applied sciences

MDPI

Review

Industry 4.0 Technologies for Manufacturing Sustainability: A Systematic Review and Future Research Directions

Anbesh Jamwal [1], Rajeev Agrawal [1], Monica Sharma [1,2] and Antonio Giallanza [3,*]

[1] Department of Mechanical Engineering, Malaviya National Institute of Technology, J.L.N. Marg, Jaipur, Rajasthan 302017, India; anveshjamwal73@gmail.com (A.J.); ragrawal.mech@mnit.ac.in (R.A.); msharma.dms@mnit.ac.in (M.S.)
[2] Department of Management Studies, Malaviya National Institute of Technology, J.L.N. Marg, Jaipur, Rajasthan 302017, India
[3] Engineering Department, University of Palermo, Viale delle Scienze Building 8, 90128 Palermo, Italy
* Correspondence: antonio.giallanza@unipa.it; Tel.: +39-091-2386-1861

Abstract: Recent developments in manufacturing processes and automation have led to the new industrial revolution termed "Industry 4.0". Industry 4.0 can be considered as a broad domain which includes: data management, manufacturing competitiveness, production processes and efficiency. The term Industry 4.0 includes a variety of key enabling technologies i.e., cyber physical systems, Internet of Things, artificial intelligence, big data analytics and digital twins which can be considered as the major contributors to automated and digital manufacturing environments. Sustainability can be considered as the core of business strategy which is highlighted in the United Nations (UN) Sustainability 2030 agenda and includes smart manufacturing, energy efficient buildings and low-impact industrialization. Industry 4.0 technologies help to achieve sustainability in business practices. However, very limited studies reported about the extensive reviews on these two research areas. This study uses a systematic literature review approach to find out the current research progress and future research potential of Industry 4.0 technologies to achieve manufacturing sustainability. The role and impact of different Industry 4.0 technologies for manufacturing sustainability is discussed in detail. The findings of this study provide new research scopes and future research directions in different research areas of Industry 4.0 which will be valuable for industry and academia in order to achieve manufacturing sustainability with Industry 4.0 technologies.

Keywords: Industry 4.0; sustainability; manufacturing; smart manufacturing; Internet of Things; cloud manufacturing; artificial intelligence; sustainable manufacturing

Citation: Jamwal, A.; Agrawal, R.; Sharma, M.; Giallanza, A. Industry 4.0 Technologies for Manufacturing Sustainability: A Systematic Review and Future Research Directions. *Appl. Sci.* **2021**, *11*, 5725. https://doi.org/10.3390/app11125725

Academic Editor: Richard (Chunhui) Yang

Received: 1 June 2021
Accepted: 18 June 2021
Published: 20 June 2021

1. Introduction

Competitive business environment, mass customization and globalization are forcing "traditional" industries to adopt new business models and shift towards Industry 4.0 [1,2]. Industry 4.0 technologies can be considered as the new revolution in manufacturing which aims to achieve maximum efficiency and output by minimum resource utilization [3]. Industry 4.0 technologies have brought a new manufacturing trend in industries which aimed at effective resource utilization for maximum output. "Smart manufacturing" or "digital manufacturing" can be considered as the core of Industry 4.0 which allows industries to perform flexible manufacturing operations with mass customization [4]. Zhong et al. [5] stated that Industry 4.0 is a German initiative which aimed at creating smart factories in which manufacturing technologies are transformed and upgraded by the Internet of Things (IoT) and cyber-physical systems (CPS). Manufacturing systems in Industry 4.0 can monitor the physical processes of industry and create a so called "digital twin" of physical entities [6]. This helps to establish real time communication, intelligent decision making and man–machine interaction in manufacturing organizations. Industry

4.0 technologies combined smart production with embedded production system which has transformed the production value chains, industry value chain and traditional business models of organizations [7]. IoT, CPS, augmented and virtual reality, blockchain technology, machine learning (ML), artificial intelligence (AI), big data analytics and digital twins can be considered as key enabling technologies for Industry 4.0 practices [8]. It is believed that Industry 4.0 technologies will help to enhance the social and economic sustainability of organizations [3]. Industry 4.0 technologies have a remarkable potential for sustainable value creation across the economic, environmental and social dimension of sustainability by improving resource efficiency [9].

Despite the probable opportunities for manufacturing sustainability in Industry 4.0, there are few review studies that have explored the Industry 4.0 technologies with different sustainability perspectives [4,8–10]. Stock and Seliger [3] highlighted the sustainable manufacturing (SM) opportunities in Industry 4.0. Kamble et al. [10] developed a sustainability framework for Industry 4.0. Jabbour et al. [9] identified critical success factors for SM in Industry 4.0 era. Machado et al. [4] highlighted new research trends and scopes for SM in Industry 4.0. Sharma et al. [8] presented a bibliometric-based review to highlight research opportunities for SM in Industry 4.0. Bag et al. [11] highlighted the relationship between the circular economy, SM and Industry 4.0 practices. This shows that there is growing interest in the area of SM and Industry 4.0, yet there is scarcity of systematic review which highlight new research scopes for manufacturing sustainability in Industry 4.0. The past review studies were limited to a specific database. This paper seeks to explore the research trends and scopes for manufacturing sustainability in Industry 4.0 with three major databases i.e., IEEE, Web of Sciences and Scopus. This paper also highlights the research trends in manufacturing area in ten different Industry 4.0 technologies and then provide the sustainability issues for manufacturing.

The structure of this review paper is as follows. Section 2 highlights the basic concepts and terminology related to sustainability and Industry 4.0. Section 3 presents the review protocol and methodology. Section 4 presents the results of systematic literature review. Section 5 presents the role of different Industry 4.0 technologies to achieve sustainability. Section 6 presents the opportunities of Industry 4.0 technologies to achieve manufacturing sustainability. Section 7 presents research gaps in Industry 4.0 to achieve sustainability, and Section 8 presents the conclusion and future scopes of study.

2. Basic Concepts and Terminology

In this section basic terminologies of sustainable manufacturing (SM) and Industry 4.0 are presented to construct the link between both these two approaches.

2.1. Concept and Definitions of Sustainable Manufacturing

Sustainable manufacturing covers the three basic elements involved in manufacturing i.e., processes, products and systems which enables economic growth and sustainable value creation in industries [12]. To ensure sustainability in manufacturing these three elements must individually demonstrate the benefits at the social, economic and environmental levels [13]. Sustainable manufacturing can be described as the integration of systems and various processes to produce a high quality of products with minimum resource utilization, sustainable resources, being safer for customers, employees and communities [14].

Main Definitions of Sustainable Manufacturing (SM)

The first definition for sustainability is discussed in the United Nations (UN) Brundtland Commission report published in 1987: “Development which meets the needs of current generation without compromising the ability of future generations to meet their own needs” [15]. This definition was further used in different initiatives e.g., the 2015 Sustainable Development Goals UN initiative. This definition is not acceptable in operational areas of manufacturing [16]. Several efforts have been made to propose a definition for SM in previously published studies [12,14]. Jayal et al. [14] defined SM as the design of industrial system which can ensure the natural resources for quality of life and have minimum negative impact on environmental and human health. The US Department of Commerce defined SM as "the creation of products through the processes that minimize both negative environmental impacts and consumption of energy and natural resources, being also safe for employees, communities, consumers and economically viable" [17].

2.2. Industry 4.0

Industry 4.0 is also termed the "fourth industrial revolution" coined at the Hanover fair, 2011, in Germany [6,18]. The German Federal Government launched Industry 4.0 as the high-technology plan for German industries in 2014 [4]. Industry 4.0 can be described as the current trends in data exchange and automation between the manufacturing technologies or activities. Industry 4.0 is focused on the development of "smart" factories which can meet the dynamic manufacturing scenarios, management goals and new business models [2]. Cyber physical systems (CPS), augmented and virtual reality, blockchain technology, additive manufacturing, flexible manufacturing system, reconfigurability, Internet of Things (IoT), machine and deep learning, artificial intelligence, big data analytics and cloud computing are the main key enabling technologies of Industry 4.0 [19,20]. The past three industrial revolutions (Industry 1.0; Industry 2.0; Industry 3.0) were driven by mechanization, electrification and information technology in manufacturing which enhanced resource utilization as well as productivity [5]. In Industry 4.0, the CPS is the underlying technology which has the potential for mass customization by modularity and changeability in production systems [10]. CPS can connect physical entities, enable man–machine interaction, infrastructure, processes and other activities in system when connected with IoT [21]. The interaction between IoT and CPS enables the communication between the physical entities and virtual world by exchanging data collected through sensors and generated from manufacturing activities [22]. Meanwhile other technologies of Industry 4.0 act as enablers for Industry 4.0-enabled business practices.

2.3. Relationship and Link between Industry 4.0 and Sustainable Manufacturing

Both sustainability and Industry 4.0 are the emerging research areas in the engineering. The main practices in these two areas are sustainable designing, life-cycle management, re-manufacturing, circular economy, lean and green management, environmental management. Stock and Seliger [3] discussed the macro and micro perspective of the sustainable manufacturing in Industry 4.0. It is found that Industry 4.0 technologies helps to create sustainable value in all three dimensions of sustainability. New opportunities have been discussed such as: (1) business models driven by smart data; (2) closed loop supply chain networks; (3) digitalization in small and medium enterprises (SMEs); (4) training of employees with information and communication technologies (ICT); (5) sustainable product design; and, (6) decentralized manufacturing lines. Kamble et al. [10] presented the sustainable Industry 4.0 framework and discussed the sustainable benefits from Industry 4.0 technologies in terms of resource efficiency and productivity. Bag et al. [11] discussed how sustainable manufacturing and Industry 4.0 practices can improve the energy consumption, waste reduction and resource efficiency. The relationship between Industry 4.0 and sustainable manufacturing was discussed with the help of a conceptual framework. Machado et al. [4] discussed the emerging research areas in the sustainable manufacturing and Industry 4.0 by a systematic literature review and highlighted some research scopes related to supply chains and man-machine interaction.

3. Materials and Methods

In the present study we have used the systematic literature review (SLR) approach which helps to deliver a comprehensive and clear overview of literature analysis as compared to a descriptive literature review. Refs. [23–25] stated that systematic literature as a suitable approach to identify the new research opportunities in a research area by analyzing and synthesizing previously published articles. However, Petticrew [26] defined a systematic literature review as:

> "An efficient technique for hypothesis testing, for summarizing the results of existing studies, and for assessing consistency among previous studies; these tasks are clearly unique to medicine."

In the past few years SLR approaches have been applied in different research areas by the use of different databases [27,28]. However, many studies have reported the use of SLR approaches with a single scientific database. Samala et al. [28] discussed the advantages of using of multiple databases in SLR approaches. Industry 4.0 is an emerging research trend among practitioners and researchers. Antony et al. [29] stated that much less literature is accessible to practitioners which provide the information regarding new innovations and research opportunities in industries. SLR can help to find out the research trends and new opportunities in a particular research area.

3.1. Research Questions

A total of three research questions (RQ) were formulated in the present study as follows:

RQ1: What is the role of different Industry 4.0 technologies in achieving manufacturing sustainability?

RQ2: How can Industry 4.0 technologies contribute to sustainability in manufacturing?

RQ3: What are main research gaps in Industry 4.0 technologies for manufacturing sustainability and what are the research issues that need to be addressed in future?

3.2. Search Strategy

The search of peer reviewed journal articles and conference articles was implemented in April 2021 for the articles related to manufacturing sustainability and Industry 4.0 technologies. The search for articles was conducted by using the keywords related to the research area as follows: (TITLE-ABS-KEY ("Industry 4.0" OR "smart manufacturing") AND TITLE-ABS-KEY ("manufacturing sustainability" OR "sustainable manufacturing" OR "Sustainability" AND "Manufacturing")).

The inclusion criteria for the study were as follows:

1. Articles published in the English language;
2. Articles published before May 2021;
3. Articles should be from peer reviewed journals or conference proceedings;
4. Articles focused in the area of Industry 4.0 technologies and manufacturing sustainability;
5. Articles must be in short or full version (not an editorial or abstract).

Three major databases linked with the research area which include the article collection from Industry 4.0 and sustainability were selected for the primary search. These databases included Scopus, IEEE explore and Web of Science. The search and selection process for articles is discussed in Figure 1.

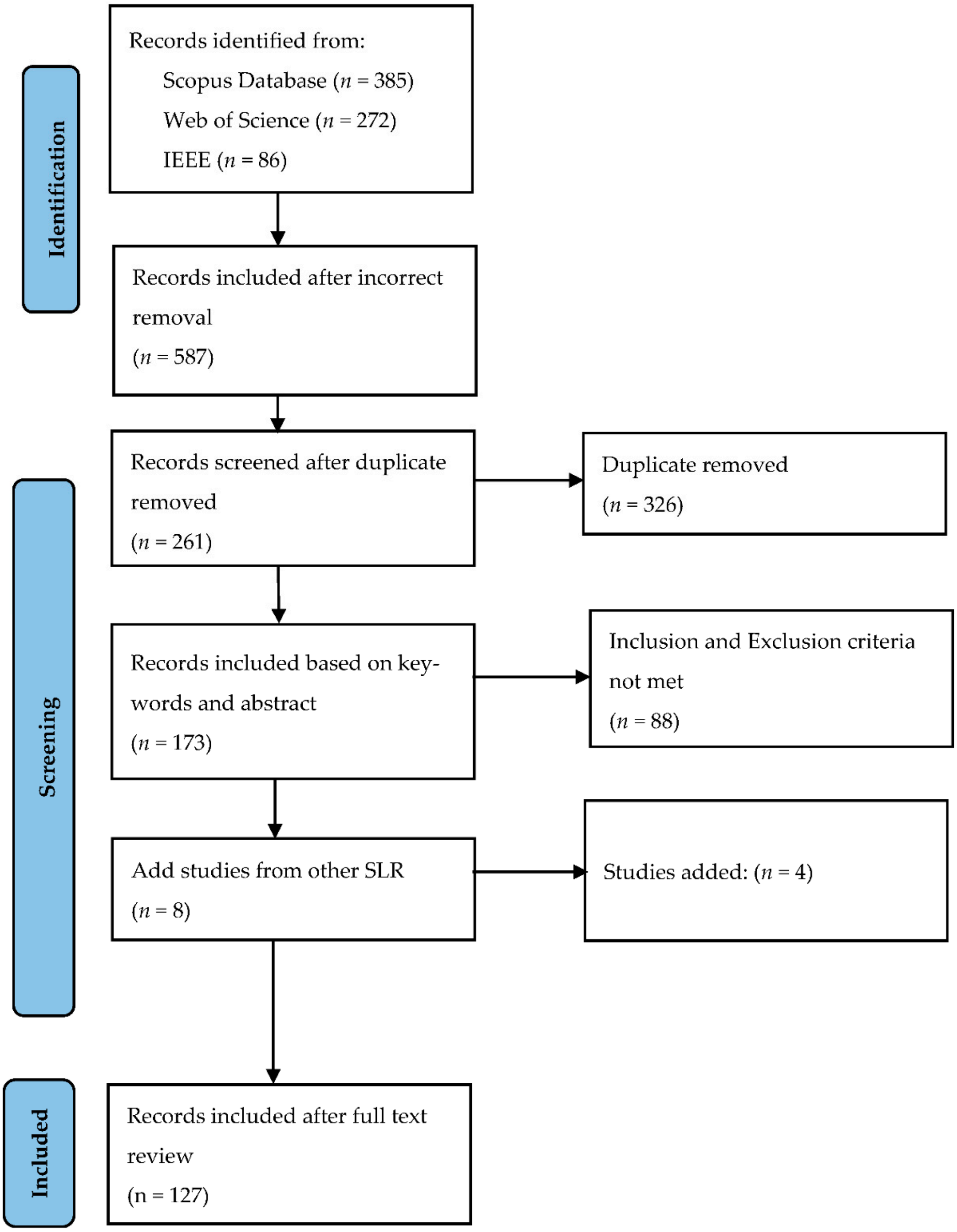

Figure 1. Literature review search and selection process.

4. Results

4.1. Year-Wise Publication Progress

Industry 4.0 and sustainability are the emerging research areas in manufacturing. In the last few years studies related to sustainability issues in Industry 4.0 has made several research scopes. The number of publications in this area is increasing every year (See Figure 2). It can be observed that very few articles were published in this area from 2015–2017. In last three years the number of publications has increased demonstrating the growing interest of researchers in Industry 4.0 and sustainability.

4.2. Highly Cited Papers (Global Citations)

The list of top cited articles in Industry 4.0 and manufacturing sustainability area is shown in the Table 1 with their contributions and total global citation. In the study three databases have been considered for the article collection so the global citation score is considered to find the top cited articles.

Table 1. Most cited articles (global citations).

Author	Contribution	Total Global Citations
[3]	Highlighted opportunities for SM in Industry 4.0	1305
[10]	Developed a sustainability framework for Industry 4.0	387
[30]	Empirical investigation on German manufacturing industries in five sectors	348
[31]	Empirical investigation on 46 German manufacturing industries	348
[9]	Identified critical success factors for SM practices in Industry 4.0	304
[32]	Challenges for Sustainable supply chain for manufacturing sustainability in Industry 4.0	278
[33]	Opportunities for IoT in sustainable supply chain for manufacturing sustainability	225

4.3. Most Productive Journals

In this study, journal classification was extracted with R studio using the bibliometrix package. In the classification of journals, it was found that the *Journal of Cleaner Production* had most publications related to Industry 4.0 and sustainability followed by *Procedia CIRP, IFAC Papersonline* and *International Journal of Production Research*. The top 10 journals with their publication count are shown in Figure 3.

Figure 2. Year-wise publication in Industry 4.0 and sustainability.

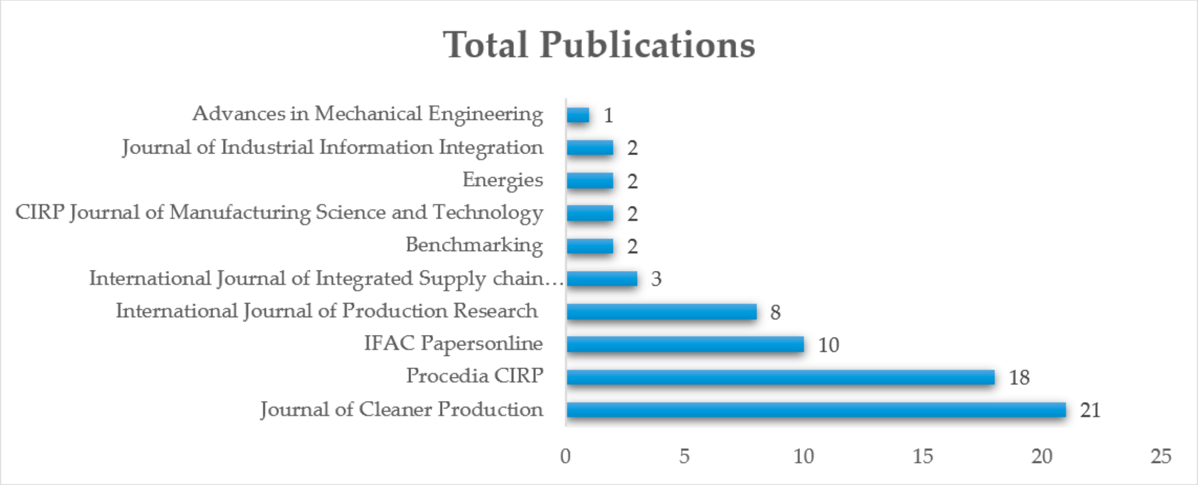

Figure 3. Journal-wise distribution of articles.

4.4. Top Subject Areas

Figure 4 shows the distribution of 127 articles by their subject area. In an analysis it was found that some articles lie in more than one subject area. Most of the articles reported from the "Engineering" subject area include sub-areas like architecture design and experimental investigations. However, some articles from "Environmental science" are focused on sub-areas like life-cycle analysis and environmental related issues.

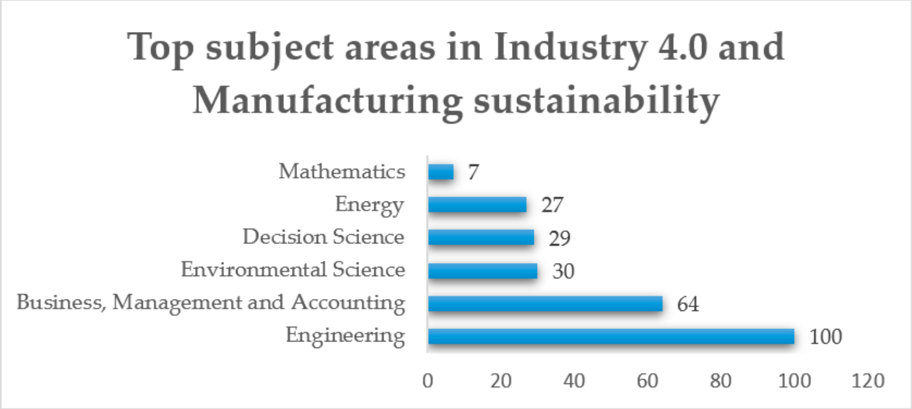

Figure 4. Articles distributed based on subject areas.

4.5. Most Used Keywords

The most used authors keywords in Industry 4.0 and manufacturing sustainability articles were extracted using the RStudio (See Figure 5). "Industry 4.0" was the mostly used keyword with 81 occurrences, followed by "Sustainable development (57) and "Sustainable Manufacturing" (40) occurrence. In most publications "Industry 4.0" was used as the main keyword while in some publications "smart manufacturing" was used as a main keyword.

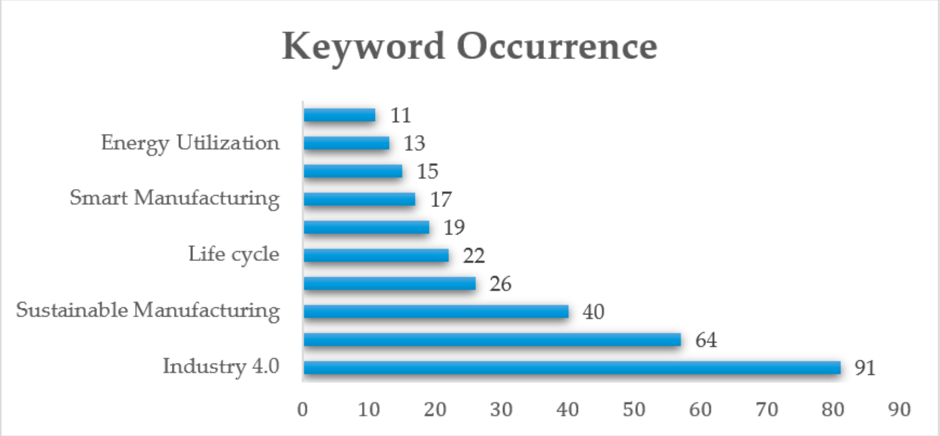

Figure 5. Main keywords used in articles related to Industry 4.0 and manufacturing sustainability.

5. Discussion on Review Results

RQ1: What is the role of different Industry 4.0 technologies in achieving manufacturing sustainability?

5.1. Concepts and Theories Related to Manufacturing in Industry 4.0

Industry 4.0 is the current research trend for data exchange and automation in manufacturing activities which connect the different physical entities in systems such as: sensors and actuators with the IoT so that they can interact and transmit the information [4,34]. In Industry 4.0 information can be exchanged between the machines as well as humans known as human–machine collaboration [35]. Production activities in Industry 4.0 are different from the traditional industry practices as real time production planning and control can be done in Industry 4.0 [36]. Industry 4.0 is driven by increased competitiveness from the use of sustainability in production, efficient manufacturing systems, horizontal and vertical integration of technologies [37].

Shop-Floor Activities

Shop-floor activities can be considered as the main elements to achieve sustainability in manufacturing processes. On the shop floor, the main entities (conveyors, pallets and machining cells), sensors and other digital technologies can communicate with each other for the data exchange [38]. This generated data can be analyzed with machine learning approaches or big data analytics and can be used for intelligent decision making [39]. The shop-floor activities in Industry 4.0 includes predictive maintenance, real time quality and safety monitoring and remote monitoring of activities which helps to create a smart shop floor [40]. Mittal et al. [41] stated that SMEs need a wide area network facility and automation facilities on the shop floor to enhance Industry 4.0 practices. Yang and Takakuwa [38] proposed a simulation based approach for flexible manufacturing system in Industry 4.0 for shop floor activities and found that the proposed model is helpful for decision making in manufacturing activities. Moica et al. [40] proposed a maturity model for an automotive industry to change the shop floor management into a smart shop floor using three main elements: (1) Envision (2) Enact and, (3) Enable. Schmidt et al. [42] proposed an Industry 4.0-based lean shop floor management system using deep learning (96.5% accuracy) and EEG(electroencephalogram) sensors. Very few studies were found directly related to shop floor management or smart shop floor activities in Industry 4.0.

5.2. Main Technologies of Industry 4.0 for Achieving Sustainability

5.2.1. Additive Manufacturing

In the traditional manufacturing processes machining operations such as drilling, cutting and grinding operations are used to convert raw material into the final product which can be referred as "subtractive manufacturing" processes. In these processes a large amount of waste is generated in the form of chips and scraps which affects sustainability in terms of both economic and environmental sustainability. In Industry 4.0 industries focus on the adoption of additive manufacturing technologies which produce less waste and environmental impacts as compared to traditional manufacturing processes [27]. Also, these technologies help to complete the customized demands of customers through layer-by-layer manufacturing working on a CAD (computer aided design) model. Generally, additive manufacturing processes helps to enhance the adoption of Industry 4.0 practices [43]. Korner et al.; Haleem and Javid [27,44] discussed the role of additive manufacturing processes in Industry 4.0. Godina et al. [43] investigated the impact assessment of additive manufacturing practices on sustainable business models in Industry 4.0. Ford and Despeisse [45] stated that additive manufacturing helps to improve resource efficiency, sustainability and enables material flow in a closed loop. Jamwal et al.; Yadav et al. [46,47] highlighted additive manufacturing practices as an enabler for Industry 4.0 practices to achieve sustainability. Mittal et al. [48] highlighted the importance of additive manufacturing technology in the Industry 4.0 roadmap development.

5.2.2. Role of Big Data Analytics and Digital Twin

Big data analytics is use of advanced computing technologies which can be used to find the trends, preferences and correlations on the larger data sets in industries for effective decision making [49]. In Industry 4.0 the role of big data analytics is very important which includes key areas such as smart factories in which data are captured from the sensors during the manufacturing or production activities [6]. This data can be analyzed with big data approaches and can be used for predictive maintenance operations in future. The main benefits of big data analytics in Industry 4.0 are optimization, real-time monitoring, production efficiency and production management automation which is currently shaping industries for fourth industrial revolution [50].

Wang and Wang [49] discussed the importance of big data analytics in Industry 4.0 and cyber physical systems. It was found that big data analytics approaches help to reduce the breakdowns and unscheduled downtime by 25% in manufacturing industries. Branco et al.; Frank et al.; Papadopoulos et al. References [51–53] discussed the implications for big data implementation in Industry 4.0 practices and discussed how big data approaches help to automate production activities by reducing human inputs. Li et al. [54] presented the big data enabled smart factory framework for Industry 4.0 practices in which shop floor activities, cloud and smart products can communicate with each other. The results of the study indicated the improvement in efficiency and load balancing.

Digital twins are the virtual representation which serves as a real-time digital counter part of physical entities in a system. Digital twins can be considered the result of continual improvements in product design and manufacturing activities in an industry. However, Kim, 2017, [6] stated digital twins are the software representation of any physical asset, process or system designed to optimize, predict and detect by the real-time data analytics. Some studies reported about 30% cost reductions, 20% planning time reductions, and 8% productivity improvements with the help of digital twins [5]. Refs. [2,55] discussed the role and opportunities for digital twins in manufacturing industries in the Industry 4.0 context. Ke et al., 2019 [56] proposed an interaction framework based on digital twin, augmented reality (AR) and virtual reality (VR) technologies for Industry 4.0 enabled manufacturing practices. Wang and Wang, 2019, [57] introduced the Industry 4.0 and digital twin enablers for waste electronic and electrical equipment recovery and discussed the role of computer graphics in the development of digital twins.

5.2.3. Artificial Intelligence and Machine Learning

Artificial intelligence (AI) and machine learning (ML) are considered as fundamental bases for Industry 4.0 which helps to make industries more productive and autonomous [58]. AI is the combination of several technologies that allow machines and software to understand, sense, act and learn based on self-learning or augmented human activities [59]. Research on AI in industry can be categorized into four major areas: (1) predictive quality and maintenance; (2) generative design; (3) supply chain activities; (4) human–robot collaboration [58]. Jamwal et al. [39] discussed the role of machine learning approaches in manufacturing sustainability. It was also found that ML approaches help to analyze the large amount of data generated from the sustainable manufacturing operations. The benefits of using ML are discussed in the three aspects of sustainability with some new research scopes for Industry 4.0 practices. The major benefits of using ML and AI approaches results in error reduction, cost reduction and revenue growth in manufacturing industries. In the initial efforts, Lee et al. [58] discussed the roadmap for AI-enabled manufacturing systems for Industry 4.0 practices. In the study, the current state of AI technologies and eco-systems for manufacturing applications is discussed in the Industry 4.0 context. Yao et al. [60] discussed the evolution of smart manufacturing from intelligent manufacturing with AI technologies. The comparison between intelligent manufacturing and smart manufacturing is discussed in detail. Bajic et al.; Cioffi et al. [61,62] discussed the applications, opportunities and challenges for AI and ML techniques in Industry 4.0. Angelopoulos et al. [63] discussed the fault diagnosis with the help ML approaches in Industry 4.0 due to machine degradation. A detailed overview of ML approaches was provided for manufacturing activities to minimize the errors and improve human–machine interaction. Cinar et al. [64] discussed opportunities of ML for predictive maintenance in Industry 4.0 by providing a comprehensive review on ML and smart manufacturing. It was found that ML and AI applications are the emerging research areas in sustainable smart manufacturing. Candanedo et al. [65] proposed a predictive model for Industry 4.0 practices. A case for HVAC(heating, ventilation and air conditioning) is presented in which data generated from a HVAC is utilized to predict and analyze that system temperature range using ML algorithms. However, few studies reported about the applications of AI and ML technologies in zero defect manufacturing. Psarommatis et al. 2020, [66] presented the state of the art on zero defect manufacturing and discussed the research opportunities for machine learning and AI technologies. Huang et al. 2018, [67] discussed about the application of machine learning and AI technologies in real-time quality prediction and monitoring of defects in micro-semiconductor manufacturing. Lindström et al., 2020, [68] proposed a zero defect manufacturing model for industries with an Industry 4.0 perspective. It was found that the proposed model helps to improve the sustainability, profitability, efficiency and manufacturing competitiveness. Eger et al., 2018, [69] discussed the zero defect manufacturing strategies in the Industry 4.0 context for scrap reduction in multi-stage production system. Psarommatis et al., 2020, [70] discussed the opportunities for AI-based algorithms for flexible job shop re-scheduling in zero-defect manufacturing. The above literature reveals that AI and machine learning based technologies delivers the skill set and zero defect manufacturing opportunities for Industry 4.0 which will help to improve the sustainability and efficiency of manufacturing industries.

5.2.4. Internet of Things (IoT)

Industries are adopting IoT technologies to improve production quality and reduce downtime by digitalization in manufacturing [71]. In developed nations, manufacturing organizations are already automated up to a good extent. Industries have already automation and digitalization on shop floor which is basic requirement for Industry 4.0 practices [46,47]. IoT is one of key enabling technologies for Industry 4.0 which contributes towards manufacturing excellence and digital transformation of industries. The major issues in industries are IT-OT (internet technology and operational technology) integration in the manufacturing activities which resulted in lack of quality, plant visibility and inefficient inventory management [72]. IoT technologies helps to bridge gap between the OT and IT systems by connected the control systems, sensors, PLCs (programmable logic controller) and data transfer to cloud and ERP (enterprise resource planning) [73]. Wan et al. [74] proposed a framework for IoT based manufacturing focused on smart factory. In the study role of dynamic resource management for complex resource allocation problems is presented. Frank et al. [1] discussed the how IoT technologies in industry help to reduce downtime, improve quality and improve predictive and preventive analysis. Gerrikagoitia et al. [75] found IoT technologies as the main driver for Industry 4.0 practices. In the review different approaches with the different manufacturing scenario i.e., dynamic market changes for digital manufacturing is discussed. Kim; Xu et al. [6,76] reported about the state of art of IoT technologies in Industry 4.0. It is noted that wireless sensors networks and RFID (radio frequency identification) are the most important devices which helps to enable a IoT based manufacturing. Beier et al. [77] stated that Industry 4.0 uses the cognitive computing approaches with IoT to automate the manufacturing activities. Saglain et al. [71] proposed a IoT-based framework for smart manufacturing which can manage process control, online monitoring and large industry data sets. In the proposed framework five main layers were considered to manage a large amount of data generated from the regular manufacturing activities in industries. Thramboulidis et al. [22] conducted two case studies to validate an IoT-based manufacturing framework in which cyber-physical microservices considered as key construct. Singh and Bhanot [78] analyzed the 10 critical challenges related to IoT-based manufacturing in industries with a DEMATEL-ISM approach and found cyber security as main challenge.

5.2.5. Cloud Computing and Manufacturing

Cloud computing in Industry 4.0 can be considered a key enabler that offers advantages like computational power required to apply ML, AI approaches and other smart technologies in Industry 4.0 [79]. Few studies reported about the uncertainties regarding the suitability of cloud computing in manufacturing organizations [6,80,81]. Cloud computing and Industry 4.0 enables the services, manufacturing networking and data over the internet in manufacturing activities [82]. Advanced cloud technologies are widely used for data sharing across the organizational boundaries which has resulted in improved flexibility and agility of systems [83]. Xu [79] stated that cloud service providers provide three kind of cloud services for manufacturing industries: (1) software as service i.e., ready to use services; (2) infrastructure as a service i.e., virtual CPUs (central processing unit) or networks; (3) platform as a service i.e., virtual machines and operating systems. Tao et al. [84] proposed a service oriented and computing based cloud manufacturing model for industries to improve resource utilization and reduce energy consumption. Li et al. [81] proposed a cloud manufacturing model which consists of IoT, AI technologies and services to achieve a life cycle in smart manufacturing. In the study, four applications of the model for large enterprises and small and medium enterprises are discussed. Adamson et al.; Liu et al.; Wu et al. [82,85,86] discussed the concept of cloud-based manufacturing for industries and highlighted research issues for the fourth industrial revolution. In the studies, various definitions related to cloud manufacturing is discussed. These studies provides future research directions for both academia and practitioners. Coronado et al. [87] stated that both mobile and cloud technologies are important for smart manufacturing. In the study, an android-based manufacturing execution system (MES) is proposed for small manufacturing facilities. The information from MES is used to create factory digital twins. Varela et al. [88] presented a systematic review of cloud-based collaborative manufacturing and highlighted process and scheduling plan generation as the main challenge for industries. Liu et al. [83] highlighted scheduling issues for cloud-based manufacturing and found workshop and supply chain scheduling as the emerging areas in cloud manufacturing. Lu and Xu [89] proposed a generic architecture for cloud-based manufacturing based on big data analytics and cyber-physical systems. It was found that the proposed architecture enables the on-demand manufacturing services via the network. Mubarok et al. [90] proposed a hierarchical reliability-based assessment model for cloud manufacturing. In the proposed model resources at three level i.e., system, machine and component levels are evaluated. Caggiano et al. [80] proposed a model for cloud manufacturing to monitor smart diagnosis in manufacturing. It was found that, based on cloud diagnosis corrective action such as tool replacement, parameter changes and process halting can be undertaken by a local server. Fisher et al. [91] stated that cloud-based manufacturing is an advanced service-oriented business model in which resources and manufacturing capabilities can be shared on a cloud platform. Cloud manufacturing can provide sustainable and robust route for manufacturing industries to achieve sustainability.

5.2.6. Augmented and Virtual Reality

Augmented reality is the set of technologies in which the real world environment can be viewed in an enhanced or augmented way with the help of computer graphics [92]. The visual aspects of physical entities in the system can be enhanced by use of various devices. Augmented reality has a wide range of applications in Industry 4.0 but the manufacturing domain is more attractive area for researchers [93]. The various stages of the product life cycle need real time information i.e., about design to prototyping, maintenance operations and assembly operations. These stages have many challenges which can be addressed by augmented reality through simulation which results in reduced downtime in industries and streamlines of operations [94]. Similarly, virtual reality technologies have opened the various avenues in industries to develop innovative solution as manufacturing units by use of simulation tools, smart machines, data analytics and high connectivity between workstations. These changes in manufacturing units have refined the production capabilities of industries and meet the dynamic demands of markets [94–96]. Lee [97] proposed a real-time material flow simulator and layout for manufacturing problems. In the proposed framework integrated AR and manufacturing techniques are used for manufacturing issues in large enterprises. The results of the study indicated the more accurate results through the simulation and AR approaches for manufacturing modeling. Nabati et al. [95] presented an overview on VR applications for energy-efficient manufacturing and found that VR technologies helps to minimize the energy consumption in Industry 4.0 during manufacturing. Rumsey and Dantec [98] conducted a study in global aviation manufacturing headquarters in the United States through surveys and interviews and provided an initial insight on organizational impact of AR and VR technologies. Shiba and Imai [96] developed a lesson support system for manufacturing applications using AR technologies. The proposed system is helpful to manage the digital data and reduce human efforts in training. Bottani and Vignali [92] presented a review on AR technology in manufacturing industries in which major application areas of manufacturing such as assembly and maintenance operations were explored. Lai et al. [94] proposed integrated Faster R-CNN (region based convolutional network) and AR instructional system for intelligent manufacturing. The results of study reported the reduction in errors and assembly time as compared to conventional method. Mittal et al. [99] found AR and VR technologies as the main enablers for smart manufacturing practices. Malik et al. [100] explored the advancements and development in VR technology for human-centered production systems. In the study, a simulation-based human centered VR framework is proposed for manufacturing to reduce cycle time, robot control, layout optimization and process plan development. Mandic [101] proposed a model-based manufacturing system for Industry 4.0 using AR and rapid technologies for design and fabrication of a sheet metal process.

5.2.7. Blockchain Technology

Blockchain technology in Industry 4.0 offers new tools to address sustainability issues, security, efficiency and resiliency of systems as well as transparent and decentralized transaction systems [102,103]. The traceability and transparency characteristics offered by blockchain enhance manufacturing network sustainability. Leng et al. [102] discussed 12 metrics for blockchain adoption in the manufacturing sector. In the study, a list of social challenges and barriers for blockchain empowered manufacturing is discussed. Li et al. [103] developed a distributed network for cloud-based manufacturing in which blockchain technology is used as standard. The results of the study indicated that the proposed approach has more advantages over the scalability and security. Lee et al. [21] discussed the blockchain technology potentials in cyber physical production systems and proposed a three-level architecture for blockchain enabled manufacturing practices. Westerkamp et al. [104] proposed a method for manufacturing goods and components traceability. In the proposed model products are represented as digital tokens created on blockchain. The results of study indicated that blockchain technology in manufacturing operations helps in process traceability. Lohmer and Lasch [105] conducted an empirical investigation on manufacturing and blockchain with the survey-based method in which legal uncertainties, unclear governance and a lack of standardization are found as major barriers. Ko et al. [106] reviewed the current blockchain applications in the manufacturing sector and examined how blockchain technology helps in cost saving and real-time transparency in manufacturing. A conceptual model is proposed to ensure sustainability in manufacturing practices. Yu et al. [107] proposed a blockchain-based architecture to enhance decentralization and transparency in manufacturing activities. The proposed model is solved with the particle swarm optimization approach and simulations were performed. Aghamohammadzadeh et al. [108] introduced a novel blockchain based manufacturing architecture. The proposed architecture can provide service collaboration for service providers and service optimality. Zhang et al. [109] investigated the blockchain based trust mechanism and security and provides a particular application for quality assurance in smart manufacturing. A survey is conducted in the dairy industry and found that blockchain technology improves the transparency and security in the smart manufacturing. Yu et al. [110] proposed a blockchain-shared manufacturing framework to support cyber physical system. It was found that a smart contract network and proof of participation assure the sustainability of resource operation blockchain and stability. Tao et al. [111] proposed a digital twin and blockchain-based framework for smart manufacturing. In the study digital twin and blockchain service management related challenges are discussed. Barenji et al. [112] used two types of blockchain network: (1) public (service provide level); (2) private (shop level), which are connected with the machine level to receive and gather the data. Ouyang et al. [113] proposed a blockchain-based framework for collaborative manufacturing to design and optimize the manufacturing.

5.2.8. Flexible and Reconfigurable Manufacturing Systems

In the past, manufacturing industries were driven by mass production aiming at same type of high-quality products at high volume. In today’s scenario, increasing customer demands and human lifestyles have changed market demands which are driven by mass customization with a higher volume of production [4,77]. Mass customization in industries requires machine intelligence as well as high level of automation which has increased manufacturing costs and slowed down production processes [38]. Reconfigurable manufacturing systems (RMS) and flexible manufacturing systems (FMS) have introduced in industries to solve these problems which are now combing with Industry 4.0 technologies [114]. Khezri et al. [115] addressed sustainability issues in reconfigurable manufacturing systems in process planning and stated that RMS systems as an enabler for Industry 4.0 practices to reduce the reconfigurability effort during dynamic changes in the market. Touzout and Benyoucef; Alcácer and Machado [114,116] stated that RMS and FMS as the main enablers for Industry 4.0 to complete mass customization demands from customers. Vaidya et al. [117] discussed the opportunities for RMS and FMS in Industry 4.0. It was noted that RMS systems helps to reduce the reconfigurable effort in manufacturing systems which can easily adapt the dynamic changes in market. Long et al. [118] proposed a model for a flexible production system in Industry 4.0 with three machines to reduce the machine failures. Suzic et al.; Wang et al. [119,120] discussed the FMS as the guidelines for the mass customization production in Industry 4.0. Khalil et al. [121] proposed a model-based system engineering method for FMS in Industry 4.0. In the study, decision support systems are proposed based on three solutions (RMS, scheduling optimization and FMS) with real-time data from industries. Florescu and Barabas [122] proposed a material flow design methodology for FMS. Different manufacturing scenarios have evaluated in the model using the simulation and virtual modelling approaches. It was found that this model is helpful in the development of intelligent manufacturing systems where control systems can use the simulations to regulate the process parameters for predictive maintenance. Luscinski and Ivanov [123] developed a simulation model for FMS using ontology on flexibility. A simulation model was developed using FlexSim modeling software and industry examples were used to check the applicability of the model. Sang et al. [124] proposed a FIWARE-based framework for predictive maintenance in FMS. The effectiveness of model is tested with the industry case study. The results indicated the reduction in cost and unnecessary downtimes.

5.2.9. Robotics

Industrial robots are more digitally connected and use more sensors which makes them less susceptible in the Industry 4.0 environment. Robotics-enabled manufacturing in Industry 4.0 helps to reduce downtime and maximize efficiency [125]. Unscheduled downtime is one the major issues at the present time which results in inefficiency in industries. Robotic technology helps to minimize the reconfigurable effort which results in minimizing errors as well as improvement quality and production [126]. Goel and Gupta, and Dhanabalan and Sathish [125,127] discussed the roadmaps for robotics in Industry 4.0. In these studies it is discussed how industries can transform themselves to Industry 4.0 with robotics and AI technologies. Braganca et al. [128] presented an overview on collaborative robotics to support workers for manufacturing in Industry 4.0. The main advantages of collaborative robotics such as human–robot collaboration, cognitive tasks and physical tasks was discussed. Xu et al. [76] stated that modern robotic technology in Industry 4.0 offers flexibility and autonomy which results in cost advantages and human safety. Robotic technology in Industry 4.0 has a wide range of capabilities that can also perform most of manufacturing operations in intelligent manufacturing environment. Karabegović et al. [129] implemented Industry 4.0 and robotic technologies in manufacturing processes. The benefits of implementation in terms of self-optimization, self-diagnosis, self-configuration, self-automation and intelligent decision making is discussed. Fragapane et al. [130] compared the production activities in traditional manufacturing and Industry 4.0 by proposing an analytical model that uses autonomous mobile robots (AMR). The sensitivity analysis results of the study revealed that number of shifts and cost of AMR are the key factors to improve productivity and flexibility in Industry 4.0 practices. Karabegović [131] discussed the role of service and industrial robots in the development of Industry 4.0 and smart manufacturing. It was noted that robotics technology ensures the safety in the shop floor and with robotic technology manufacturing has become more flexible. Wan et al. [132] introduced a context-aware robotic model for material handling in industries. In the study, challenges, advantages and system architecture are discussed in detail. A case study is performed to minimize the energy consumption and cost reduction in material-handling problems. Simulation results of study shows the reduction in cost and energy consumption in material handling operations.

5.2.10. Cyber Security

Smart factories in Industry 4.0 can be subjected to vulnerability exploitation, device hacking, malware attacks and other common attacks which are also faced the other network [133]. The cyber-attacks in Industry 4.0 can disrupt manufacturing activities and will be difficult for manufacturers to detect and defend from cyber attacks [134]. Manufacturing in Industry 4.0 is based on cyber-physical production systems and IoT based network which are connected to many sensors and communication devices in the system [10]. At present, cyber security threats are major issues in Industry 4.0. Once malicious software or any virus attack enter a cyber physical production system they can communicate with different machines and layers through communication networks which can affect the manufacturing activities [135]. These viruses or malicious software can destroy the manufacturer data or change the manufacturing process which result in system breakdown or downtime. Industrial data is highly sensitive as it requires information related to products and other copyright details which can be affected by cyber attacks [136]. Culot et al., and Ervural and Ervural [133,134] addressed the challenges related to cyber security for cyber physical based production systems in Industry 4.0 in which modification in firmware and malware intrusions are found to be major issues. Lezzi et al. [137] presented an overview of current issues related to cybersecurity for manufacturing in Industry 4.0. Ghobakhloo [138] discussed the importance of cyber security-related issues for Industry 4.0 roadmap development. It is noted that cyber-attacks can disrupt the manufacturing activities. So, the industries need to work more on cyber security related issues. Wegner et al. [139] presented a new approach for cybersecurity issues in Industry 4.0 which limits the information flow to authorized and internal floor devices in a system. Rubio et al. [135] analyzed the cyber security-related threats in Industry 4.0 context.

RQ2: How can Industry 4.0 technologies contribute to sustainability in manufacturing?

6. Manufacturing Sustainability in Industry 4.0

Manufacturing sustainability is more about development and growth of industries in a socially equitable and eco-friendly manner rather than minimizing carbon emission and pollution [140]. Sustainability can be considered as the core of business strategy which is highlighted in the UN Sustainability 2030 agenda which includes smart manufacturing, energy efficient buildings and low impact industrialization [141]. Stock and Seliger [3] discussed the role of sustainable manufacturing practices in Industry 4.0 and found that Industry 4.0 technologies will open the opportunities for sustainability in business. Jabbour et al. [9] found that Industry 4.0 practices will unlock opportunities for green manufacturing practices. A future research agenda and framework for sustainability practices in Industry 4.0 is proposed. Yadav et al. [47] find the critical enablers for the Industry 4.0 technologies to achieve sustainability in manufacturing practices. In the study it was found that adoption of renewable energy sources and adoption of sustainable policies in manufacturing practices help to achieve sustainability in Industry 4.0 practices. Jamwal et al. [46] proposed a sustainability framework for Industry 4.0 practices. It was noted that multi-national enterprises are now investing more in emerging economies for Industry 4.0 practices because of cheap labour cost. Developing nations have more opportunities for the sustainability in Industry 4.0 as the economy is largely dependent on small and medium enterprises (SMEs). Mittal et al. [48] reviewed the maturity models for Industry 4.0 and found that opportunities for MNCs (multi-national companies) and SMEs are different. There is need to different roadmap and maturity model for SMEs to unlock the sustainability benefits of Industry 4.0 practices. Ghobakhloo [142] discussed the sustainability opportunities in Industry 4.0. In the study, critical sustainability functions for Industry 4.0 were analyzed with the ISM (interpretive structural modeling) approach and found that business model innovation and production efficiency are the main critical functions for sustainability.

6.1. Economic Sustainability

Only few studies are reported about economic sustainability in Industry 4.0. (Ghobakhloo) [142] found business model innovation and production efficiency are the main function for industries to maintain economic sustainability in Industry 4.0. Braccini and Margherita [143] found that improvement in economic sustainability affects the environmental sustainability by improving resource efficiency and social sustainability by higher taxes. It was noted that manufacturing organizations are using sensors in their assembly lines for warehouse and inventory management which helps to improve economic sustainability. Jamwal et al. [46] stated that in developing economies manufacturing sustainability in Industry 4.0 depends on economic and political factors. A case study was undertaken in the electronics manufacturing industry and found that social and economic factors are the effect enablers while information technology, supply chain and environmental related enablers are cause enablers for Industry 4.0 sustainability. Brozzi et al. [144] concluded in a survey study that industries are now focusing more on economic sustainability as compared to social and environmental sustainability. Müller and Voigt [145] concluded that Industry 4.0 offers innovative business models which can help to achieve economic sustainability as well as enhance competitiveness. Luthra et al. [146] stated that managers should understand the need of Industry 4.0 adoption for the economic, ecological and environmental benefits in emerging economies. Varela et al. [37] found that the Industry 4.0 revolution will be more favorable for economic sustainability by reducing manpower, energy consumption, lead time and improving productivity in manufacturing processes. Stock and Seliger, and Jabbour et al. [3,9] found that Industry 4.0 practices helps to reduce operational costs, improve circular economy, market share of products and create new business model which enhance economic sustainability in industries. The main influence of Industry 4.0 on economic sustainability is presented in Table 2.

Table 2. Influence of Industry 4.0 technologies on economic sustainability.

Sustainability Dimension in I4.0	Main Influence from I4.0	References
Economic	Sustainable value creation, efficiency and profits	[3,8,10,11,37]
	Reduction in operational costs	[4,8]
	Impact on market share, supply chain, security	[9,46,47,146]
	New business model opportunities, turnover	[3,4,8,48]

6.2. Social Sustainability

Economic sustainability in Industry 4.0 can be considered another paradox which is generated by Industry 4.0 technologies. The basic requirement for the Industry 4.0 is digitalization and automation in manufacturing activities [48]. The more automation in industry will result in less manual labour. Introducing a new machine in the system will affect certain jobs previously done by employees. These jobs include shop floor activities and low-skilled jobs in industries which results in increasing unemployment [52]. It is true that innovations in Industry 4.0 will generate new kinds of services and products in various sectors. Employees needs to have flexible and keen learner to adapt the changes done by fourth industrial revolution [43]. In the case of developed nations, the industries are already working on their employee training from the long time which now has a skilled set of labour which can adapt the Industry 4.0 environment. But, developing nations still require a highly skilled set of labour which can perform tasks and adapt the changes arising from Industry 4.0 technologies [46,47,146]. The new training models in industries should have a focus on the development of the interdisciplinary skills that can increase the capabilities of employees and make them ready to deal with the challenges in Industry 4.0. The new technologies in Industry 4.0 generate a large amount of data which can be useful for the future decision making and other operations such as predictive maintenance [53]. Workers need to be skilled for these challenges so that they can manage this data and perform the changes required in the organization. Most of the skillset required for Industry 4.0 is not available in SMEs because there is no dedicated team in SMEs for Industry 4.0 activities. These industries need to improve their skills through continuous innovation and training by introducing new approaches in industries such as: (1) development in technical skills; (2) virtual training programs; (3) user's view-centered processes; (4) development in digital and soft skills; (5) manufacturing systems; on which industries have been working for a long time. The manufacturing systems in Industry 4.0 are highly flexible which need more technical skills to deal with dynamic changes in market. To complete this requirement, industries are collaborating with universities and research institutes to develop improved education and training plans for their workers. Some studies found Education 4.0 will be helpful to generate skilled labour in future for Industry 4.0. Our findings indicated that there is limited research on theoretical and empirical investigations on the social sustainability aspect of Industry 4.0. Therefore, we suggest that future studies need to address the solution required to enhance the abilities and skills of workers with digital manufacturing support. The main influence of Industry 4.0 on social sustainability is presented in Table 3.

Table 3. Influence of Industry 4.0 technologies on social sustainability.

Sustainability Dimension in I4.0	Main Influence from I4.0	References
Social	Employment	[48]
	Better collaboration among stakeholders	[4,8]
	Reduction in accidents	[37,128]
	Improved living conditions for societies	[9,10,48]
	Improved working conditions	[3,9]

6.3. Environmental Sustainability

Due to strict government regulations and customer awareness, industries are now focusing more on improving standards of living and environment-related issues. Environmental sustainability can be considered one of the major pillars which contribute to the sustainability in business practices [14]. The development in innovations and technology are growing at a faster rate to improve the quality of life [8,10]. These developments are not very sustainable because of a lack of proper knowledge about Industry 4.0 technologies and their potentials [4]. Most of the developments in the environmental sustainability are focused on the resource efficiency and climate issues. Industry 4.0 technologies consist of cyber physical systems, intelligent sensors and smart logistics which have the potential to reduce the energy, water and resource consumption in industry [39]. Additive manufacturing technologies work on a pull strategy which has the potential to reduce the inventory levels, lead times as well as complete the mass customized demands [44]. Industry 4.0 technologies require higher energy consumption as these technologies are based on sensors, data centers and smart equipment which have a negative impact on the environment during manufacturing operations [147]. Hazardous waste disposal and greenhouse gases emissions are the major concern in the environmental sustainability [115]. During manufacturing, activities many scraps and other waste is generated which affect both environmental and economic sustainability. There is a requirement for sustainable processing and scheduling plans which can minimize the emissions and waste at the machine level. However, few studies have addressed these research issues but they have limitations and subjective to some constraints [47,148]. Hazardous chemical disposal may lead to accidents which is the major concern in developing nations due to lack of standardized technologies for Industry 4.0. Therefore, there is a need to develop new tools and methods for detection and control of these type of issues in industries. The main influence of Industry 4.0 on environmental sustainability is presented in Table 4.

Table 4. Influence of Industry 4.0 technologies on environmental sustainability.

Sustainability Dimension in I4.0	Main Influence from I4.0	References
Environmental	Industrial waste reduction	[3,47,149]
	Promote circular economy	[9,11]
	Use and production of renewable sources	[46,47,102]
	Reduction in use of non-renewable sources and energy consumption	[4,8,9]
	Reduction in global warming, resource consumption, energy consumption	[8,147]

RQ3: What are main research gaps in Industry 4.0 technologies for manufacturing sustainability and what are the research issues that need to be addressed in future?

7. Future Research Directions

This section discusses the future research directions to achieve manufacturing sustainability from Industry 4.0 technologies. From the literature review, six major research areas are found which can be explored in future studies, discussed with research gaps below:

7.1. Lean Production Systems for Environment Management in Industry 4.0

Studies published on lean manufacturing state the benefits of lean production systems in mass production [37,42]. These studies explain how lean manufacturing can help to satisfy customer requirements. Ghobakhloo and Fathi [150] discuss the practical implications of lean-enabled Industry 4.0 practices and stated some research scopes related to lean enabled practices for small- and large-scale industries. Varela et al. [37] investigate the relationship between lean practices and Industry 4.0 technologies and found that sustainability pillars are strongly related to Industry 4.0. The studies on lean Industry 4.0 integration are still limited. It would be more interesting to know the impact of lean manufacturing practices from Industry 4.0 technologies. In future studies, an integrated lean-industry 4.0 framework can be proposed to enhance performance and minimize the waste from manufacturing activities.

7.2. Establish Relationship between Sustainability and Industry 4.0 Factors

Most of the studies on Industry 4.0 are from developed nations which shows that they are more focused on Industry 4.0. However, studies and adoption of Industry 4.0 is less in the developing nations due to technological advancements and resources required for Industry 4.0 implementation. Studies conducted by Yadav et al.; Jamwal et al.; Luthra et al. [46,47,146] discussed the research opportunities for Industry 4.0 technologies to achieve sustainability by identifying influencing factors. Very few studies discuss the relationship between sustainability and Industry 4.0 factors for business practices. Furthermore, there is need to incorporate the factors related to political and risk-related factors. The effect of these factors on sustainability is discussed by [151]. There is need to include these factors with Industry 4.0 theories for the successful implementation of sustainability practices in Industry 4.0 manufacturing. This will be helpful to provide a guideline for emerging industry sectors. In future studies, hybrid multi-criteria decision-making approaches, decision making in uncertainty and statistical tools can be used to find the influence and relationship between the factors related to Industry 4.0 and sustainability.

7.3. Impact of Sustainable Supply Chain in Industry 4.0

Industry 4.0 technologies has created disruption in supply chains which forced the manufacturing industries to rethink their supply chain design [146]. In the past few years several new technologies have emerged which have altered traditional supply chain practices. Now the industries are transforming their business models and adapting digital supply chain models. Digitalization in the supply chain is aided by disruptive new technologies such as big data analytics, AI, machine learning, automation, blockchain and IoT [152]. Studies reported that digitalization in supply chains helps to lower the operational costs by 30%, inventory requirements by 70% and lost sale opportunities by 60% [153–155]. In the digital transition of supply chain practices, long-term investments and significant efforts are required. This will help to achieve operation effectiveness and cost reduction in supply chain practices.

In future studies, the impact of sustainable supply chain on smart manufacturing, remanufacturing, reverse logistics, and product cycling can be explored. However, in blockchain-enabled supply chains, few studies have addressed environmental issues [152]. Table 5 presents the research issues and challenges for sustainable supply chains for manufacturing sustainability.

Table 5. Research issues in sustainable supply chain practices in Industry 4.0 for manufacturing sustainability.

Category	Research Issue	References
Supply chain strategies for Industry 4.0	How digital transformation is forcing manufacturing industries to rethink their business models? What is the relationship between Industry 4.0 technologies and supply chain strategies? What is the effect of supply chain digitalization on network value?	[23,24,50]
Supply chain orientation in Industry 4.0	Role and benefits of sustainable supply chain management (SSCM) in Industry 4.0? What are the benefits and drawbacks of technological infrastructure manufacturing industries required for SSCM practices?	[4,8,23,50]
Customer value creation	What are the effects of data driven SSCM practices in Industry 4.0? How Industry 4.0 technologies will help to implement SSCM in manufacturing industries?	[3,50,154]
Human centric issues in SSCM	What is role of human in digitalized supply chain network and practices? How machine learning and AI based approaches can help to achieve sustainability in SCM(supply chain management)?	[9,153,155]

7.4. Big Data Analytics and Sustainability

The use of big data analytics in manufacturing context offer several opportunities for manufacturing industries in terms of production monitoring and real-time optimization which contributes to sustainability.

Both IoT and big data analytics are the significant contributor in the development of Industry 4.0. Big data analytics approaches are based on 3V (volume, variety and velocity) which can handle large amounts of data and can be classified according to different lifecycle stages [156]. Ren et al. [157] argued that big data analytics help to deal with the future challenges related to smart manufacturing. In the last few years, advancements in big data approaches have gained the attention of practitioners. Now, these approaches are used by many industries to improve their services and maintenance operations. Wang and Wang [49] found that manufacturing challenges in Industry 4.0 can be efficiently handled by big data analytics due to its ability to handle large amount of data.

Future studies can be conducted to develop new big data analytics approaches to achieve sustainability in manufacturing. There is a need to evaluate and analyze high amount of data generated from the various stages of manufacturing processes. In future studies, simulation and optimization techniques can be integrated data analytics which will help to provide a better understanding of models for shop floor management. Studies related to the development of IT-enabled big data analytics are also limited. In future studies, the role of these architectures to achieve sustainability in manufacturing can be investigated. Few studies have discussed big data analytics (BDA) opportunities for sustainable manufacturing in which condition-based predictive maintenance issues discussed [158]. In this area, future research studies can be conducted by considering the multicomponent-based systems which is a limitation in most of the studies. Table 6 presents the research issues and challenges for big data-enabled practices for manufacturing sustainability.

Table 6. Research issues in big data analytics in Industry 4.0 for manufacturing sustainability.

Future Research Challenge	References
Architecture development for sustainable smart manufacturing (SSM) practices	[6,89]
Data acquisition issues for SSM	[24,50]
Data aggregation and integration issues	[49,54]
Algorithms and model development for BDA enabled SSM practices	[49,54,159]
Data quality management issues for SSM	[160,161]
Role of cloud-based technologies for SSM	[89]
Issues related to energy consumption and optimization	[162]

7.5. Impact of Machine Learning and Artificial Intelligence (AI) Approaches on Sustainability

The emergence of machine learning and AI approaches is shaping industrial sectors and is expected to affect global productivity and environmental outcomes. AI and machine learning have both a negative and positive impact on sustainable development [141]. Jamwal et al. [39] found that AI and machine learning approaches are helping industries to achieve sustainability in manufacturing as well as Industry 4.0 implementation. Machine learning approaches can be beneficial for manufacturing systems optimization, recovery plans, and condition monitoring. Table 7 presents the research challenges for AI and machine learning-enabled practices for manufacturing sustainability.

Table 7. Research issues in artificial intelligence (AI) and machine learning-enabled practices for manufacturing sustainability.

Future Research Challenge	References
Development of integrated SM layouts by machine learning approaches	[148]
What is impact of AI and machine learning approaches in Industry 4.0 from sustainability perspective	[39]
Prediction modelling and condition-based monitoring issues	[35,158]
AI and Machine learning based intelligent decision making	[163,164]
Quality prediction issues	[165,166]

7.6. Integrated Process Planning and Scheduling for Sustainability on the Shop Floor

Industry 4.0 on the shop floor level uses advanced technologies and complete automation in which data can be transferred with the internet network. Industry 4.0 consists of the key enabling technologies such as cyber physical systems which can work autonomously and have self-optimization performance across the network. Optimization of subcomponents in manufacturing does not necessarily optimize the overall manufacturing process [40]. There is a need for global optimization to achieve synergy in the entire manufacturing system. Decisions in industries about what to produce, when and where to produce it, fall in the domain of planning and scheduling [38]. Without an ability to make decisions in manufacturing industries from the global point of view it is not possible to experience the full benefits of Industry 4.0 practices. In the present time, global supply chain practices require a new level of planning and scheduling sophistication which can be termed "Planning and Scheduling 4.0". Industry 4.0 technologies are transforming manufacturing industries and driving the need for integrated planning and scheduling systems which can support greater transparency, automation and integration. Opessa MLS V7+ can be considered as the solution for the planning and scheduling 4.0.

Future research work can be conducted on how process planning and scheduling in Industry 4.0 can contribute to sustainability (economic and environmental dimensions) and resource efficiency. In the context of manufacturing sustainability, there are two major elements: (1) inputs elements (raw materials, inventories and man-machine); (2) output elements (pollution, scrap, waste and hazards). How can these elements be considered as decision variables when computing the scheduling plans in reactive or predictive manner? Scheduling in Industry 4.0 requires dynamic, efficient and decentralized decision methods. In future studies, intelligent algorithms can be introduced to investigate the real-time autonomous behavior of manufacturing systems. Innovative approaches and concepts such as product service systems, intelligent products and cyber physical systems can be used to develop efficient and effective sustainable scheduling plans.

7.7. Non-Destructive Quality Control for Manufacturing Sustainability

Industry 4.0 technologies are enhancing the non-destructive methods for quality control in manufacturing which have a great impact on sustainability, safety and product quality. Non-destructive testing in Industry 4.0 comprises all aspects including the inspection of raw material to product delivery. Despite the development in non-destructive quality control in the last few years, there are still many limitations related to skilled labour, complex user interfaces, slow data sharing processes and inspection speeds, and complicated data interpretation which can be addressed in future studies. Some major research issues in non-destructive quality control for manufacturing sustainability are as follows:

1. What are the main challenges and requirements for non-destructive testing in the Industry 4.0 scenario?
2. Standardization of digital connections for non-destructive testing methods in Industry 4.0.
3. Skill development and cost-related issues for non-destructive testing in the Industry 4.0 context.

These are some major issues which can be addressed in future studies.

8. Conclusions

In the present study role of Industry 4.0 technologies to achieve manufacturing sustainability is discussed. The present study aimed to identify the current research progress in Industry 4.0 and sustainability by using a systematic literature review approach. In the study, a SLR was performed on three well-regarded digital scientific databases i.e., IEEE, Web of Science and Scopus. A total of 127 articles were selected after screening for review. The role of different key enabling technologies for Industry 4.0 was discussed in detail. The results indicate that manufacturing sustainability can be enhanced with Industry 4.0 technologies. The research in Industry 4.0 and manufacturing sustainability have several new scopes.

In the literature it is found that the majority of studies focused on a general discussion about the Industry 4.0 concepts and theories. However, very few studies discuss the role of shop floor activities and different technologies for achieving manufacturing sustainability. In shop floor management, case studies and simulation approaches were used to validate the proposed architectures. There is lack of studies on planning and scheduling which can contribute to achieve manufacturing sustainability.

As a new service-oriented and network-based manufacturing paradigm, manufacturing sustainability has experienced rapid advancement and development in the last few years. Within the SM system, the emerging key enabling technologies of Industry 4.0 such as blockchain, big data, AI, machine learning and IoT are being increasingly used by industries to capture and analyze data in different life-cycles of products. Consequently, a large amount of data is available and used for decision making in life-cycle management with BDA. The literature review revealed that Industry 4.0 has a significant impact on the manufacturing sustainability in different stages. However, research in this area is still limited. To address these research limitations, authors have provided insights for future research work in different areas. The following significant contributions are from this SLR:

- This study discusses the role and opportunities for Industry 4.0 technologies for various manufacturing operations in industries. The previous published studies were limited to the general concepts related to Industry 4.0 theories and concepts. The role and opportunities for shop floor management in Industry 4.0 are discussed. Furthermore, this study provides the impact of various Industry 4.0 technologies on each sustainability dimension which will be helpful for future studies.
- Secondly, this study uses the three major scientific databases i.e., IEEE explore, Scopus and Web of science, for the literature collection which was the limitation in previously published studies. This study followed the PRISMA approach for a systematic literature review and, on the basis of final articles, different opportunities for the manufacturing sustainability with Industry 4.0 technologies are discussed.
- Finally, from the literature review various research issues and challenges in Industry 4.0 were identified which can be explored in the future studies.

Both industry and academics leaders will obtain insights from the findings of this study. Future studies should be focused on the framework development with the different Industry 4.0 technologies to achieve sustainability in both large enterprises and small enterprises. In addition, areas like lean production in Industry 4.0 and the role of AI and machine learning for manufacturing sustainability can be explored.

Author Contributions: Conceptualization, A.J. and A.G.; methodology, A.J.; software, A.J.; validation, R.A., M.S. and A.G.; formal analysis, R.A., M.S. and A.G.; investigation, R.A.; resources, M.S. and A.G.; writing—original draft preparation, A.J.; writing—review and editing, A.J.; visualization, A.J.; supervision, R.A., M.S. and A.G.; project administration, A.G.; funding acquisition, A.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Aiello, G.; Giallanza, A.; Vacante, S.; Fasoli, S.; Mascarella, G. Propulsion Monitoring System for Digitized Ship Management: Preliminary Results from a Case Study. *Procedia Manuf.* **2020**, *42*, 16–23.
2. Oztemel, E.; Gursev, S. Literature Review of Industry 4.0 and Related Technologies. *J. Intell. Manuf.* **2020**, *31*, 127–182, doi:10.1007/s10845-018-1433-8.
3. Stock, T.; Seliger, G. Opportunities of Sustainable Manufacturing in Industry 4.0. In *Procedia CIRP, Proceedings of the 13th Global Conference on Sustainable Manufacturing—Decoupling Growth from Resource Use, Binh Duong, Vietnam, 16–18 September 2016*; Seliger, G., Malon, J., Kohl, H., Eds.; Elsevier B.V.: Amsterdam, The Netherlands, 2016; Volume 40, pp. 536–541.
4. Machado, C.G.; Winroth, M.P.; Ribeiro da Silva, E.H.D. Sustainable Manufacturing in Industry 4.0: An Emerging Research Agenda. *Int. J. Prod. Res.* **2020**, *58*, 1462–1484, doi:10.1080/00207543.2019.1652777.
5. Zhong, R.Y.; Xu, X.; Klotz, E.; Newman, S.T. Intelligent Manufacturing in the Context of Industry 4.0: A Review. *Engineering* **2017**, *3*, 616–630.
6. Kim, J.H. A Review of Cyber-Physical System Research Relevant to the Emerging IT Trends: Industry 4.0, IoT, Big Data, and Cloud Computing. *J. Ind. Integr. Manag.* **2017**, *2*, 1750011.
7. Ejsmont, K.; Gladysz, B.; Kluczek, A. Impact of Industry 4.0 on Sustainability-Bibliometric Literature Review. *Sustainability* **2020**, *12*, doi:10.3390/su12145650.

8. Sharma, R.; Jabbour, C.J.C.; Lopes de Sousa Jabbour, A.B. Sustainable Manufacturing and Industry 4.0: What We Know and What We Don't. *J. Enterp. Inf. Manag.* **2020**, doi:10.1108/JEIM-01-2020-0024.
9. de Sousa Jabbour, A.B.L.; Jabbour, C.J.C.; Foropon, C.; Filho, M.G. When Titans Meet—Can Industry 4.0 Revolutionise the Environmentally-Sustainable Manufacturing Wave? The Role of Critical Success Factors. *Technol. Forecast. Soc. Change* **2018**, *132*, 18–25, doi:10.1016/j.techfore.2018.01.017.
10. Kamble, S.S.; Gunasekaran, A.; Gawankar, S.A. Sustainable Industry 4.0 Framework: A Systematic Literature Review Identifying the Current Trends and Future Perspectives. *Process. Saf. Environ. Prot.* **2018**, *117*, 408–425, doi:10.1016/j.psep.2018.05.009.
11. Bag, S.; Pretorius, J.H.C. Relationships between Industry 4.0, Sustainable Manufacturing and Circular Economy: Proposal of a Research Framework. *Int. J. Organ. Anal.* **2020**, doi:10.1108/IJOA-04-2020-2120.
12. Haapala, K.R.; Zhao, F.; Camelio, J.; Sutherland, J.W.; Skerlos, S.J.; Dornfeld, D.A.; Jawahir, I.S.; Clarens, A.F.; Rickli, J.L. A Review of Engineering Research in Sustainable Manufacturing. *J. Manuf. Sci. Eng. Trans. ASME* **2013**, *135*, doi:10.1115/1.4024040.
13. Garetti, M.; Taisch, M. Sustainable Manufacturing: Trends and Research Challenges. *Prod. Plan. Control.* **2012**, *23*, 83–104, doi:10.1080/09537287.2011.591619.
14. Jayal, A.D.; Badurdeen, F.; Dillon, O.W., Jr.; Jawahir, I.S. Sustainable Manufacturing: Modeling and Optimization Challenges at the Product, Process and System Levels. *CIRP J. Manuf. Sci. Technol.* **2010**, *2*, 144–152, doi:10.1016/j.cirpj.2010.03.006.
15. ITA, U. How Does Commerce Define Sustainable Manufacturing? 2012. Available online: https://oneill.indiana.edu/doc/research/sustainability-2014.pdf (accessed on 17 May , 2021).
16. Sartal, A.; Bellas, R.; Mejías, A.M.; García-Collado, A. The Sustainable Manufacturing Concept, Evolution and Opportunities within Industry 4.0: A Literature Review. *Adv. Mech. Eng.* **2020**, *12*, doi:10.1177/1687814020925232.
17. McElnea, W.K. Sustainable Manufacturing Initiative: U.S. Department of Commerce. *Int. J. Powder Metall. Princet. N. J.* **2011**, *47*, 12–16.
18. Giallanza, A.; Aiello, G.; Marannano, G.; Nigrelli, V. Industry 4.0: Smart Test Bench for Shipbuilding Industry. *Int. J. Interact. Des. Manuf. IJIDeM* **2020**, *14*, 1525–1533.
19. Borregan-Alvarado, J.; Alvarez-Meaza, I.; Cilleruelo-Carrasco, E.; Garechana-Anacabe, G. A Bibliometric Analysis in Industry 4.0 and Advanced Manufacturing: What about the Sustainable Supply Chain? *Sustainability* **2020**, *12*, doi:10.3390/SU12197840.
20. Giallanza, A.; Aiello, G.; Marannano, G. Industry 4.0: Advanced Digital Solutions Implemented on a Close Power Loop Test Bench. *Procedia Comput. Sci.* **2021**, *180*, 93–101.
21. Lee, J.; Azamfar, M.; Singh, J. A Blockchain Enabled Cyber-Physical System Architecture for Industry 4.0 Manufacturing Systems. *Manuf. Lett.* **2019**, *20*, 34–39.
22. Thramboulidis, K.; Vachtsevanou, D.C.; Kontou, I. CPuS-IoT: A Cyber-Physical Microservice and IoT-Based Framework for Manufacturing Assembly Systems. *Annu. Rev. Control* **2019**, *47*, 237–248, doi:10.1016/j.arcontrol.2019.03.005.
23. Abdirad, M.; Krishnan, K. Industry 4.0 in Logistics and Supply Chain Management: A Systematic Literature Review. *EMJ Eng. Manag. J.* **2020**, 1–15, doi:10.1080/10429247.2020.1783935.
24. Chalmeta, R.; Santos-deLeón, N.J. Sustainable Supply Chain in the Era of Industry 4.0 and Big Data: A Systematic Analysis of Literature and Research. *Sustainability* **2020**, *12*, doi:10.3390/su12104108.
25. Moher, D.; Shamseer, L.; Clarke, M.; Ghersi, D.; Liberati, A.; Petticrew, M.; Shekelle, P.; Stewart, L.A. Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P) 2015 Statement. *Syst. Rev.* **2015**, *4*, 1–9.
26. Petticrew, M. Systematic Reviews from Astronomy to Zoology: Myths and Misconceptions. *BMJ* **2001**, *322*, 98–101.
27. Korner, M.E.H.; Lambán, M.P.; Albajez, J.A.; Santolaria, J.; Corrales, L.C.N.; Royo, J. Systematic Literature Review: Integration of Additive Manufacturing and Industry 4.0. *Metals* **2020**, *10*, 1–24, doi:10.3390/met10081061.
28. Samala, T.; Manupati, V.K.; Varela, M.L.R.; Putnik, G. Investigation of Degradation and Upgradation Models for Flexible Unit Systems: A Systematic Literature Review. *Future Internet* **2021**, *13*, 57.
29. Antony, J.; Psomas, E.; Garza-Reyes, J.A.; Hines, P. Practical Implications and Future Research Agenda of Lean Manufacturing: A Systematic Literature Review. *Prod. Plan. Control* **2020**, 1–37.
30. Müller, J.M.; Kiel, D.; Voigt, K.-I. What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability. *Sustainability* **2018**, *10*, doi:10.3390/su10010247.
31. Kiel, D.; Müller, J.M.; Arnold, C.; Voigt, K.-I. Sustainable Industrial Value Creation: Benefits and Challenges of Industry 4.0. *Int. J. Innov. Manag.* **2017**, *21*, doi:10.1142/S1363919617400151.
32. Luthra, S.; Mangla, S.K. Evaluating Challenges to Industry 4.0 Initiatives for Supply Chain Sustainability in Emerging Economies. *Process Saf. Environ. Prot.* **2018**, *117*, 168–179, doi:10.1016/j.psep.2018.04.018.
33. Manavalan, E.; Jayakrishna, K. A Review of Internet of Things (IoT) Embedded Sustainable Supply Chain for Industry 4.0 Requirements. *Comput. Ind. Eng.* **2019**, *127*, 925–953, doi:10.1016/j.cie.2018.11.030.
34. Aiello, G.; Giallanza, A.; Mascarella, G. Towards Shipping 4.0. A Preliminary Gap Analysis. *Procedia Manuf.* **2020**, *42*, 24–29.
35. Cica, D.; Sredanovic, B.; Tesic, S.; Kramar, D. Predictive Modeling of Turning Operations under Different Cooling/Lubricating Conditions for Sustainable Manufacturing with Machine Learning Techniques. *Appl. Comput. Inform.* **2020**, doi:10.1016/j.aci.2020.02.001.
36. Pickard, M.; Grecu, I.; Grecu, G. Sustainable Smart Manufacturing in Industry 4.0: Real-Time Resource Planning, Process Monitoring, and Production Control. *Econ. Manag. Financ. Mark.* **2019**, *14*, 30–36, doi:10.22381/EMFM14320194.
37. Varela, L.; Araújo, A.; Ávila, P.; Castro, H.; Putnik, G. Evaluation of the Relation between Lean Manufacturing, Industry 4.0, and Sustainability. *Sustainability* **2019**, *11*, doi:10.3390/su11051439.

38. Yang, W.; Takakuwa, S. Simulation-Based Dynamic Shop Floor Scheduling for a Flexible Manufacturing System in the Industry 4.0 Environment. In Proceedings of the 2017 Winter Simulation Conference, Las Vegas, NV, USA, 3–6 December 2017; IEEE: New York, NY, USA, 2017; pp. 3908–3916.
39. Jamwal, A.; Agrawal, R.; Sharma, M.; Kumar, A.; Kumar, V.; Garza-Reyes, J.A.A. Machine Learning Applications for Sustainable Manufacturing: A Bibliometric-Based Review for Future Research. *J. Enterp. Inf. Manag.* **2021**, doi:10.1108/JEIM-09-2020-0361.
40. Moica, S.; Ganzarain, J.; Ibarra, D.; Ferencz, P. Change Made in Shop Floor Management to Transform a Conventional Production System into an "Industry 4.0": Case Studies in SME Automotive Production Manufacturing. In *Proceedings of the 7th International Conference on Industrial Technology and Management (ICITM 2018), Oxford, UK, 7–9 March 2018*; IEEE: New York, NY, USA, 2018; pp. 51–56.
41. Mittal, S.; Romero, D.; Wuest, T. Towards a Smart Manufacturing Toolkit for SMEs. *Prod. Lifecycle Manag. Support. Ind. 4.0.* **2018**, 476–487, doi:10.1007/978-3-030-01614-2_44.
42. Schmidt, D.; Villalba Diez, J.; Ordieres-Meré, J.; Gevers, R.; Schwiep, J.; Molina, M. Industry 4.0 Lean Shopfloor Management Characterization Using EEG Sensors and Deep Learning. *Sensors* **2020**, *20*, doi:10.3390/s20102860.
43. Godina, R.; Ribeiro, I.; Matos, F.; Ferreira, B.T.; Carvalho, H.; Peças, P. Impact Assessment of Additive Manufacturing on Sustainable Business Models in Industry 4.0 Context. *Sustainability* **2020**, *12*, doi:10.3390/su12177066.
44. Haleem, A.; Javaid, M. Additive Manufacturing Applications in Industry 4.0: A Review. *J. Ind. Integr. Manag.* **2019**, *4*, 1930001.
45. Ford, S.; Despeisse, M. Additive Manufacturing and Sustainability: An Exploratory Study of the Advantages and Challenges. *J. Clean. Prod.* **2016**, *137*, 1573–1587, doi:10.1016/j.jclepro.2016.04.150.
46. Jamwal, A.; Agrawal, R.; Sharma, M.; Kumar, V.; Kumar, S. Developing A Sustainability Framework for Industry 4.0. *Procedia CIRP* **2021**, *98*, 430–435.
47. Yadav, G.; Kumar, A.; Luthra, S.; Garza-Reyes, J.A.; Kumar, V.; Batista, L. A Framework to Achieve Sustainability in Manufacturing Organisations of Developing Economies Using Industry 4.0 Technologies' Enablers. *Comput. Ind.* **2020**, *122*, doi:10.1016/j.compind.2020.103280.
48. Mittal, S.; Khan, M.A.; Romero, D.; Wuest, T. A Critical Review of Smart Manufacturing & Industry 4.0 Maturity Models: Implications for Small and Medium-Sized Enterprises (SMEs). *J. Manuf. Syst.* **2018**, *49*, 194–214.
49. Wang, L.; Wang, G. Big Data in Cyber-Physical Systems, Digital Manufacturing and Industry 4.0. *Int. J. Eng. Manuf. IJEM* **2016**, *6*, 1–8.
50. Addo-Tenkorang, R.; Helo, P.T. Big Data Applications in Operations/Supply-Chain Management: A Literature Review. *Comput. Ind. Eng.* **2016**, *101*, 528–543, doi:10.1016/j.cie.2016.09.023.
51. Castelo-Branco, I.; Cruz-Jesus, F.; Oliveira, T. Assessing Industry 4.0 Readiness in Manufacturing: Evidence for the European Union. *Comput. Ind.* **2019**, *107*, 22–32.
52. Frank, A.G.; Dalenogare, L.S.; Ayala, N.F. Industry 4.0 Technologies: Implementation Patterns in Manufacturing Companies. *Int. J. Prod. Econ.* **2019**, *210*, 15–26.
53. Papadopoulos, T.; Singh, S.P.; Spanaki, K.; Gunasekaran, A.; Dubey, R. Towards the next Generation of Manufacturing: Implications of Big Data and Digitalization in the Context of Industry 4.0. **2021**, doi:10.1080/09537287.2020.1810767.
54. Li, D.; Tang, H.; Wang, S.; Liu, C. A Big Data Enabled Load-Balancing Control for Smart Manufacturing of Industry 4.0. *Clust. Comput.* **2017**, *20*, 1855–1864.
55. Tao, F.; Qi, Q.; Wang, L.; Nee, A.Y.C. Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison. *Engineering* **2019**, *5*, 653–661, doi:10.1016/j.eng.2019.01.014.
56. Ke, S.; Xiang, F.; Zhang, Z.; Zuo, Y. A Enhanced Interaction Framework Based on VR, AR and MR in Digital Twin. *Procedia Cirp* **2019**, *83*, 753–758.
57. Wang, X.V.; Wang, L. Digital Twin-Based WEEE Recycling, Recovery and Remanufacturing in the Background of Industry 4.0. *Int. J. Prod. Res.* **2019**, *57*, 3892–3902.
58. Lee, J.; Davari, H.; Singh, J.; Pandhare, V. Industrial Artificial Intelligence for Industry 4.0-Based Manufacturing Systems. *Manuf. Lett.* **2018**, *18*, 20–23.
59. Ayvaz, S., & Alpay, K. (2021). Predictive maintenance system for production lines in manufacturing: A machine learning approach using IoT data in real-time. *Expert Systems with Applications*, *173*, 114598.
60. Yao, X.; Zhou, J.; Zhang, J.; Boër, C.R. From Intelligent Manufacturing to Smart Manufacturing for Industry 4.0 Driven by next Generation Artificial Intelligence and Further On. In *Proceedings of the 2017 5th International Conference on Enterprise Systems (ES), Beijing, China, 22–24 September 2017*; IEEE: New York, NY, USA, 2017; pp. 311–318.
61. Bajic, B.; Cosic, I.; Lazarevic, M.; Sremcev, N.; Rikalovic, A. Machine Learning Techniques for Smart Manufacturing: Applications and Challenges in Industry 4.0. *Dep. Ind. Eng. Manag. Novi Sad Serbia* **2018**, *29*.
62. Cioffi, R.; Travaglioni, M.; Piscitelli, G.; Petrillo, A.; De Felice, F. Artificial Intelligence and Machine Learning Applications in Smart Production: Progress, Trends, and Directions. *Sustainability* **2020**, *12*, 492.
63. Angelopoulos, A.; Michailidis, E.T.; Nomikos, N.; Trakadas, P.; Hatziefremidis, A.; Voliotis, S.; Zahariadis, T. Tackling Faults in the Industry 4.0 Era—a Survey of Machine-Learning Solutions and Key Aspects. *Sensors* **2020**, *20*, 109.
64. Çınar, Z.M.; Abdussalam Nuhu, A.; Zeeshan, Q.; Korhan, O.; Asmael, M.; Safaei, B. Machine Learning in Predictive Maintenance towards Sustainable Smart Manufacturing in Industry 4.0. *Sustainability* **2020**, *12*, 8211.

65. Candanedo, I.S.; Nieves, E.H.; González, S.R.; Martín, M.T.S.; Briones, A.G. *Machine Learning Predictive Model for Industry 4.0*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 501–510.
66. Psarommatis, F.; May, G.; Dreyfus, P.-A.; Kiritsis, D. Zero Defect Manufacturing: State-of-the-Art Review, Shortcomings and Future Directions in Research. *Int. J. Prod. Res.* **2020**, *58*, 1–17.
67. Huang, Z.; Angadi, V.C.; Danishvar, M.; Mousavi, A.; Li, M. Zero Defect Manufacturing of Microsemiconductors—An Application of Machine Learning and Artificial Intelligence. In Proceedings of the 2018 5th International Conference on Systems and Informatics (ICSAI), Nanjing, China, 10–18 November 2018; IEEE: New York, NY, USA, 2018; pp. 449–454.
68. Lindström, J.; Kyösti, P.; Birk, W.; Lejon, E. An Initial Model for Zero Defect Manufacturing. *Appl. Sci.* **2020**, *10*, doi:10.3390/app10134570.
69. Eger, F.; Coupek, D.; Caputo, D.; Colledani, M.; Penalva, M.; Ortiz, J.A.; Freiberger, H.; Kollegger, G. Zero Defect Manufacturing Strategies for Reduction of Scrap and Inspection Effort in Multi-Stage Production Systems. *Procedia CIRP* **2018**, *67*, 368–373.
70. Psarommatis, F.; Vuichard, M.; Kiritsis, D. Improved Heuristics Algorithms for Re-Scheduling Flexible Job Shops in the Era of Zero Defect Manufacturing. *Procedia Manuf.* **2020**, *51*, 1485–1490.
71. Saqlain, M.; Piao, M.; Shim, Y.; Lee, J.Y. Framework of an IoT-Based Industrial Data Management for Smart Manufacturing. *J. Sens. Actuator Netw.* **2019**, *8*, 25.
72. Islam, M.M.; AlGeddawy, T. The Industrial Internet of Things Models, Challenges and Opportunities in Sustainable Manufacturing. In Proceedings of the 39th International Annual Conference of the American Society for Engineering Management, ASEM 2018: Bridging the Gap Between Engineering and Business, Coeur D'Alene, ID, USA, 17–20 October 2018; American Society for Engineering Management: Huntsville, AL, USA, 2018; pp. 122–131.
73. Belli, L.; Davoli, L.; Medioli, A.; Marchini, P.L.; Ferrari, G. Toward Industry 4.0 with IoT: Optimizing Business Processes in an Evolving Manufacturing Factory. *Front. ICT* **2019**, *6*, 17.
74. Wan, J.; Chen, B.; Imran, M.; Tao, F.; Li, D.; Liu, C.; Ahmad, S. Toward Dynamic Resources Management for IoT-Based Manufacturing. *IEEE Commun. Mag.* **2018**, *56*, 52–59.
75. Gerrikagoitia, J.K.; Unamuno, G.; Urkia, E.; Serna, A. Digital Manufacturing Platforms in the Industry 4.0 from Private and Public Perspectives. *Appl. Sci.* **2019**, *9*, 2934.
76. Xu, L.D.; Xu, E.L.; Li, L. Industry 4.0: State of the Art and Future Trends. *Int. J. Prod. Res.* **2018**, *56*, 2941–2962.
77. Beier, G.; Ullrich, A.; Niehoff, S.; Reißig, M.; Habich, M. Industry 4.0: How It Is Defined from a Sociotechnical Perspective and How Much Sustainability It Includes—A Literature Review. *J. Clean. Prod.* **2020**, *259*, doi:10.1016/j.jclepro.2020.120856.
78. Singh, R.; Bhanot, N. An Integrated DEMATEL-MMDE-ISM Based Approach for Analysing the Barriers of IoT Implementation in the Manufacturing Industry. *Int. J. Prod. Res.* **2020**, *58*, 2454–2476.
79. Xu, X. From Cloud Computing to Cloud Manufacturing. *Robot. Comput. Integr. Manuf.* **2012**, *28*, 75–86.
80. Caggiano, A. Cloud-Based Manufacturing Process Monitoring for Smart Diagnosis Services. *Int. J. Comput. Integr. Manuf.* **2018**, *31*, 612–623.
81. Li, B.-H.; Zhang, L.; Ren, L.; Chai, X.-D.; Tao, F.; Wang, Y.-Z.; Yin, C.; Huang, P.; Zhao, X.-P.; Zhou, Z.-D. Typical Characteristics, Technologies and Applications of Cloud Manufacturing. *Comput. Integr. Manuf. Syst.* **2012**, *18*, 1345–1356.
82. Adamson, G.; Wang, L.; Holm, M.; Moore, P. Cloud Manufacturing–a Critical Review of Recent Development and Future Trends. *Int. J. Comput. Integr. Manuf.* **2017**, *30*, 347–380.
83. Liu, Y.; Wang, L.; Wang, X.V.; Xu, X.; Zhang, L. Scheduling in Cloud Manufacturing: State-of-the-Art and Research Challenges. *Int. J. Prod. Res.* **2019**, *57*, 4854–4879.
84. Tao, F.; Zhang, L.; Venkatesh, V.; Luo, Y.; Cheng, Y. Cloud Manufacturing: A Computing and Service-Oriented Manufacturing Model. *Proc. Inst. Mech. Eng. Part. B J. Eng. Manuf.* **2011**, *225*, 1969–1976.
85. Liu, Y.; Wang, L.; Wang, X.V.; Xu, X.; Jiang, P. Cloud Manufacturing: Key Issues and Future Perspectives. *Int. J. Comput. Integr. Manuf.* **2019**, *32*, 858–874.
86. Wu, D.; Greer, M.J.; Rosen, D.W.; Schaefer, D. Cloud Manufacturing: Strategic Vision and State-of-the-Art. *J. Manuf. Syst.* **2013**, *32*, 564–579.
87. Coronado, P.D.U.; Lynn, R.; Louhichi, W.; Parto, M.; Wescoat, E.; Kurfess, T. Part Data Integration in the Shop Floor Digital Twin: Mobile and Cloud Technologies to Enable a Manufacturing Execution System. *J. Manuf. Syst.* **2018**, *48*, 25–33.
88. Varela, M.L.; Putnik, G.D.; Manupati, V.K.; Rajyalakshmi, G.; Trojanowska, J.; Machado, J. Collaborative Manufacturing Based on Cloud, and on Other I4. 0 Oriented Principles and Technologies: A Systematic Literature Review and Reflections. *Manag. Prod. Eng. Rev.* **2018**, *9*.
89. Lu, Y.; Xu, X. Cloud-Based Manufacturing Equipment and Big Data Analytics to Enable on-Demand Manufacturing Services. *Robot. Comput. Integr. Manuf.* **2019**, *57*, 92–102.
90. Mubarok, K.; Xu, X.; Ye, X.; Zhong, R.Y.; Lu, Y. Manufacturing Service Reliability Assessment in Cloud Manufacturing. *Procedia CIRP* **2018**, *72*, 940–946.
91. Fisher, O.; Watson, N.; Porcu, L.; Bacon, D.; Rigley, M.; Gomes, R.L. Cloud Manufacturing as a Sustainable Process Manufacturing Route. *J. Manuf. Syst.* **2018**, *47*, 53–68.
92. Bottani, E.; Vignali, G. Augmented Reality Technology in the Manufacturing Industry: A Review of the Last Decade. *IISE Trans.* **2019**, *51*, 284–310.
93. Damiani, L.; Revetria, R.; Morra, E. Safety in Industry 4.0: The Multi-Purpose Applications of Augmented Reality in Digital Factories. *Adv. Sci. Technol. Eng. Syst.* **2020**, *5*, 248–253, doi:10.25046/aj050232.

94. Lai, Z.-H.; Tao, W.; Leu, M.C.; Yin, Z. Smart Augmented Reality Instructional System for Mechanical Assembly towards Worker-Centered Intelligent Manufacturing. *J. Manuf. Syst.* **2020**, *55*, 69–81.
95. Nabati, E.; Nieto, M.A.; Decker, A.; Thoben, K.-D. *Application of Virtual Reality Technologies for Achieving Energy Efficient Manufacturing: Literature Analysis and Findings*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 479–486.
96. Shiba, Y.; Imai, S. *Development of Engineering Educational Support System for Manufacturing Using Augmented Reality*; IEEE: New York, NY, USA, 2020; pp. 198–202.
97. Lee, H. Real-Time Manufacturing Modeling and Simulation Framework Using Augmented Reality and Stochastic Network Analysis. *Virtual Real.* **2019**, *23*, 85–99.
98. Rumsey, A.; Le Dantec, C.A. Manufacturing Change: The Impact of Virtual Environments on Real Organizations. In Proceedings of the CHI '20: CHI Conference on Human Factors in Computing Systems, Honolulu, HI, USA, 25–30 April 2020; pp. 1–12.
99. Mittal, S.; Khan, M.A.; Romero, D.; Wuest, T. Smart Manufacturing: Characteristics, Technologies and Enabling Factors. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2019**, *233*, 1342–1361.
100. Malik, A.A.; Masood, T.; Bilberg, A. Virtual Reality in Manufacturing: Immersive and Collaborative Artificial-Reality in Design of Human-Robot Workspace. *Int. J. Comput. Integr. Manuf.* **2020**, *33*, 22–37.
101. Mandic, V. *Model-Based Manufacturing System Supported by Virtual Technologies in an Industry 4.0 Context*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 215–226.
102. Leng, J.; Ruan, G.; Jiang, P.; Xu, K.; Liu, Q.; Zhou, X.; Liu, C. Blockchain-Empowered Sustainable Manufacturing and Product Lifecycle Management in Industry 4.0: A Survey. *Renew. Sustain. Energy Rev.* **2020**, *132*, doi:10.1016/j.rser.2020.110112.
103. Li, Z.; Barenji, A.V.; Huang, G.Q. Toward a Blockchain Cloud Manufacturing System as a Peer to Peer Distributed Network Platform. *Robot. Comput. Integr. Manuf.* **2018**, *54*, 133–144.
104. Westerkamp, M.; Victor, F.; Küpper, A. Tracing Manufacturing Processes Using Blockchain-Based Token Compositions. *Digit. Commun. Netw.* **2020**, *6*, 167–176.
105. Lohmer, J.; Lasch, R. Blockchain in Operations Management and Manufacturing: Potential and Barriers. *Comput. Ind. Eng.* **2020**, *149*, 106789.
106. Ko, T.; Lee, J.; Ryu, D. Blockchain Technology and Manufacturing Industry: Real-Time Transparency and Cost Savings. *Sustainability* **2018**, *10*, 4274.
107. Yu, C.; Zhang, L.; Zhao, W.; Zhang, S. A Blockchain-Based Service Composition Architecture in Cloud Manufacturing. *Int. J. Comput. Integr. Manuf.* **2020**, *33*, 701–715.
108. Aghamohammadzadeh, E.; Fatahi Valilai, O. A Novel Cloud Manufacturing Service Composition Platform Enabled by Blockchain Technology. *Int. J. Prod. Res.* **2020**, *58*, 5280–5298.
109. Zhang, Y.; Xu, X.; Liu, A.; Lu, Q.; Xu, L.; Tao, F. Blockchain-Based Trust Mechanism for IoT-Based Smart Manufacturing System. *IEEE Trans. Comput. Soc. Syst.* **2019**, *6*, 1386–1394.
110. Yu, C.; Jiang, X.; Yu, S.; Yang, C. Blockchain-Based Shared Manufacturing in Support of Cyber Physical Systems: Concept, Framework, and Operation. *Robot. Comput. Integr. Manuf.* **2020**, *64*, 101931.
111. Tao, F.; Zhang, Y.; Cheng, Y.; Ren, J.; Wang, D.; Qi, Q.; Li, P. Digital Twin and Blockchain Enhanced Smart Manufacturing Service Collaboration and Management. *J. Manuf. Syst.* **2020**.
112. Barenji, A.V.; Li, Z.; Wang, W.M. Blockchain Cloud Manufacturing: Shop Floor and Machine Level. In Proceedings of the Smart SysTech 2018; European Conference on Smart Objects, Systems and Technologies, Dresden, Germany, 12–13 June 2018; VDE: Berlin, Germany, 2018; pp. 1–6.
113. Ouyang, L.; Yuan, Y.; Wang, F.-Y. A Blockchain-Based Framework for Collaborative Production in Distributed and Social Manufacturing. In Proceedings of the IEEE International Conference on Service Operations and Logistics, and Informatics, SOLI, Zhengzhou, China, 11–13 October 2019; IEEE: New York, NY, USA, 2019; pp. 76–81.
114. Touzout, F.A.; Benyoucef, L. Multi-Objective Sustainable Process Plan Generation in a Reconfigurable Manufacturing Environment: Exact and Adapted Evolutionary Approaches. *Int. J. Prod. Res.* **2019**, *57*, 2531–2547, doi:10.1080/00207543.2018.1522006.
115. Khezri, A.; Benderbal, H.H.; Benyoucef, L. A Sustainable Reconfigurable Manufacturing System Designing with Focus on Environmental Hazardous Wastes. In Proceedings of the IEEE International Conference on Emerging Technologies and Factory Automation, ETFA, Zaragoza, Spain, 10–13 September 2019; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2019; Vol. 2019-Septe, pp. 317–324.
116. Alcácer, V.; Cruz-Machado, V. Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems. *Eng. Sci. Technol. Int. J.* **2019**, *22*, 899–919, doi:10.1016/j.jestch.2019.01.006.
117. Vaidya, S.; Ambad, P.; Bhosle, S. Industry 4.0—A Glimpse. *Procedia Manuf.* **2018**, *20*, 233–238, doi:10.1016/j.promfg.2018.02.034.
118. Long, F.; Zeiler, P.; Bertsche, B. Modelling the Flexibility of Production Systems in Industry 4.0 for Analysing Their Productivity and Availability with High-Level Petri Nets. *IFAC Pap.* **2017**, *50*, 5680–5687.
119. Suzić, N.; Forza, C.; Trentin, A.; Anišić, Z. Implementation Guidelines for Mass Customization: Current Characteristics and Suggestions for Improvement. *Prod. Plan. Control* **2018**, *29*, 856–871.
120. Wang, Y.; Ma, H.-S.; Yang, J.-H.; Wang, K.-S. Industry 4.0: A Way from Mass Customization to Mass Personalization Production. *Adv. Manuf.* **2017**, *5*, 311–320.
121. Khalil, T.; Olivia, P.; Thierno, M.D.; Romdhane, B.K.; Noureddine, B.Y.; Jean-Yves, C. Model Based Systems Engineering Approach for the Improvement of Manufacturing System Flexibility. In Proceedings of the International Workshop on Research and Education in Mechatronics (REM), Cracow, Poland, 10 December 2020; IEEE: New York, NY, USA, 2020; pp. 1–6.

122. Florescu, A.; Barabas, S.A. Modeling and Simulation of a Flexible Manufacturing System—A Basic Component of Industry 4.0. *Appl. Sci.* **2020**, *10*, 8300.
123. Luscinski, S.; Ivanov, V. A Simulation Study of Industry 4.0 Factories Based on the Ontology on Flexibility with Using FlexSimr Software. *Manag. Prod. Eng. Rev.* **2020**.
124. Sang, G.M.; Xu, L.; de Vrieze, P.; Bai, Y. *Towards Predictive Maintenance for Flexible Manufacturing Using FIWARE*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 17–28.
125. Goel, R.; Gupta, P. Robotics and industry 4.0. In *A Roadmap to Industry 4.0: Smart Production, Sharp Business and Sustainable Development*; Nayyar, A., Kumar, A., Eds.; Springer: Berlin/Heidelberg, Germany, 2020; pp. 157–169.
126. Krueger, V.; Rovida, F.; Grossmann, B.; Petrick, R.; Crosby, M.; Charzoule, A.; Martin Garcia, G.; Behnke, S.; Toscano, C.; Veiga, G. Testing the Vertical and Cyber-Physical Integration of Cognitive Robots in Manufacturing. *Robot. Comput. Integr. Manuf.* **2019**, *57*, 213–229, doi:10.1016/j.rcim.2018.11.011.
127. Dhanabalan, T.; Sathish, A. Transforming Indian Industries through Artificial Intelligence and Robotics in Industry 4.0. *Int. J. Mech. Eng. Technol.* **2018**, *9*, 835–845.
128. Bragança, S.; Costa, E.; Castellucci, I.; Arezes, P.M. A Brief Overview of the Use of Collaborative Robots in Industry 4.0: Human Role and Safety; In *Occupational and Environmental Safety and Health*; Arezes, P.M., Baptista, J.S., Barroso, M.P., Carneiro, P., Cordeiro, P., Costa, N., Melo, R.B., Miguel, A.S., Perestrelo, G., Eds.; Springer: Berlin/Heidelberg, Germany, 2019; pp. 641–650.
129. Karabegović, I.; Karabegović, E.; Mahmić, M.; Husak, E. *Implementation of Industry 4.0 and Industrial Robots in the Manufacturing Processes*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 3–14.
130. Fragapane, G.; Ivanov, D.; Peron, M.; Sgarbossa, F.; Strandhagen, J.O. Increasing Flexibility and Productivity in Industry 4.0 Production Networks with Autonomous Mobile Robots and Smart Intralogistics. *Ann. Oper. Res.* **2020**, 1–19, doi:10.1007/s10479-020-03526-7.
131. Karabegović, I. The Role of Industrial and Service Robots in the 4th Industrial Revolution—“Industry 4.0”. *Acta Tech. Corviniensis Bull. Eng.* **2018**, *11*, 11–16.
132. Wan, J.; Tang, S.; Hua, Q.; Li, D.; Liu, C.; Lloret, J. Context-Aware Cloud Robotics for Material Handling in Cognitive Industrial Internet of Things. *IEEE Internet Things J.* **2017**, *5*, 2272–2281.
133. Culot, G.; Fattori, F.; Podrecca, M.; Sartor, M. Addressing Industry 4.0 Cybersecurity Challenges. *IEEE Eng. Manag. Rev.* **2019**, *47*, 79–86.
134. Ervural, B.C.; Ervural, B. Overview of cyber security in the industry 4.0 era. In *Industry 4.0: Managing the Digital Transformation*; Ustundag, A., Cevikcan, E., Eds.; Springer: Berlin/Heidelberg, Germany, 2018; pp. 267–284.
135. Rubio, J.E.; Roman, R.; Lopez, J. A*nalysis of Cybersecurity Threats in Industry 4.0: The Case of Intrusion Detection*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 119–130.
136. Elmamy, S.B.; Mrabet, H.; Gharbi, H.; Jemai, A.; Trentesaux, D. A Survey on the Usage of Blockchain Technology for Cyber-Threats in the Context of Industry 4.0. *Sustainability* **2020**, *12*, 1–19, doi:10.3390/su12219179.
137. Lezzi, M.; Lazoi, M.; Corallo, A. Cybersecurity for Industry 4.0 in the Current Literature: A Reference Framework. *Comput. Ind.* **2018**, *103*, 97–110.
138. Ghobakhloo, M. The Future of Manufacturing Industry: A Strategic Roadmap toward Industry 4.0. *J. Manuf. Technol. Manag.* **2018**.
139. Wegner, A.; Graham, J.; Ribble, E. A new approach to cyberphysical security in industry 4.0. In *Cybersecurity for Industry 4.0*; Thames, L., Schaefer, D., Eds.; Springer: Berlin/Heidelberg, Germany, 2017; pp. 59–72.
140. Jamwal, A.; Agrawal, R.; Sharma, M.; Kumar, V. Review on Multi-Criteria Decision Analysis in Sustainable Manufacturing Decision Making. *Int. J. Sustain. Eng.* **2021**, doi:10.1080/19397038.2020.1866708.
141. Vinuesa, R.; Azizpour, H.; Leite, I.; Balaam, M.; Dignum, V.; Domisch, S.; Felländer, A.; Langhans, S.D.; Tegmark, M.; Nerini, F.F. The Role of Artificial Intelligence in Achieving the Sustainable Development Goals. *Nat. Commun.* **2020**, *11*, 1–10.
142. Ghobakhloo, M. Industry 4.0, Digitization, and Opportunities for Sustainability. *J. Clean. Prod.* **2020**, *252*, doi:10.1016/j.jclepro.2019.119869.
143. Braccini, A.M.; Margherita, E.G. Exploring Organizational Sustainability of Industry 4.0 under the Triple Bottom Line: The Case of a Manufacturing Company. *Sustainability* **2018**, *11*, doi:10.3390/su11010036.
144. Brozzi, R.; Forti, D.; Rauch, E.; Matt, D.T. The Advantages of Industry 4.0 Applications for Sustainability: Results from a Sample of Manufacturing Companies. *Sustainability* **2020**, *12*, doi:10.3390/su12093647.
145. Müller, J.M.; Voigt, K.-I. Sustainable Industrial Value Creation in SMEs: A Comparison between Industry 4.0 and Made in China 2025. *Int. J. Precis. Eng. Manuf. Green Technol.* **2018**, *5*, 659–670, doi:10.1007/s40684-018-0056-z.
146. Luthra, S.; Kumar, A.; Zavadskas, E.K.; Mangla, S.K.; Garza-Reyes, J.A. Industry 4.0 as an Enabler of Sustainability Diffusion in Supply Chain: An Analysis of Influential Strength of Drivers in an Emerging Economy. *Int. J. Prod. Res.* **2020**, *58*, 1505–1521, doi:10.1080/00207543.2019.1660828.
147. Vrchota, J.; Pech, M.; Rolínek, L.; Bednář, J. Sustainability Outcomes of Green Processes in Relation to Industry 4.0 in Manufacturing: Systematic Review. *Sustainability* **2020**, *12*, 5968, doi:10.3390/su12155968.
148. Tayal, A.; Solanki, A.; Singh, S.P. Integrated Frame Work for Identifying Sustainable Manufacturing Layouts Based on Big Data, Machine Learning, Meta-Heuristic and Data Envelopment Analysis. *Sustain. Cities Soc.* **2020**, *62*, doi:10.1016/j.scs.2020.102383.

149. Waibel, M.W.; Oosthuizen, G.A.; Du Toit, D.W. Investigating Current Smart Production Innovations in the Machine Building Industry on Sustainability Aspects. In *Procedia Manufacturing, Proceedings of the 15th Global Conference on Sustainable Manufacturing, Haifa, Israel, 25–27 September 2018*; Shpitalni, M., Kagermann, H., Seliger, G., Wertheim, R., Fischer, A., Eds.; Elsevier B.V.: Amsterdam, The Netherlands, 2018; Volume 21, pp. 774–781.
150. Ghobakhloo, M.; Fathi, M. Corporate Survival in Industry 4.0 Era: The Enabling Role of Lean-Digitized Manufacturing. *J. Manuf. Technol. Manag.* **2020**, *31*, 1–30, doi:10.1108/JMTM-11-2018-0417.
151. Bhanot, N.; Rao, P.V.; Deshmukh, S.G. Enablers and Barriers of Sustainable Manufacturing: Results from a Survey of Researchers and Industry Professionals. In *Procedia CIRP, Proceedings of the 22nd CIRP Conference on Life Cycle Engineering, Sydney, Australia, 7–9 April 2015*; Kara, S., Ed.; Elsevier B.V.: Amsterdam, The Netherlands, 2015; Volume 29, pp. 562–567.
152. Manupati, V.K.; Schoenherr, T.; Ramkumar, M.; Wagner, S.M.; Pabba, S.K.; Inder Raj Singh, R. A Blockchain-Based Approach for a Multi-Echelon Sustainable Supply Chain. *Int. J. Prod. Res.* **2020**, *58*, 2222–2241.
153. Afshari, H.; Searcy, C.; Jaber, M.Y. The Role of Eco-Innovation Drivers in Promoting Additive Manufacturing in Supply Chains. *Int. J. Prod. Econ.* **2020**, *223*, doi:10.1016/j.ijpe.2019.107538.
154. Bag, S.; Telukdarie, A.; Pretorius, J.H.C.; Gupta, S. Industry 4.0 and Supply Chain Sustainability: Framework and Future Research Directions. *Benchmarking* **2018**, doi:10.1108/BIJ-03-2018-0056.
155. Belaud, J.-P.; Prioux, N.; Vialle, C.; Sablayrolles, C. Big Data for Agri-Food 4.0: Application to Sustainability Management for by-Products Supply Chain. *Comput. Ind.* **2019**, *111*, 41–50, doi:10.1016/j.compind.2019.06.006.
156. Laney, D. 3D Data Management: Controlling Data Volume, Velocity and Variety. *META Group Res. Note* **2001**, *6*, 1.
157. Ren, S.; Zhang, Y.; Liu, Y.; Sakao, T.; Huisingh, D.; Almeida, C.M.V.B. A Comprehensive Review of Big Data Analytics throughout Product Lifecycle to Support Sustainable Smart Manufacturing: A Framework, Challenges and Future Research Directions. *J. Clean. Prod.* **2019**, *210*, 1343–1365, doi:10.1016/j.jclepro.2018.11.025.
158. Kumar, A.; Shankar, R.; Thakur, L.S. A Big Data Driven Sustainable Manufacturing Framework for Condition-Based Maintenance Prediction. *J. Comput. Sci.* **2018**, *27*, 428–439, doi:10.1016/j.jocs.2017.06.006.
159. Collins, K. Cyber-Physical Production Networks, Real-Time Big Data Analytics, and Cognitive Automation in Sustainable Smart Manufacturing. *J. Self-Gov. Manag. Econ.* **2020**, *8*, 21–27, doi:10.22381/JSME8220203.
160. Dubey, R.; Gunasekaran, A.; Childe, S.J.; Wamba, S.F.; Papadopoulos, T. The Impact of Big Data on World-Class Sustainable Manufacturing. *Int. J. Adv. Manuf. Technol.* **2016**, *84*, 631–645, doi:10.1007/s00170-015-7674-1.
161. Hack-Polay, D.; Rahman, M.; Billah, M.M.; Al-Sabbahy, H.Z. Big Data Analytics and Sustainable Textile Manufacturing: Decision-Making about the Applications of Biotechnologies in Developing Countries. *Manag. Decis.* **2020**, doi:10.1108/MD-09-2019-1323.
162. Plumpton, D. Cyber-Physical Systems, Internet of Things, and Big Data in Industry 4.0: Digital Manufacturing Technologies, Business Process Optimization, and Sustainable Organizational Performance. *Econ. Manag. Financ. Mark.* **2019**, *14*, 23–29, doi:10.22381/EMFM14320193.
163. Ali, S.S.; Kaur, R.; Persis, D.J.; Saha, R.; Pattusamy, M.; Sreedharan, V.R. Developing a Hybrid Evaluation Approach for the Low Carbon Performance on Sustainable Manufacturing Environment. *Ann. Oper. Res.* **2020**, doi:10.1007/s10479-020-03877-1.
164. Hayhoe, T.; Podhorska, I.; Siekelova, A.; Stehel, V. Sustainable Manufacturing in Industry 4.0: Cross-Sector Networks of Multiple Supply Chains, Cyber-Physical Production Systems, and Ai-Driven Decision-Making. *J. Self-Gov. Manag. Econ.* **2019**, *7*, 31–36, doi:10.22381/JSME7220195.
165. Jung, H.; Jeon, J.; Choi, D.; Park, J.-Y. Application of Machine Learning Techniques in Injection Molding Quality Prediction: Implications on Sustainable Manufacturing Industry. *Sustainability* **2021**, *13*, 4120.
166. Schorr, S.; Möller, M.; Heib, J.; Fang, S.; Bähre, D. Quality Prediction of Reamed Bores Based on Process Data and Machine Learning Algorithm: A Contribution to a More Sustainable Manufacturing. In *Procedia Manufacturing, Proceedings of the 17th Global Conference on Sustainable Manufacturing, Shanghai, China, 9–11 October 2020*; Seliger, G., Kagermann, H., Ganiyusufoglu, O.S., Zhang, W., Eds.; Elsevier B.V.: Amsterdam, The Netherlands, 2020; Volume 43, pp. 519–526.