandhagen, J. O., & Chan, F. T. S. (2018). The link between Industry 4.0 and lean manufacturing: Mapping current research and establishing a research agenda. *International Journal of Production Research*, *56*(8), 2924-2940. https://doi.org/10.1080/00207543.2018.1442945

Cheng, J., Chen, W., Tao, F., & Lin, C. L. (2018). Industrial IoT in 5G environment towards smart manufacturing. *Journal of Industrial Information Integration*, *10*, 10-19. https://doi.org/10.1016/j.jii.2018.04.001

Cheng, Y., Zhang, Y., Ji, P., Xu, W., Zhou, Z., & Tao, F. (2018). Cyber-physical integration for moving digital factories forward towards smart manufacturing: A survey. *The International Journal of Advanced Manufacturing Technology*, *97*(1-4), 1209-1221. https://doi.org/10.1007/s00170-018-2001-2

Ching, N. T., Ghobakhloo, M., Iranmanesh, M., Maroufkhani, P., & Asadi, S. (2022). Industry 4.0 applications for sustainable manufacturing: A systematic literature review and a roadmap to sustainable development. *Journal of Cleaner Production*, *334*, 130133. https://doi.org/10.1016/j.jclepro.2021.130133

Dantas, T. E. T., de-Souza, E. D., Destro, I. R., Hammes, G., Rodriguez, C. M. T., & Soares, S. R. (2021). How the combination of circular economy and Industry 4.0 can contribute towards achieving the Sustainable Development Goals. *Sustainable Production and Consumption*, *26*, 213-227. https://doi.org/10.1016/j.spc.2020.10.005

Davis, J., Edgar, T., Porter, J., Bernaden, J., & Sarli, M. (2012). Smart manufacturing, manufacturing intelligence and demand-dynamic performance. *Computers and Chemical Engineering*, *47*, 145-156. https://doi.org/10.1016/j.compchemeng.2012.06.037

De Sousa Jabbour, A. B. L., Jabbour, C. J. C., Foropon, C., & Filho, M. G. (2018). When titans meet - Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors. *Technological Forecasting & Social Change*, *132*, 18-25. https://doi.org/10.1016/j.techfore.2018.01.017

Ding, K., Chan, F. T. S., Zhang, X., Zhou, G., & Zhang, F. (2019). Defining a digital twin-based cyber-physical production system for autonomous manufacturing in smart shop floors. *International Journal of Production Research*, *57*(20), 6315-6334. https://doi.org/10.1080/00207543.2019.1566661

Egorov, A., Semenov, A., Bebikhov, Y., & Sigaenko, A. (2019). Assessment of energy efficiency of the modernized main fan unit for an underground mine. *International Journal of Energy for a Clean Environment*, *20*(2). https://doi.org/10.1615/InterJEnerCleanEnv.2019026505

Ejsmont, K., Gladysz, B., & Kluczek, A. (2020). Impact of Industry 4.0 on sustainability: Bibliometric literature review. *Sustainability*, *12*, 1-29. https://doi.org/10.3390/su12145650

Frank, A. G., Dalenogare, L. S., & Ayala, N. F. (2019). Industry 4.0 technologies: Implementation patterns in manufacturing companies. *International Journal of Production Economics*, *210*, 15-26. https://doi.org/10.1016/j.ijpe.2019.01.004

Ghobakhloo, M. (2018). The future of manufacturing industry: A strategic roadmap toward Industry 4.0. *Journal of Manufacturing Technology Management*, *29*(6), 910-936. https://doi.org/10.1108/JMTM-02-2018-0057

Ghobakhloo, M. (2020). Industry 4.0, digitization and opportunities for sustainability. *Journal of Cleaner Production*, *252*, 1-21. https://doi.org/10.1016/j.jclepro.2019.119869

Govindan, K., Soleimani, H., & Kannan, D. (2015). Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future. *European Journal of Operational Research*, *240*(3), 603-626. https://doi.org/10.1016/j.ejor.2014.07.012

Gupta, S., Modgil, S., & Gunasekaran, A. (2019). Big data in lean six sigma: A review and further research directions. *International Journal of Production Research*, *58*(3), 947-969. https://doi.org/10.1080/00207543.2019.1598599

Han, H., & Trimi, S. (2022). Towards a data science platform for improving SME collaboration through Industry 4.0 technologies. *Technological Forecasting and Social Change*, *174*, 121242. https://doi.org/10.1016/j.techfore.2021.121242

Haseeb, M., Hussain, H. I., Slusarczyk, B., & Jermsittiparsert, K. (2019). Industry 4.0: A solution towards technology challenges of sustainable business performance. *Social Sciences*, *8*(5), 1-24. https://doi.org/10.3390/socsci8050154

Helo, P., Suorsa, M., Hao, Y., & Anussornnitisarn, P. (2014). Toward a cloud-based manufacturing execution system for distributed manufacturing. *Computers in Industry*, *65*, 646-656. https://doi.org/10.1016/j.compind.2014.01.015

Ivanov, D., Dolgui, A., Sokolov, B., Werner, F., & Ivanova, M. (2016). A dynamic model and an algorithm for short-term supply chain scheduling in the smart factory industry 4.0. *International Journal of Production Research*, *54*(2), 386-402. https://doi.org/10.1080/00207543.2014.999958

Javaid, M., Haleem, A., Singh, R. P., Suman, R., & Gonzalez, E. S. (2022). Understanding the adoption of Industry 4.0 technologies in improving environmental sustainability. *Sustainable Operations and Computers*, *3*, 203-217. https://doi.org/10.1016/j.susoc.2022.01.008

Kamble, S. S., Gunasekaran, A., & Sharma, R. (2018). Analysis of the driving and dependence power of barriers to adopt Industry 4.0 in Indian manufacturing industry. *Computers in Industry*, *101*, 107-119. https://doi.org/10.1016/j.compind.2018.06.004

Kamble, S. S., Gunasekaran, A., & Dhone, N. C. (2020). Industry 4.0 and lean manufacturing practices for sustainable organizational performance in Indian manufacturing companies. *International Journal of Production Research*, *58*(5), 1319-1337. https://doi.org/10.1080/00207543.2019.1630772

Kang, H. S., & Lee, J. Y. (2019). A dynamic processing methodology of manufacturing data for the automated throughput analysis in cyber-physical production environment. *Concurrent Engineering: Research and Applications*, *27*(2), 155-169. https://doi.org/10.1177/1063293X19842264

Kaswan, M. S., Rathi, R., Cross, J., Garza-Reyes, J. A., Antony, J., & Yadav, V. (2022). Integrating Green Lean Six Sigma and Industry 4.0: A conceptual framework. *Journal of Manufacturing Technology Management*, *34*(1), 87-121. https://doi.org/10.1108/JMTM-03-2022-0115

Khan, U., & Haleem, A. (2015). Improving to smart organization: An integrated ISM and fuzzy-MICMAC modelling of barriers. *Journal of Manufacturing Technology Management*, *26*(6), 807-829. https://doi.org/10.1108/JMTM-05-2014-0062

Khan, I. S., Ahmad, M. O., & Majava, J. (2021). Industry 4.0 and sustainable development: A systematic mapping of triple bottom line, circular economy and sustainable business models perspectives. *Journal of Cleaner Production*, *297*, 126655. https://doi.org/10.1016/j.jclepro.2021.126655

Kumar, A. (2017). Methods and materials for smart manufacturing: Additive manufacturing, internet of things, flexible sensors and soft robotics. *Manufacturing Letters*, *15*(B), 122-125. https://doi.org/10.1016/j.mfglet.2017.12.014

Kusiak, A. (2017). Smart manufacturing. *International Journal of Production Research*, *56*(1-2), 508-517. https://doi.org/10.1080/00207543.2017.1351644

Kusiak, A. (2019). Fundamentals of smart manufacturing: A multi-thread perspective. *Annual Reviews in Control*, *47*, 214-220. https://doi.org/10.1016/j.arcontrol.2019.02.001

Lee, J., Bagheri, B., & Kao, H. (2015). A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters*, *3*, 18-23. https://doi.org/10.1016/j.mfglet.2014.12.001

Lelli, F. (2019). Interoperability of the time of Industry 4.0 and the Internet of Things. *Future Internet*, *11*(36), 1-13. https://doi.org/10.3390/fi11020036

Leng, J., Zhang, H., Yan, D., Liu, Q., Chen, X., & Zhang, D. (2018). Digital twin-driven manufacturing cyber-physical system for parallel controlling of smart workshop. *Journal of Ambient Intelligence and Humanized Computing*, *10*(3), 1155-1166. https://doi.org/10.1007/s12652-018-0881-5

Leng, J., Ruan, G., Jiang, P., Xu, K., Liu, Q., Zhou, X., & Liu, C. (2020). Blockchain-empowered sustainable manufacturing and product lifecycle management in Industry 4.0: A survey. *Renewable and Sustainable Energy Reviews*, *132*, 110112. https://doi.org/10.1016/j.rser.2020.110112

Lin, D., Lee, C. K. M., Lau, H., & Yang, Y. (2018). Strategic response to Industry 4.0: An empirical investigation on the Chinese automotive industry. *Industrial Management & Data Systems*, *118*(3), 589-605. https://doi.org/10.1108/IMDS-09-2017-0403

Lin, T. C., Wang, K. J., & Sheng, M. L. (2019). To assess smart manufacturing readiness by maturity model: A case study on Taiwan enterprises. *International Journal of Computer Integrated Manufacturing*, *33*(1), 101-115. https://doi.org/10.1080/0951192X.2019.1699255

Liu, C., Vengayil, H., Zhong, R. Y., & Xu, X. (2018). A systematic development method for cyber-physical machine tools. *Journal of Manufacturing Systems*, *48*(C), 13-24. https://doi.org/10.1016/j.jmsy.2018.02.001

Lu, Y. (2017). Industry 4.0: A survey on technologies, applications and open research. *Journal of Industrial Information Integration*, *6*, 1-10. https://doi.org/10.1016/j.jii.2017.04.005

Lu, Y., Liu, C., Wang, K. I. K., Huang, H., & Xu, X. (2020). Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues. *Robotics and Computer-Integrated Manufacturing*, *61*, 1-14. https://doi.org/10.1016/j.rcim.2019.101837

Ma, S., Zhang, Y., Lv, J., Yang, H., & Wu, J. (2019). Energy-cyber-physical system enabled management for energy-intensive manufacturing industries. *Journal of Cleaner Production*, *226*(20), 892-903. https://doi.org/10.1016/j.jclepro.2019.04.134

Machado, C. G., Winroth, M. P., & Ribeiro da Silva, E. H. D. (2020). Sustainable manufacturing in Industry 4.0: An emerging research agenda. *International Journal of Production Research*, *58*(5), 1462-1484. https://doi.org/10.1080/00207543.2019.1652777

Manavalan, E., & Jayakrishna, K. (2018). A review of Internet of Things (IoT) embedded sustainable supply chain for Industry 4.0 requirements. *Computers and Industrial Engineering*, *127*, 925-953. https://doi.org/10.1016/j.cie.2018.11.030

Matthyssens, P. (2019). Reconceptualizing value innovation for Industry 4.0 and the Industrial Internet of Things. *Journal of Business & Industrial Marketing*, *34*(6), 1203-1209. https://doi.org/10.1108/JBIM-11-2018-0348

Mitlin, D. (1992). Sustainable development: A guide to the literature. *Environment and Urbanization*, *4*(1), 111-124. https://doi.org/10.1177/095624789200400112

Mittal, S., Ahmad, M., Romero, D., & Wuest, T. (2018). A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). *Journal of Manufacturing Systems*, *49*, 194-214. https://doi.org/10.1016/j.jmsy.2018.10.005

Mittal, S., Khan, M. A., Romero, D., & Wuest, T. (2019). Smart manufacturing: Characteristics, technologies and enabling factors. *Journal of Engineering Manufacture*, *233*(5), 1342-1361. https://doi.org/10.1177/0954405417736547

Moeuf, A., Lamouri, S., Pellerin, R., Tamayo-Giraldo, S., Tobon-Valencia, E., & Eburdy, R. (2019). Identification of critical success factors, risks and opportunities of Industry 4.0 in SMEs. *International Journal of Production Research*, *58*(5), 1-17. https://doi.org/10.1080/00207543.2019.1636323

Moreno, A., Velez, G., Ardanza, A., Barandiaran, I., Ruiz de Infante, A., & Chopitea, R. (2017). Virtualization process of a sheet metal punching machine within the Industry 4.0 vision. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *11*, 365-373. https://doi.org/10.1007/s12008-016-0319-2

Moyne, J., & Iskandar, J. (2017). Big data analytics for smart manufacturing: Case studies in semiconductor manufacturing. *Processes, 5*(3), 39.

Muller, J. M., Kiel, D., & Voigt, K. I. (2018). What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability. *Sustainability*, *10*(247), 1-24. https://doi.org/10.3390/su10010247

Nagy, J., Olah, J., Erdei, E., Mate, D., & Popp, J. (2018). The role and impact of Industry 4.0 and the Internet of Things on the business strategy of the value chain: The case of Hungary. *Sustainability*, *10*(10), 1-25. https://doi.org/10.3390/su10103491

Nara, E. O. B., da Costa, M. B., Baierle, I. C., Schaefer, J. L., Benitez, G. B., do Santos, L. M. A. L., & Benitez, L. B. (2021). Expected impact of Industry 4.0 technologies on sustainable development: A study in the context of Brazil's plastic industry. *Sustainable Production and Consumption*, *25*, 102-122. https://doi.org/10.1016/j.spc.2020.07.018

Nascimento, D. L. M., Alencastro, V., Quelhas, O. L. G., Caiado, R. G. G., Garza-Reyes, J. A., Lona, L. R., & Tortorella, G. (2018). Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context. *Journal of Manufacturing Technology Management*, *30*(3), 607-627. https://doi.org/10.1108/JMTM-03-2018-0071

Nedaei, M., Walsh, P., & Assareh, E. (2020). Sustainable energy planning of a wind power plant by coordinating clean development strategies. *International Journal of Energy for a Clean Environment*, *21*(1). https://doi.org/10.1615/InterJEnerCleanEnv.2020033676

Oláh, J., Aburumman, N., Popp, J., Khan, M. A., Haddad, H., & Kitukutha, N. (2020). Impact of Industry 4.0 on environmental sustainability. *Sustainability*, *12*(11), 4674. https://doi.org/10.3390/su12114674

Oesterreich, T. D., & Teuteberg, F. (2016). Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Computers in industry, 83*, 121-139.

Qandil, M. D., Abbas, A. I., Abdelhadi, A. I., Salem, A. R., & Amano, R. S. (2021). Energy analysis: Ways to save energy and reduce the emissions in wastewater treatment plants. *International Journal of Energy for a Clean Environment*, *22*(1). https://doi.org/10.1615/InterJEnerCleanEnv.2020035138

Qian, C., Zhang, Y., Jiang, C., Pan, S., & Rong, Y. (2020). A real-time data-driven collaborative mechanism in fixed-position assembly systems for smart manufacturing. *Robotics and Computer Integrated Manufacturing*, *61*, 1-13. https://doi.org/10.1016/j.rcim.2019.101841

Qin, J., Liu, Y., & Grosvenor, R. (2016). A categorical framework of manufacturing for industry 4.0 and beyond. *Procedia cirp, 52*, 173-178.

Radziwon, A., Bilberg, A., Bogers, M., & Madsen, E. S. (2014). The smart factory: exploring adaptive and flexible manufacturing solutions. *Procedia engineering, 69*, 1184-1190.

Rafique, M. Z., Ab Rahman, M. N., Saibani, N., Arsad, N., & Saadat, W. (2016). RFID impacts on barriers affecting lean manufacturing. *Industrial Management & Data Systems, 116*(8), 1585-1616.

Raj, A., Dwivedi, G., Sharma, A., de Sousa Jabbour, A. B. L., & Rajak, S. (2019). Barriers to the adoption of Industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective. *International Journal of Production Economics*, *224*, 1-50. https://doi.org/10.1016/j.ijpe.2019.107546

Rajput, S., & Singh, S. P. (2019). Identifying Industry 4.0 IoT enablers by integrated PCA-ISM-DEMATEL approach. *Management Decision, 57*(8), 1784-1817.

Ren, S., Zhang, Y., Liu, Y., Sakao, T., Huisingh, D., & Almeida, C. M. V. (2018). A comprehensive review of big data analytics throughout product lifecycle to support sustainable smart manufacturing: A framework, challenges and future research directions. *Journal of Cleaner Production*, *210*(10), 1343-1365. https://doi.org/10.1016/j.jclepro.2018.11.025

Roblek, V., Meško, M., & Krapež, A. (2016). A complex view of Industry 4.0. *Sage Open*, *6*(2), 2158244016653987. https://doi.org/10.1177/2158244016653987

Rosin, F., P. Forget, S. Lamouri, and R. Pellerin. 2019. "Impacts of Industry 4.0 technologies on Lean principles." *International Journal of Production Research. 50*(6): 1644-1661.

Rosin, F., Forget, P., Lamouri, S., & Pellerin, R. (2020). Impacts of Industry 4.0 technologies on Lean principles. *International Journal of Production Research, 58*(6), 1644-1661.

Rossit, D. A., Tohme, F., & Frutos, M. (2019). Industry 4.0: Smart scheduling. *International Journal of Production Research*, *57*(12), 3802-3813. https://doi.org/10.1080/00207543.2018.1504248

Ruggerio, C. A. (2021). Sustainability and sustainable development: A review of principles and definitions. *Science of the Total Environment*, *786*, 147481. https://doi.org/10.1016/j.scitotenv.2021.147481

Saniuk, S., & Grabowska, S. (2020). Social expectations and market changes in the context of developing the Industry 4.0 concept. *Sustainability*, *12*(1362), 1-21. https://doi.org/10.3390/su12041362

Sartal, A., Bellas, R., Mejías, A. M., & García-Collado, A. (2020). The sustainable manufacturing concept, evolution and opportunities within Industry 4.0: A literature review. *Advances in Mechanical Engineering*, *12*(5), 1-17. https://doi.org/10.1177/1687814020925232

Schlechtendahl, J., Keinert, M., Kretschmer, F., Lechler, A., & Verl, A. (2014). Making existing production systems Industry 4.0-ready: Holistic approach to the integration of existing production systems in Industry 4.0 environments. *Production Engineering Research Development*, *9*, 143-148. https://doi.org/10.1007/s11740-014-0586-3

Schmidt, R., Mohring, M., Harting, R. C., Reichstein, C., Neumaier, P., & Jozinovic, P. (2015). Industry 4.0 - Potentials for creating smart products: Empirical research. In W. Abramowicz (Ed.), *BIS 2015* (pp. 16-27). Springer. https://doi.org/10.1007/978-3-319-19027-3

Serrano-Ruiz, J. C., Mula, J., & Poler, R. (2021). Smart manufacturing scheduling: A literature review. *Journal of Manufacturing Systems*, *61*, 265-287. https://doi.org/10.1016/j.jmsy.2021.09.011

Sharma, R., Jabbour, C. J. C., & de Sousa Jabbour, A. B. L. (2020). Sustainable manufacturing and Industry 4.0: What we know and what we don't. *Journal of Enterprise Information Management*, *34*(1), 230-266. https://doi.org/10.1108/JEIM-01-2020-0024

Sharp, M., Ak, R., & Hedberg, T. (2018). A survey of the advancing use and development of machine learning in smart manufacturing. *Journal of Manufacturing Systems*, *48*, 170-179. https://doi.org/10.1016/j.jmsy.2018.02.004

Singh, R., & Bhanot, N. (2020). An integrated DEMATEL-MMDE-ISM based approach for analysing the barriers of IoT implementation in the manufacturing industry. *International Journal of Production Research, 58*(8), 2454-2476.

Sony, M., & Naik, S. (2019). Key ingredients for evaluating Industry 4.0 readiness for organizations: A literature review. *Benchmarking: An International Journal*, *27*(7), 2213-2232. https://doi.org/10.1108/BIJ-09-2018-0284

Strange, R., & Zucchella, A. (2017). Industry 4.0, global value chains and international business. *Multinational Business Review*, *25*(3), 174-184. https://doi.org/10.1108/MBR-05-2017-0028

Tao, F., Qi, Q., Liu, A., & Kusiak, A. (2018). Data-driven smart manufacturing. *Journal of Manufacturing Systems*, *1*-13. https://doi.org/10.1016/j.jmsy.2018.01.006

Thomas, A., & Trentesaux, D. (2014). Are intelligent manufacturing systems sustainable? *Service Orientation in Holonic and Multi-Agent Manufacturing and Robotics*, 3-14.

Tortorella, G. Z., & Fettermann, D. (2017). Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies. *International Journal of Production Research*, *56*(8), 2975-2987. https://doi.org/10.1080/00207543.2017.1391420

Tuptuk, N., & Hailes, S. (2018). Security of smart manufacturing systems. *Journal of Manufacturing Systems*, *47*, 93-106. https://doi.org/10.1016/j.jmsy.2018.04.007

Urbina Coronado, P. D., Louhichi, R. L. W., Parto, M., Wescoat, E., & Kurfess, T. (2018). Part data integration in the shop floor digital twin: Mobile and cloud technologies to enable a manufacturing enable system. *Journal of Manufacturing Systems*. https://doi.org/10.1016/j.jmsy.2018.02.002

Varela, L., Ara, A., Paulo, A., & Castro, H. (2019). Evaluation of the relation between lean manufacturing, Industry 4.0, and sustainability. *Sustainability*, *11*(5), 1-19. https://doi.org/10.3390/su11051439

Wang, S., Wan, J., Zhang, D., Li, D., & Zhang, C. (2016). Towards smart factory for Industry 4.0: A self-organized multi-agent system with big data based feedback and coordination. *Computer Networks*, *101*, 158-168. https://doi.org/10.1016/j.comnet.2015.12.017

Wang, J., Ye, L., Gao, R. X., Li, C., & Zhang, L. (2018). Digital Twin for rotating machinery fault diagnosis in smart manufacturing. *International Journal of Production Research*, *57*(12), 3920-3934. https://doi.org/10.1080/00207543.2018.1552032

Wang, J., Ma, Y., Zhang, L., Gao, R. X., & Wu, D. (2018). Deep learning for smart manufacturing: Methods and applications. *Journal of Manufacturing Systems*, *48*, 144-156. https://doi.org/10.1016/j.jmsy.2018.01.003

Wang, W., Zhang, Y., & Zhong, R. Y. (2020). A proactive material handling method for CPS enabled shop-floor. *Robotics and Computer-Integrated Manufacturing*, *61*, 1-14. https://doi.org/10.1016/j.rcim.2019.101849

Xu, X. (2012). From cloud computing to cloud manufacturing ubiquitous product life cycle support. *Robotics and Computer-Integrated Manufacturing*, *28*(1), 75-86. https://doi.org/10.1016/j.rcim.2011.07.002

Yadav, N., Shankar, R., & Singh, S. P. (2020). Impact of Industry 4.0/ICTs, Lean Six Sigma and quality management systems on organizational performance. *TQM Journal*, *32*(4), 815-835. https://doi.org/10.1108/TQM-10-2019-0251

Yadav, V. S., Singh, A. R., Raut, R. D., Mangla, S. K., Luthra, S., & Kumar, A. (2022). Exploring the application of Industry 4.0 technologies in the agricultural food supply chain: A systematic literature review. *Computers & Industrial Engineering*, *169*, 108304. https://doi.org/10.1016/j.cie.2022.108304

Yang, F., & Gu, S. (2021). Industry 4.0, a revolution that requires technology and national strategies. *Complex & Intelligent Systems*, *7*, 1311-1325. https://doi.org/10.1007/s40747-020-00267-9

Yue, X., Cai, H., Yan, H., Zou, C., & Zhou, K. (2015). Cloud-assisted industrial cyber-physical systems: An insight. *Microprocessors and Microsystems*, *39*(8), 1262-1270. https://doi.org/10.1016/j.micpro.2015.08.013

Zhang, Y., Zhang, G., Wang, J., Sun, S., Si, S., & Yang, T. (2014). Real-time information capturing and integration framework of the internet of manufacturing things. *International Journal of Computer Integrated Manufacturing*, *28*(8), 811-822. https://doi.org/10.1080/0951192X.2014.900874

Zhang, A., Venkatesh, V. G., Wang, J., Venkatesh, M., Wan, M., & Qu, T. (2019). Drivers of Industry 4.0-enabled smart waste management in supply chain operations: A circular economy perspective in China. *Production Planning & Control*, 1-51.

Zheng, P., Wang, H., Sang, Z., Zhong, R. Y., Liu, Y., Liu, C., Mubarok, K., Yu, S., & Xu, X. (2018). Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios and future perspectives. *Frontier Mechanical Engineering*, *13*(2), 137-150. https://doi.org/10.1007/s11465-018-0499-5

Zheng, T., Ardolino, M., Bacchetti, A., & Perona, M. (2021). The applications of Industry 4.0 technologies in manufacturing context: a systematic literature review. *International Journal of Production Research, 59*(6), 1922-1954. https://doi.org/10.1080/00207543.2020.1824085

Zhou, F., Lin, X., Liu, C., Zhao, Y., Xu, P., Ren, L., Xue, T., & Ren, L. (2018). A survey of visualization for smart manufacturing. *Journal of Visualization*, *22*, 419-435. https://doi.org/10.1007/s12650-018-0530-2

Zhuang, C., Liu, J., & Xiong, H. (2018). Digital twin-based smart production management and control framework for the complex product assembly shop-floor. *International Journal of Advanced Manufacturing Technology*, *96*, 1149-1163. https://doi.org/10.1007/s00170-018-1617-6

Zwetsloot, I. M., Kuiper, A., Akkerhuis, T. S., & de Koning, H. (2018). Lean Six Sigma meets data science: Integrating two approaches based on three case studies. *Quality Engineering*, *30*(3), 419-431. https://doi.org/10.1080/08982112.2018.1434892

