A Review on Industry 4.0 Technologies for Sustainability: State of the Art and Future Trends

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Abstract: In recent years, Industry 4.0 (I4.0) has emerged as a most significant concept in global manufacturing. Current manufacturing landscape is transforming towards smart and intelligent manufacturing to produce customized products with greater flexibility and productivity. Industry 4.0 serves as a pivotal enabler for sustainable development by seamlessly integrating cutting-edge technologies with industrial processes. Its data-driven approach enhances resource efficiency, reducing waste and energy consumption while optimizing production. Empirical research in the field of I4.0 or Smart Manufacturing (SM) is dominating continuously with great emphasis on conceptual models and case studies. Literature reviews of I4.0 or SM are less portrayed as compared to other manufacturing theories. In the present study, a categorized review of the published literature on I4.0 and SM is lucubrated and precisely visualized. The study covers analysis of total 121 articles considering distinct parameters such as concept or definition, key terms, publishers, year of publication, countries, research methods, journals, author's profile, active authors, enablers, barriers and sustainability. The review analysis focuses on descriptive statistics of shortlisted articles from peer-reviewed journals published over a time span of 12 years (2011-2022) and highlights the present status of research carried out in I4.0. The review analysis is followed by gap identification and future research opportunities in I4.0 domain. The results presented in this study can empower the manufacturers to develop a strategic roadmap for proper adopting of this emerging phase of manufacturing.

Keywords: Industry 4.0, Smart manufacturing, Intelligent manufacturing, Flexibility, Productivity, Sustainability

1. Introduction

The current industries are transforming from analog and centralized concepts to digital and decentralized one. Industries are changing the present scenario of mass production to customized production. The fourth industrial revolution has emerged as new approach which focuses on real-time control and monitoring of production processes. More recently, manufacturing companies are continuously shifting towards technological paradigm shift to ensure economic growth, productivity improvement with sustainable manufacturing. Therefore, Governments in various countries have started smart initiatives namely 'Smart Manufacturing (SM)' in USA, 'Industry 4.0 (I4.0)' in Germany and *'Made in China 2025'* in China [1]. Indian government has also started *'Make in India'* and *'Digital India'* mission and provide resources for the industries to shift towards fourth generation of manufacturing. This building block of advanced technologies enables the production of personalized and customized products [2]. I4.0 is digitization and intelligentization of various processes of entire life cycle of the product. Many disruptive technologies i.e. Cloud Computing (CC), Internet of Things (IoT), Big Data (BD), and Artificial Intelligence (AI) have permeated the manufacturing industries. These technologies enable the blend of physical and virtual worlds through cyber-physical systems (CPS) that streaks the introduction of the fourth stage of industrial production (i.e., Industry 4.0). I4.0 increases flexibility, mass customization which results in increased speed and improved quality. This facilitates enhanced productivity in manufacturing and assists companies to cope with various challenges like

personalized products, shortened lead time to market, and high product quality [3]. Smart manufacturing is autonomy, evolution, simulation and optimization of the manufacturing enterprise depending on the availability of data and tools. Big data, IoT, cloud computing and AI offers opportunity to transform traditional way of manufacturing to smart manufacturing [4].

Rapid advancements in industries, technologies and applications, have emerged with new concept of Industry 4.0 in manufacturing [6]. Lu (2017) proposed framework to solve critical issues related to interoperability for Industry 4.0 design principles and elaborated that I4.0 was initiated in Germany and combines Cyber-Physical Systems, Internet of Things, Enterprise Architecture (EA), Integration of Enterprises (IoE), Information and Communication Technology (ICT). Industry 4.0 adoption requires high investment and support from top management due to dependent technologies [7].

The German government has considered "Industry 4.0" as a high-tech technology for upcoming years and this term has become a hotspot for global industries. Industry 4.0 concepts will provide great opportunities. Industry 4.0 and lean manufacturing (LM) support each other and both aims to increase productivity and flexibility. The integration of both the domains affects different dimensions of production system [8]. Small and Medium Scale Enterprises (SMEs) need to map themselves with emerging technologies of I4.0 while practicing existing lean manufacturing philosophies to be competitive in the global market . Manufacturing industries are converging different ICT technologies along with existing manufacturing technologies in order to make real time decisions.

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

In this review process, first of all it was decided to analyze 17 review articles based on I4.0 or SM (as shown in Table 1) out of total 121 articles which are screened in the study. The objective of doing this was to elucidate the overview of the review method to be adopted in the presented work. The review articles were analyzed based on 'type of review method applied in reviewing' and 'dimensions covered or focused points in the review' to extract the major dimensions to be covered in the present review. After analysis, it was found that most of the articles have covered very limited review parameters on the selected topics. It is also clear from Table 1 that I4.0 or SM technologies, challenges and opportunities are elaborated by most of the authors critically reviewed existing maturity models of I4.0 and SM [9-10].

Table 1: Analysis of 17 existing review articles

S. No.	Author	Type of review method	Dimensions covered / focused points
1	Sharma, Jabbour, and de Sousa Jabbour (2020)	Bibliometric and intellectual network analysis	Outlined Industry 4.0 technologies and sustainability aspects
2	Ejsmont, Gladysz, and Kluczek (2020)	Systematic literature review and bibliometric network analysis	Impacts of I4.0 on sustainability
3	Sartal et al. (2020)	Descriptive work	Interpretations about concepts, evolution and opportunities of sustainable manufacturing in Industry 4.0
4	Alcacer and Cruz-Machado (2019)	Architectural review	Review of enabling technologies of Industry 4.0
5	Bonilla et al. (2018)	Concise description	Sustainability implications (impacts and challenges) of I 4.0-deployment, operation and technologies, integration and compliance
6	Gupta, Modgil, and Gunasekaran. 2019	Systematic literature review and investigation framework	Big data techniques for LSS phases
7	Kusiak (2019)	Comprehensive assessment and multi-thread perspective	Characteristics of smart and sustainable manufacturing
8	Sony and Naik (2018)	Systematic literature review	Explored the key ingredients for assessing the readiness of organizations for Industry 4.0.
9	Ghobakhloo (2018)	State-of-the-art review	I4.0 design principles and technologies trends
10	Mittal, Ahmad et al. (2018)	Critical review	Review of existing I4.0 and smart manufacturing maturity models for SMEs
11	Ahuett-Garza and Kurfess (2018)	Descriptive review	Review of habilitating technologies of I4.0 and smart manufacturing
12	Kusiak (2017)	Exploratory study	Six pillars and ten conjectures characterizing smart

			manufacturing
13	Strange and Zucchella (2017)	Descriptive review	Provide assessment of adoption of I4.0
14	Yue et al. (2015)	Architectural review	Development and character of Cyber-Physical Systems

After analysis of the review articles (Table 1) included in this qualitative synthesis, it is concluded that though the authors have covered various dimensions such as technologies, design principles, sustainable manufacturing in perspective of I4.0 or SM. But, very few or limited studies have critically reviewed the existing articles in I4.0 or SM, and none of the existing reviews categorized the published articles over multiple parameters. Hence, there is need to synthesize the past work in the research domain which elucidate the current trends and vistas of I4.0 or SM. Therefore, the present study aims to evaluate and build a conceptual platform within the research domain through categorized review and analysis of articles over different dimensions. The articles on the selected themes came into existence in 2011 when Germany coined the I4.0. Hence, this review study comprised the articles published between 2011 and 2020.

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

2. Research background

In this section, evolution, concept and definitions of I4.0 or SM are discussed. The evolution of the manufacturing paradigms has gone through three industrial revolutions in the past. It was late 18th century when the first industrial revolution was coined with the development of water and steam power [11]. Second industrial revolution was started in the beginning of 19th century when mass production was becoming popular through assembly line concept, electrical power and division of labour. Later in early 1970s, the third industrial revolution came in loop with the advent of IT automated production using PLCs. In the beginning of 21st century, the manufacturing paradigm is becoming more digital and intelligent with the emergence of fourth industrial revolution, also termed as I4.0 or SM. The term Industry 4.0 was coined in 2011 at the Hannover Fair in Germany [12]. The current factories are striving to become smart to cope up with the challenges of dynamic demands of customers. Global manufacturing scenario is transforming towards Industry 4.0 with the advent of disrupting technologies such as IoT, cloud computing, big data and AI. It is basically adding IoT and CPS concepts into manufacturing companies. In this transformation, physical objects i.e. machines, work, vehicles etc. are connected with cyber technologies such as RFIDs, microprocessors, sensors, actuators and other embedded systems. Manufacturing organizations in Germany are promoting inclusion of computerization in their processing, monitoring, supply chain, production planning, scheduling etc.

2.1 Definitions and concepts of I4.0 or SM

There appears little unanimity in defining the I4.0 or SM. The authors in their research have defined the term in different forms as shown in Table 2. Industry 4.0 improves responsiveness and efficiency of a production system by combining advanced technologies and achieves process intelligence through smart factories [13]. Industry 4.0 creates smartness in existing production systems by integrating digital and physical worlds using CPS and IoT [14]. Saniuk and Grabowska (2020) explored that I4.0 refers to CPS and set new horizon in production and management with sustainable manufacturing. The fourth industrial revolution is the collection of connected and embedded systems that erase the barriers between real and virtual world through CPS and IoT [15]. I4.0 has been considered as key enabler of digital transformation of the entire value chain [16].

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

3. Research methodology

The literature review is an investigation method, that is usually applied to extract the valuable insights from the existing literature on the selected topic and establishes strong foundation to know future research

directions as well as current research trends in emerging fields [17]. This categorized review follows transparent steps as shown in Figure 1, to capture the snapshot about the research being done in the area of I4.0 or SM. For this study, the articles reported in reputed journals and recognized conferences, containing the word "*Industry 4.0*" and "*Smart Manufacturing*" in the title or in keywords, are included in this review (as per the methodology inputs, shown in Table 3).

Table 2: Summary of methodology

s	**Research articles**
Literature review methodology	Categorized review of existing literature
Period covered	2011-2020
Databases used and publishers	Scopus, Google Scholar, ScienceDirect (Elsevier) , Emeraldinsight, Taylor & Francis, Springer, MDPI and SAGE
Keywords and phrases used to search articles from databases	Industry 4.0, Smart Manufacturing, Internet of Things, Cyber-Physical Systems, digital twin, barriers in Industry 4.0 implementation, enablers or critical success factors of Industry 4.0, Intelligent Manufacturing, Sustainability in Industry 4.0, Lean and Industry 4.0, Lean Six Sigma and Industry 4.0, Additive Manufacturing, Smart Factory, cloud manufacturing, Industrial Internet of Things
Total number of articles considered	121

This review analysis comprises peer-reviewed journal articles from ScienceDirect, Emerald insights, Taylor & Francis, Springer, MDPI and SAGE. Preliminary search was carried out from Scopus and Google Scholar data bases. Total 207 articles were considered at this stage. In the second stage, the articles having 'Industry 4.0' or 'Smart Manufacturing' in title or in keywords were included for the review. Total 169 articles were screened at this stage of the methodology. At the third level of screening, 48 articles out of 169 were found not related to the selected themes. Conference papers, vague and non-english, short survey, editorial notes, news reports, viewpoints, unpublished articles and textbooks were not included in this review paper. Therefore, based on the exclusion criteria mentioned in Figure 1, finally 121 articles were selected for in-depth analysis based on multiple parameters. But, before that, the authors decided to analysis 14 review based research papers of SM/I4.0 (shown in Table 1 and as discussed in section 1.1) to identify the gaps and extract key dimensions to be covered in this analysis.

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

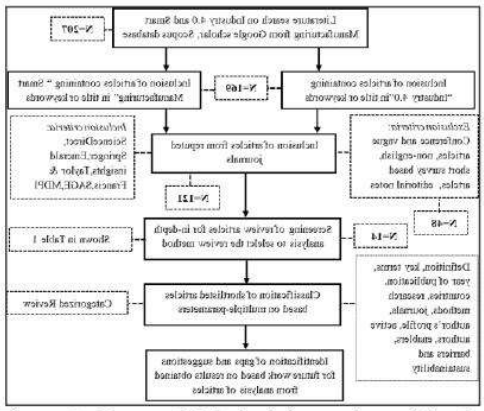

Figure 1: Research Methodology adopted for the study

Each article shortlisted in this study is deeply reviewed and best efforts were applied to extract conclusive information that can be helpful to understand the smart manufacturing and Industry 4.0. Although the study presented in this review is not exhaustive but, this will be a beneficial tool for practitioners working in this domain.

4. Analysis of classifications

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

4.1 Categorization of articles based on publishers/journals

Comprehensive representation of all contributing

publishers in terms of number of articles and percentage is shown in Figure 2. Among the prominent publishers, ScienceDirect has contributed major role in publication articles on I4.0 or SM followed by Taylor & Francis, Emeraldinsight, Springer, MDPI and SAGE. It is observed from analysis that ScienceDirect, Taylor & Francis, Emeraldinsights and Springer are the key publishers.

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

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

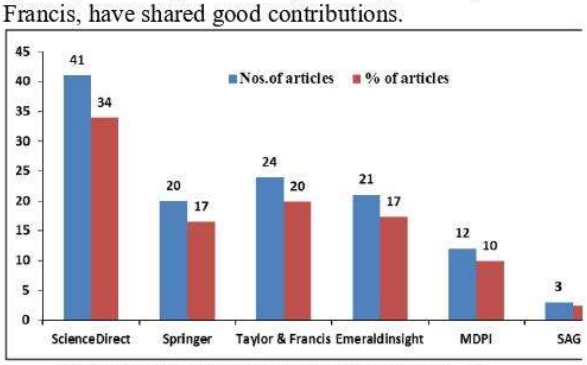

Figure 2: Classification of articles based on publishers

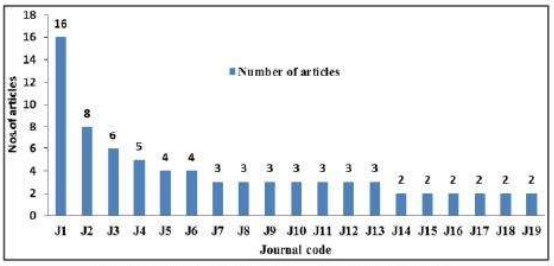

Figure 3: Articles based on journals

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

4.2 Categorization of articles based on year of publication

Figure 4 shows the categorization of the articles based on the year of publication. This review analysis covers the articles published over the span of last 10 years from 2011 to 2020. There appears very limited research between 2011 and 2013, as the research on I4.0 during this span of time was in initial phase when Germany coined this word.

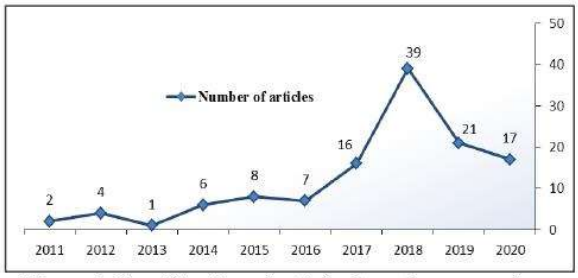

Figure 4 Classification of articles based on year of publication

As per the analysis, it is found that after 2016, the research trend is blooming continuously and very large number of articles are published on the integrating manufacturing aspects i.e. lean manufacturing and I4.0, sustainable manufacturing and SM. It has been also observed that limited articles are on *integration of I4.0 and Lean Six Sigma*. Tremendous growth was observed in year 2018, as technological development was at its highest level in the field of I4.0. Therefore, year 2018 have significant share in publication based on I4.0 and SM disciplines.

4.3 Categorization of articles based on countries

The findings from research on I4.0 or SM across literature have covered 31 countries around the world.

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

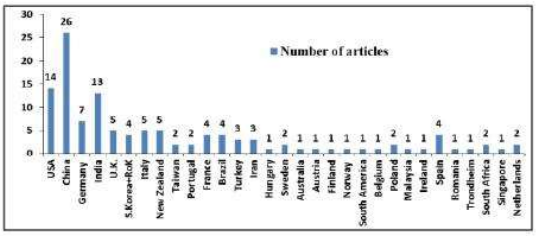

Figure 5: Classification of articles based on countries

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

4.4 Categorization of articles based on research methods

Each article is deeply studied to identify the research method used by the authors. Figure 6 shows distribution of articles based on research method such as literature review, conceptual model, case study, survey, mathematical model, interviews, descriptive study and others.

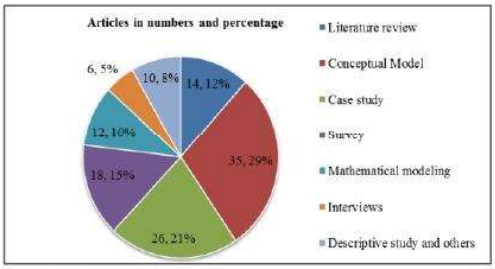

Figure 6: Articles based on research method adopted (Numbers and Percentage)

The major articles have focused on conceptual model (29 percentage) and case studies (21 percent). The authors have proposed *conceptual models for I4.0 barriers* (Singh and Bhanot 2019; Aggarwal, Gupta and Ojha 2019; Zheng et al. 2018; Sevinc, Gur, and Eren 2018) and *enablers* (Rajput and Singh 2018; Devi, Paranitharan, and Agniveesh 2020) for better understanding about them. Conceptual model development is the most common method adopted by the authors in their research work and it counts highest numbers in the study.

It is clear from above discussion that conceptual model and case study methods have been adopted by the most of the authors followed by literature review, survey and mathematical models.

5. **Conclusions**

The objective of this categorized review is to scrutinize the status of research trends in I4.0 or SM in terms of various parameters such as definition, synonyms, research methods, journals, author's profile etc. In continuation, classification framework is also designed for categorization of the articles based on enablers, barriers and sustainability aspects of I4.0 or SM. A span of online database (2011-2020) was searched to obtain the critical listing of articles for getting better insights about the discipline. The articles were shortlisted after following the certain inclusion criterions using specific keywords and phrases listed in Table 3. Finally, total 121 articles were thoroughly reviewed and information gathered on different classification variables. Based on different dimensions, the articles were classified for better analysis and depiction of what the existing research has covered about I4.0 or SM. Research aimed to interpret the information on current trends, issues and future directions of the discipline. All the shortlisted articles were distributed in categories based on various parameters. Across the globe, this manufacturing paradigm is drawing the attention of academicians/practitioners/researchers. China, USA, India and Germany are leading in the publications on fourth industrial revolution which was reported in the literature during the study. The major outcomes depict that the conceptual models have highest credibility and the drift is stirring in the direction of case studies, survey and mathematical modeling. It is evident from the study that despite of plenty amount of research have published on I4.0 or SM among the different publishers; still there exist ample opportunities for future research work on the topic to disclose various hidden aspects.

5.1 Future research scope and limitation of the research

The study has covered I4.0 spread in the articles using categorized review of the existing literature during

period of last 10 years (2011-2020). The classification based on different parameters in this review analysis opens positive research directions in the area of fourth industrial revolution. The study has focused on the efficacy of I4.0 or SM and has documented various attributes such as definitions proposed by different researchers, contribution in publication across the countries, research methods adopted by the authors. Despite of these, the authors have illustrated the research work interlinking I4.0 with Lean principles, Lean Six Sigma and sustainable manufacturing. Barriers and enablers are also demonstrated to plan the better implementation strategies by the practitioners. The researchers and practitioners can refer this review analysis for getting more insights in this new area of the research. The researchers and practitioners need deeper understanding of the challenges that can hinder the diffusion of I4.0 in current manufacturing organizations. The research presented could be used to develop a strong foundation of I4.0 practices while transforming the current manufacturing facilities towards smart and intelligent one. This may act as reference framework for the researchers as well as practitioners. However, this review paper has compiled various dimensions of I4.0 reflecting the spread of definitions, current research trends in the domain but in future, research can be carried out on studying design principles, technologies and practical applications of this emerging approach of manufacturing. The future research can also be focused on explaining the barriers and enablers of I4.0 in more descriptive way with the development of more conceptualized framework. It is expected that the divergent view of ongoing research presented in this paper would definitely help practitioners to develop plan for implementing I4.0 concepts. The study builds up the knowledge base for practitioners and academicians to get better understanding about the research trends in I4.0 domain.

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