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Evolution and Emerging Trends of Sustainability in Manufacturing Based on Literature Visualization Analysis

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ABSTRACT Sustainability is necessary for improving the quality of the manufacturing industry, which is an important pillar of the economy. The existing studies can hardly realize a comprehensive reflection of the research status of sustainability in manufacturing. Thus, this study adopts science mapping as the main research method for the systematic and accurate mastery of the overall research status, development track, research hotspots, and trends within this field. Moreover, this work provides a systematic review of related studies. This study examines 6,591 articles (1999–2019), including in core journals on Web of Science as research samples, and deeply explores core journal, core author, core country, discipline distribution, keyword co-occurrence, and literature co-citation via CiteSpace software. According to results, authoritative journals regarding sustainability in manufacturing place particular emphasis on theory, method, or application in different degrees. The number of published articles in the U.S.A. tops the ranking, and the influence of Chinese research institutes and scholars is continuously enhanced, where the main research fields are engineering, environmental science, and so on. Sustainable innovativeness in the manufacturing industry is generally at a high level. Moreover, research hotspots have evolved from traditional to modern and undergone three phases: theory construction—industry or enterprise technology construction—the emergence of new problems and application of new technologies. This study further analyzes the four clusters with citation bursts, namely, additive manufacturing, power consumption, green supply chain, and green information system in terms of grasping the knowledge structures and probing the classical research results. Future research should emphasize 3D printing design and application in the information era, the business model integrating the manufacturing industry and service industry, optimization of production modeling, and so on. This study aims to provide a systematic, comprehensive, dynamic, and objective review of the literature on sustainability in manufacturing to deepen and perfect the research in this field.

INDEX TERMS Manufacturing industry, sustainability, bibliometrics, science mapping, evolution, emerging trends.

I. INTRODUCTION

The manufacturing industry is known as the driving force for the growth, structural change, and acceleration of the economy, which exerts far-reaching and extensive influence on the national economy [1]. Especially after the 2008 Global Financial Crisis, the importance of the real economy has been re-recognized, and the development trend and competitive pattern of the manufacturing industry are faced with significant changes. Many countries with renewed interest in the manufacturing industry have proposed high expectations for industry inclusiveness and sustainable growth. The concept of sustainability is derived from Brundtland's report in 1987 at the earliest, which refers to the path to improve our current and descendants' living quality and well-being [2]. The presentation of the concept of sustainable manufacturing is the product fusing sustainable development theory and the paradigm transformation of the manufacturing industry. No international consensus has been reached over the definition of sustainable manufacturing. In a narrow sense, sustainable manufacturing is a production model, which mitigates negative environmental impacts while transforming materials into products through new technologies and skills [3]. According to the U.S. Department of Commerce, sustainable

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manufacturing means creating manufactured materials using materials and processing flows with minimum negative environmental impact and by economically reasonable means; such means should conserve energy and natural resources and be safe for staff, society, and consumers [4]. Broadly, sustainable manufacturing serves as a comprehensive strategy, which can systematically relieve the environmental impacts of the manufacturing industry and provide performance assessment [5]. Sustainability is suitable for implementing an organization scheme of new methods, measures, and technologies in the manufacturing field to cope with worldwide resource shortage, relieve environmental pressure and make an environmentally friendly product life cycle possible [6]. As the concept of sustainability is introduced in the manufacturing industry, related scholars have considerably discussed and formed different research branches.

Sustainability research is an interdisciplinary field that enjoys rapid development, including engineering, environmental sustainability, the science of mathematics, materials science, social sciences, chemistry, public policy, economic management, and so on. First, focusing on conceptual theories, many scholars have established an extensive research framework for sustainability in manufacturing and the exertion of influence, e.g., demarcation of 51 sustainability terminologies in the field of environmental engineering [7], the practice of sustainable manufacturing industry, and strategic framework and development [8]. Second, many scholars concentrate on the summarization and analysis of sustainability in manufacturing. Moon analyzed 192 conference papers from 2000–2015 and sought for the most common simulation method in the field of sustainable manufacturing [9]. Chan *et al.* classified 100 pieces of literature regarding the systematic management of sustainability according to three major elements: production planning and control, inventory management, and production network design of the manufacturing system [10]. In addition, many scholars have regarded related industries or enterprises as the research objects of sustainability. Gerner and Benlemlih pointed out that sustainable enterprise development can promote the innovation ability of business model evolution [11] and help to exploit financing channels [12]. Karlsson compared and verified the setting of internal and external stakeholders of an enterprise in commercial sustainable practice [13]. Sanchez-Bueno revealed a negative correlation between R&D activity and the downsizing of middle- and small-sized enterprises in the manufacturing industry [14]. Tran found that state corporations in Southeast Asia paid high attention to information disclosure in sustainable development [15]. Some scholars have improved and innovated research methods for sustainability in manufacturing. Ojstersek proposed amulticriterion optimization method to evaluate the influence of manufacturing flexibility on sustainable rationality [16]. Martinez-Sentana innovatively proposed supply adjustment and guarantee in the field of energy sustainability research and quantitatively compared different countries with the energy sustainability index [17]. Furthermore, some scholars have analyzed the research hotspots and development trends of sustainability in manufacturing. Henao combed the development direction and challenges in the lean manufacturing industry and sustainable performance according to the five-step synthesis method, contributing to the recognition of the main research trends at present [18].

Through the nearly 20-year development in the sustainability field of the manufacturing industry, rich knowledge reserves and theoretical contributions have been formed, which are worthy of careful summarization and extraction. However, most of the existing literature reviews on the manufacturing industry remain at the interdisciplinary microscope of knowledge, industry level, or enterprise-level and focus on optimization and practice of research methods or evolution of the development trends of the sustainability field of the manufacturing industry. Although these studies are essential for scholars to understand the current status of the sustainability field of the manufacturing industry, the research scope and number in the current literature review are quite limited. Thus, comprehensively and objectively reflecting the overall situation of manufacturing sustainability studies is difficult. Most of the existing literature centers on qualitative literature review and simple word frequency statistics. Moreover, these studies generally adopt artificial consultation and organization. In the subjective summarization and generalization of research status and development trend, researchers can be easily influenced by subjective thought and knowledge blind zone. Therefore, understanding and mastering the history, current status, and trend of sustainability in manufacturing research are significant in further understanding the development path of sustainability in manufacturing research and discovering new research problems to provide a reference for topic selection, academic innovation, and development trend in the field.

II. RESEARCH DESIGN

A. RESEARCH METHOD AND TOOL

Science mapping is a kind of image-displaying development course and structural relation of scientific knowledge by taking knowledge graphs as the object [19]. Based on existing theory and previous practice, this method is commonly used to interpret the discipline development trend [19], research progress, hotspot front [20], disciplinary knowledge structure [21], and dynamic evolutionary relationship [22]. First, this study conducted a basic statistical analysis of core journals, core authors, core country, and discipline distribution in the field of sustainability in manufacturing and presented the basic conditions of this field. Then, the researchers carried out a keyword co-occurrence network analysis of literature in this field and summarized the focus of attention and subfields of this field. This study deeply analyzed the knowledge structure of hotspot clustering on the basis of literature co-citation knowledge graphs. Ultimately, this study explored the emerging trend of the field of sustainability in manufacturing on the basis of citation bursts. Fig. 1 shows the framework diagram of this study.

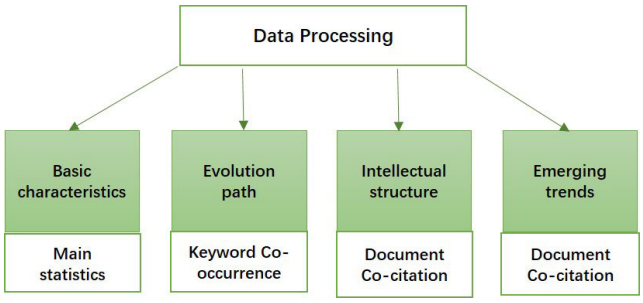

FIGURE 1. The research framework of sustainability in manufacturing.

B. DATA SOURCE AND PROCESSING

To realize the research objectives properly, strictly controlling the scientificity and comprehensiveness of the literature selection process is necessary. According to Bradford's Literature Scattering Law, most key pieces of literature are intensively included in core journals. Therefore, all research literature in this study was derived from core databases SCIE and SSCI of Web of Science, which include core academic journals with the greatest influence in the fields of natural and social sciences. This study carried out a duplicate checking of the literature records and ultimately obtained 6,591 literature records. The time parameter was set as 1999–2019 and Year per Slice as 3. The first 30% high-frequency nodes in each time period were used. Tab. 1 displays the additional search details.

TABLE 1. Summary of searching for details.

Search Settings	Content
Database	*SCIE, SSCI*
Searching term	TS = ("sustainability and manufacturing")OR TS = ("sustainable manufacturing")
Literature	*ARTICLE; REVIEW*
Time period	1999–2019
Searching time	2020/02/19
Results	6591

III. BASIC STATISTICAL ANALYSIS OF LITERATURE REGARDING FILED SUSTAINABILITY IN MANUFACTURING

The statistical analysis of research literature related to sustainability in manufacturing mainly refers to the comprehensive analysis of the research summary in this field in number and quality to gain a comprehensive understanding of related research scholars, regional research institutes, and countries.

A. STATISTICAL ANALYSIS OF CORE JOURNALS

Tab. 2 lists core journals of high co-citation in the field of sustainability in manufacturing in 1999–2019. All impact factors are greater than 2, and the average influence factor is greater than 9, indicating that high-quality research results have appeared in the sustainability field in the manufacturing industry in recent years. Different journals have different themes and emphasize different contents. For instance, the Journal of Cleaner Production pays attention to the theory and practice of cleaner production. The number of articles it issues exceeds those of other journals. Thus, it has the greatest influence in this field, followed by the International Journal of Production Economics and the International Journal of Production Research. The former focuses on solving the interaction problem between engineering and management and attaches importance to the preciseness and innovation of research methods. The latter particularly emphasizes innovation management, product design, manufacturing process, production, and logistics system. Resources, Conservation and Recycling highlights the transition toward a sustainable production and consumption system. Different from other academic journals, Renewable and Sustainable Energy Reviews mainly summarizes academic opinions and management practice in the field of renewable and sustainable energy.

B. CORE AUTHOR ANALYSIS

The number of articles published is the manifestation of researcher productivity in one research field and also a basic factor facilitating the rapid development of this field. This study used CiteSpace to analyze related author networks and mined the core authors that have made outstanding contributions to this field (Fig. 2). In Fig. 2, many similar nodes exist, which are dispersed with a small number of node ligatures. This pattern indicates that studies regarding sustainability in manufacturing are quite dispersed. In addition, the association between researchers in academic exchange and scientific research is not close, and most researchers have carried out their studies in individual form or small group form. Therefore, no authoritative large-scale organizations have been formed. American professor Angappa Gunasekaran ranks first with 30 published articles, followed by Indian professor Vinodh with 29 published articles.

FIGURE 2. The network of main authors.

High co-citation frequency is among the important indexes used to measure important influence exerted by one research field. Through the high co-citation network of authors

TABLE 2. List of cited journals (Top 10).

Ranking	Count	Year	Name of cited journal	2018 Impact factor
1	2979	2003	Journal of Cleaner Production	6.396
2	1251	2000	International Journal of Production Economics	4.998
3	1154	2000	International Journal of Production Research	3.199
4	980	2002	Resources, Conservation and Recycling	7.044
5	948	2008	Renewable and Sustainable Energy Reviews	10.556
6	934	2000	Environmental Science and Technology	7.149
7	855	2007	International Journal of Advanced Manufacturing Technology	2.496
8	832	2000	Science	41.037
9	790	2007	European Journal of Operational Research	3.806
10	787	2008	CIRP Annals-Manufacturing Technology	3.826

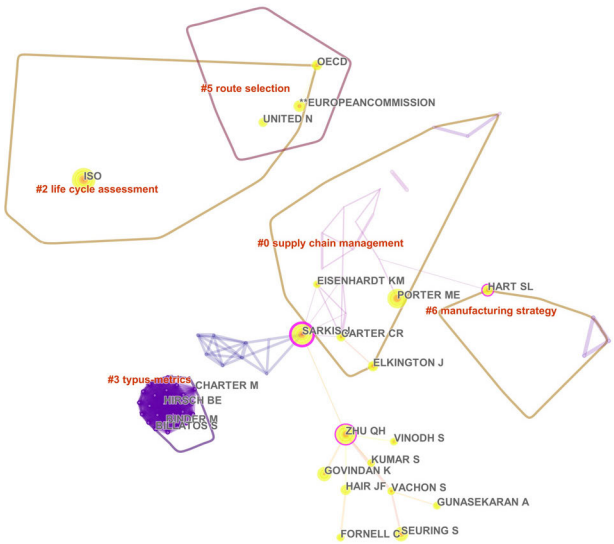

FIGURE 3. The network of main cited authors.

in Fig. 3, institutions and organizations play a significant role in the sustainability field of the manufacturing industry, e.g., International Standardization Organization (ISO), European Union (EU), United Nations (UN), Organization for Economic Cooperation and Development (OECD), and so on. OECD conducted environmental policy studies on the sustainable production field, including enterprise behaviors and environmental policies, the role played by governments in stimulating environmental management system, different system needs of small- and medium-sized enterprises, and so on. The United Nations Environmental Protection Agency identified three policy tools: regulatory tool, market-based tool, and information-based tool [23]. Porter established his status in competitiveness research through his classical works, namely, Competitive Strategy, Competitive Advantage, and National Competitive Advantage Theory. Chinese scholar Zhu investigated the practice of green supply chain management in China from different perspectives, such as influence factors [24], measurement model [25], organization size [26], enterprise management [27], and transnational comparison [28], which became research hotspots of sustainability in manufacturing. American scholar Meade concentrated on quantitative research on the process of the manufacturing industry and further promoted the development of the business process [29], decision-making model [30], and assessment model [30] fields in the manufacturing industry. German professor Seuring comprehensively combed the theoretical framework [31] and modeling method [32] of supply chain management and enterprise competition [33] in the supply chain through a literature review. The number of articles published is not necessarily correlated with cited frequency, and scholars ranking first in a number of published articles may not have outstanding performance in the aspect of cited frequency.

C. ANALYSIS OF MAIN COUNTRIES/RESEARCH INSTITUTES

The number of published articles reflects the research level and field contribution of different countries, regions, and scientific research institutions. The core areas where a large number of articles were published regarding the sustainability in manufacturing are distributed in North America, Europe, and Asia (Tab. 3). First, America tops the list with 1,402 published articles, accounting for 15.5% of the total number of published articles where Illinois University is the main research front of this field in America. Second, representative Asian countries with large numbers of published articles are China and India, both reaching over 400. The Chinese Academy of Sciences, Hong Kong Polytechnic University, Tsinghua University, National Institute of Advanced Industrial Science and Technology (Japan), and the University of Malaya are research institutions with numbers of published articles ranking Top 10. The related studies in Europe are mainly concentrated in developed countries, such as Britain, Italy, Spain, and Germany where the University of Manchester, University of Nottingham, the University of Cambridge in Britain, and Polytechnic University of Milan in Italy are

TABLE 3. Countries and institutions (Top 10).

Ranking	Count	Country	Count	Institution
1	1402	USA	73	Chinese Acad Sci
2	1067	PEOPLES R CHINA	65	Univ Manchester
3	699	ENGLAND	62	Politecn Milan
4	481	ITALY	61	Hong Kong Polytech Univ
5	443	INDIA	50	Natl Inst Technol
6	428	SPAIN	48	Univ Illinois
7	311	GERMANY	48	Univ Malaya
8	284	AUSTRALIA	47	Univ Nottingham
9	270	BRAZIL	45	Univ Cambridge
10	260	FRANCE	43	Tsinghua Univ

	Categories	1999–2001	2002–2004	2005–2007	2008–2010	2011–2013	2014–2016	2017–2019	Total	%
1	ENGINEERING	33	39	53	106	417	875	1663	3186	14.70%
2	ENVIRONMENTAL SCIENCES AND ECOLOGY	13	26	27	58	181	506	1271	2082	9.61%
3	SCIENCE AND TECHNOLOGY - OTHER TOPICS	2	6	15	27	141	492	1222	1905	8.79%
4	ENVIRONMENTAL SCIENCES	13	25	25	56	163	463	1154	1899	8.76%
5	GREEN AND SUSTAINABLE SCIENCE AND TECHNOLOGY	0	5	12	25	114	436	1118	1710	7.89%
6	ENGINEERING, ENVIRONMENTAL	5	21	16	46	108	332	660	1188	5.48%
7	MATERIALS SCIENCE	2	8	8	26	127	243	470	884	4.08%
8	ENGINEERING, MANUFACTURING	10	8	17	18	134	253	425	865	3.99%
9	CHEMISTRY	7	4	3	14	103	177	356	664	3.06%
10	BUSINESS AND ECONOMICS	16	7	3	7	79	181	325	618	2.85%

FIGURE 4. Discipline distribution of sustainability in manufacturing.

important research institutions dedicated to studies on sustainability in manufacturing. Research institutions in China rank top not only in the number of published articles but also the number of cited Chinese authors, indicating that the strength and influence of sustainability research of the manufacturing industry in China, which has the largest manufacturing industry across the world, have been gradually recognized by international academic journals.

D. ANALYSIS OF DISCIPLINE ATTRIBUTES

Fig. 4 shows the discipline attribute distribution regarding sustainability in manufacturing over the past 20 years. From left to right, the darker the shade of red, the more the contributions of one discipline. Studies on sustainability in manufacturing mainly concentrate on engineering science, accounting for 14.7%, because great technical support is needed in the actual sustainability process of the manufacturing industry, followed by environmental science and science and technology, which have generated 2,082 and 1,905 pieces of literature, respectively. Sustainability in manufacturing presents an interdisciplinary development trend, involving various research fields, such as environmental science, green and sustainable science and technology, materials science, chemistry, business, and economics. In terms of the overall growth speed, the heat degree of the engineering field maintains an explosion-type growth. However, studies on business and economic fields have lagged.

IV. EVOLUTIONARY ANALYSIS OF RESEARCH HOTSPOTS REGARDING SUSTAINABILITY IN MANUFACTURING

This study tracked the dynamic change of studies on sustainability in manufacturing on the basis of Schneider's scientific discipline theory [34]. Schneider deemed that a scientific field usually undergoes four development phases. In the first phase, a series of problems in new fields are mainly confirmed, belonging to the conceptualization phase. In the next phase, known as the tool construction phase, researchers survey phenomena in a broader scope by virtue of development technologies or tools. The third phase is the application phase, in which new technologies merge endlessly and support the existing research problems while research branches continue to arise. In the final phase or the codification phase, previous theoretical and practical experiences are organized and utilized. At present, research on sustainability in manufacturing is in the third phase.

Keyword co-occurrence network construction is based on co-word analysis, namely, calculating the number of times every two words (as one group) that appear in the same

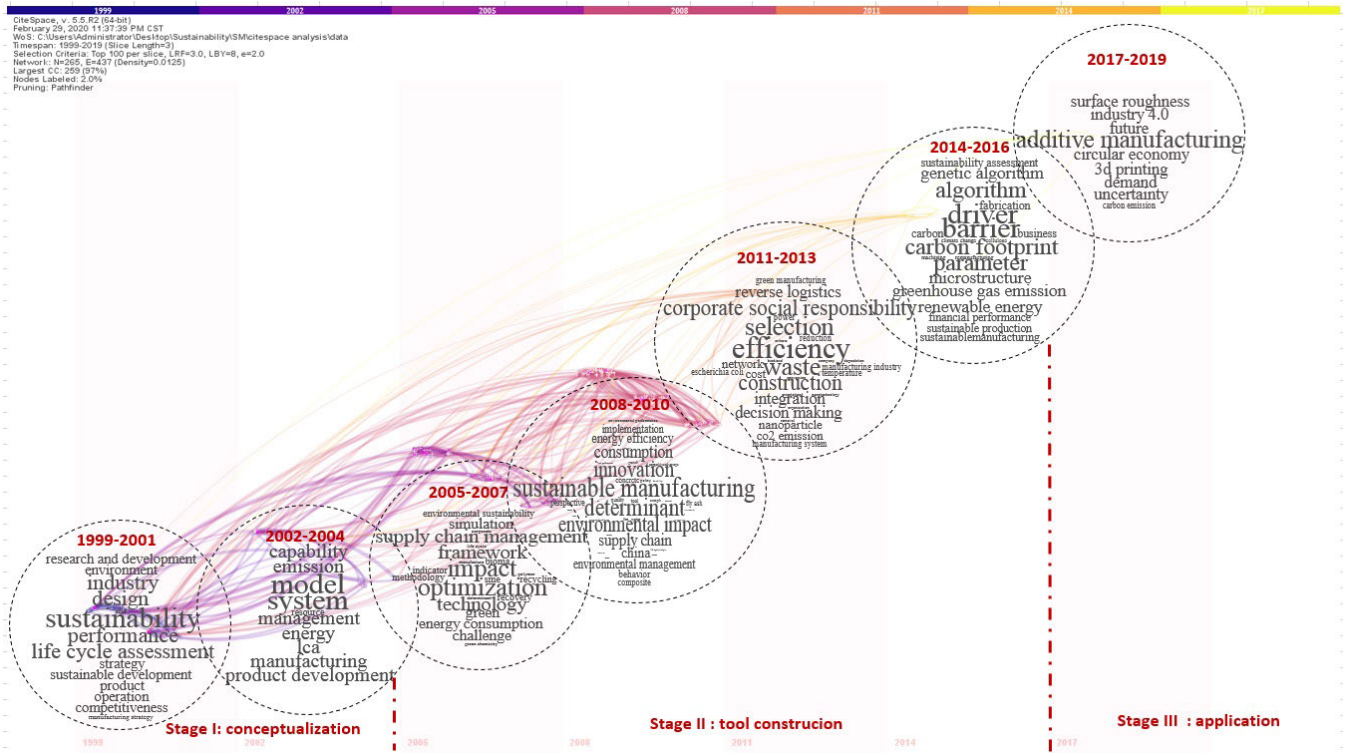

FIGURE 5. Evolution of knowledge of sustainability in manufacturing in 1999–2019.

group of literature. Through keyword co-occurrence analysis, the relations of related themes in the research field can be confirmed to find hotspots in this field. This study adopted a time-zone map to explore the process of keyword association (time level) and knowledge evolution. In this research field, 146 keywords surfaced in 1999–2019, and the total frequency of occurrence reached 17,551. Fig. 5 shows the high-frequency keywords in the sustainability studies of the manufacturing industry in different periods and presents the research emphases of scholars, which varied from phase to phase. Fig. 5 shows the keywords that appeared more than five times in the past 20 years. In each time zone, font size denotes the frequency of keyword occurrence, that is, the larger the font size, the higher the frequency of keyword occurrence.

The first phase (1999–2004) was a conceptualization phase in which new objects and new phenomena were introduced in new studies with a small number of pieces of literature, which mainly discussed sustainability definition [35] and life cycle assessment [36]. The performance was a critical problem in the sustainability research of the manufacturing industry [37]. Moreover, a systematic angle was taken as the entry point [38], modeling was the main research method [39], and sustainability in manufacturing was introduced into the management field [40]. The research hotspots in this phase reflected a typical research trend, namely, starting from conceptual research of theoretical definition and settling on design and verification of research methods.

In the second phase (2005–2016), or the tool construction phase, the increased amplitude of literature was enlarged, scholars attempted to explore some methods and technologies to solve the problems they encountered. Scholars paid attention to the influence of sustainability in manufacturing [41], introduced the optimization [42] and simulation [43] as the main research methods, carried out extensive discussion different fields within the theoretical framework [44] about mechanical properties [45] and implementation technology [46], and highlighted the importance of innovation [47], and so on. Scholars in this phase were dedicated to sustainable manufacturing [48], supply chain management [41], energy consumption [49], and enterprise social responsibility [50], hinting that related scholars started attaching importance to coordinating the relationships among economy, ecology, and society. The abovementioned hotspot evolution manifested that the sustainability studies of the manufacturing industry were continuously refined, and they did not discuss extensive concepts such as sustainability any longer. Second, multilevel and rich research topics were proposed to improve sustainability in manufacturing.

In the third phase (after 2016), namely, the application phase, the ability to understand and solve problems greatly improved. In comparison with the second phase, the research perspectives of scholars experienced evident changes, and scientific and technological development hastened the generation of professional solutions. Modern topics, such as additive manufacturing, circular economy, Industry 4.0, future,

and 3D printing, attracted extensive attention. Such topics reflect epochal and cutting-edge characters and the evolution of research topics to a certain degree. The scale and distribution of the manufacturing industry were modified because of the demands for advanced manufacturing technologies and customized services to facilitate the development of additive manufacturing technologies [51]. The mastery of origin, basic principles, and advantages and disadvantages of circular economy and modeling at different levels and the implementation provided references for decision makers to promote the circular economy [52]. Muller believed that strategy, operation, environment, and social opportunity were the positive driving forces for implementing Industry 4.0, while challenges in competitiveness, survivability, and integrating the degree between organization and production impeded the progress of Industry 4.0 [53].

V. ANALYSIS OF KNOWLEDGE STRUCTURE REGARDING SUSTAINABILITY IN MANUFACTURING

Co-citation analysis means that if two pieces of literature simultaneously appear in the bibliography from which third literature is cited, then the two pieces of literature form a co-citation relationship. Co-citation analysis reflects the main problems and methods researched by academic articles and the main contributions. This analysis is a condensation of main research opinions and is taken as a critical index for literature clustering analysis, which reveals the knowledge structure of one field and reflects important scholars and classical literature.

The co-citation network regarding sustainability in manufacturing includes 357 nodes, 913 links, and 61 clusters. The researchers excluded the small-scale and non-primary clusters and were able to obtain 11 core clusters. Tab. 4 lists 193 nodes of the 11 clusters, accounting for 54% of the whole network. Each cluster is named according to the LLR algorithm, and the keyword phrase markers in the articles of this cluster are cited [54]. The silhouette values of the main clusters in the sustainability field of the manufacturing industry range from 0.8 to 1, indicating high cluster homogeneity. Year expresses the average publishing year of each cluster.

CiteSpace provides a rich and visualized demonstration in the analysis of emerging trends and changes in the network. The link between two nodes in Fig. 6 means that two literature are co-cited, and node size denotes cited frequency. The different colors of nodes and links distinguish different times. The researchers excluded classical literature with high co-cited frequency in each cluster. Classical literature represents the knowledge base of one field, and cutting-edge literature represents research hotspots and trends in one field as well as the current research status. This study used modularity Q and mean silhouette to evaluate the clustering effect of knowledge maps. Researchers used the modularity of the overall network to evaluate the network modularization index. The greater the value, the better the cluster obtained by the network. If the value was greater than 0.3, the obtained network community structure was remarkable. The higher the clustering mean silhouette, the higher the clustering homogeneity, thus manifesting the consistency of literature in the cluster. When the value was greater than 0.5, the clustering structure could be considered reasonable. The modularity of this network was 0.8515, and the mean silhouette value was 0.478, meaning that the sustainability research network of the manufacturing industry was of high credibility (Fig.6). Fig. 6 shows the co-citation and citation burst of literature regarding sustainability in manufacturing. Citation burst represents areas with the most active studies, marked by red circles, which can clearly track the focus of their disciplinary

TABLE 4. Major clusters of co-cited references.

Cluster#	Size	Silhouette	Year	Label (LLR)
1	30	0.899	2004	sustainable design
4	23	0.936	2012	additive manufacturing
2	23	0.972	2010	green supply chain management
3	23	0.814	2004	green chemistry
5	20	0.847	2005	life cycle assessment
6	18	0.987	2008	green information systems
8	17	0.889	2005	lactide
7	17	0.937	2009	power consumption
9	13	0.967	2000	biotechnology
15	5	0.988	2003	material flows
18	4	0.983	2007	n-fertilizer

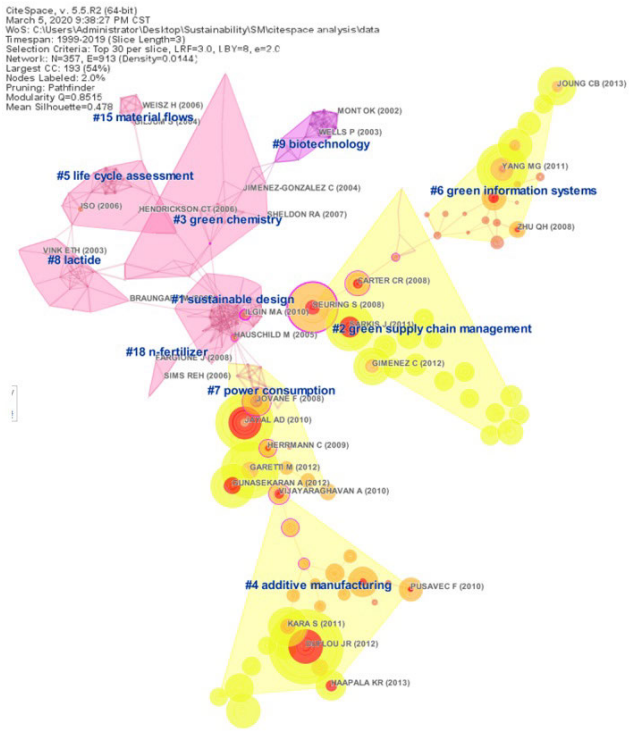

FIGURE 6. Knowledge map of co-citation.

TABLE 5. Cited references and citing articles of Cluster 4 on additive manufacturing (Top 5).

Cited References		Citing Articles
Cites	Author (Year) Journal, Volume, Page	Author (Year) Title
525	Duflou J.R. (2012) CIRP ANN-MANUF TECHN, V61, P. 587	Yoon, Hae-Sung (2014) A Comparison of Energy Consumption in Bulk Forming
286	Kara S. (2011) CIRP ANN-MANUF TECHN, V60, P. 37	Ingarao, Giuseppe (2014) A comprehensive analysis of electric energy consumption of single point incremental forming processes
259	Haapala K.R. (2013) J MANUF SCI E-T ASME, V135, P. 041013-1	Peng, Tao (2014) Energy-efficient machining systems: A critical review
234	Rajemi M.F. (2010). J CLEAN PROD, V18, P. 1059	Liu, Ying (2014) An investigation into minimizing total energy consumption and total weighted tardiness in job shops
217	Ford S. (2016) J CLEAN PROD, V137, P. 1573	Li, Yufeng (2014) A framework for characterizing energy consumption of machining manufacturing systems

TABLE 6. Cited references and citing articles of Cluster 7 on power consumption (Top 5).

Cited References		Citing Articles
Cites	Author (Year) Journal, Volume, Page	Author (Year) Title
703	Jayal A.D. (2010) CIRP J MANUF SCI TEC, V2, P. 144	Tolio, T. (2010) SPECIES-Co-evolution of products, processes, and production systems
273	Herrmann C. (2009) CIRP J MANUF SCI TEC, V1, P. 221	Peng, Tao (2014) Energy-efficient machining systems: A critical review
271	Garetti M. (2012) PROD PLAN CONTROL, V23, P. 83	Liu, Ying (2014) An investigation into minimizing total energy consumption and total weighted tardiness in job shops
228	Gunasekaran A. (2012) INT J PROD ECON, V140, P. 35	Shrouf, Fadi (2014) Optimizing the production scheduling of a single machine to minimize total energy consumption costs
195	Jovane F. (2008) CIRP ANN-MANUF TECHN, V57, P. 641	Liu, Chen Guang (2014) Sustainable performance oriented operational decision making of single machine systems with deterministic product arrival time

TABLE 7. Cited references and citing articles of Cluster 2 on green supply chain management (Top 5).

Cited References		Citing Articles
Cites	Author (Year) Journal, Volume, Page	Author (Year) Title
1967	Seuring S. (2008) J CLEAN PROD, V16, P.1699	Ulku, M. Ali (2017) Towards sustainable consumption and production: Competitive pricing of modular products for green consumers
709	Sarkis J. (2011) INT J PROD ECON, V130, P.1	Stindt, Dennis (2017) A generic planning approach for sustainable supply chain management - How to integrate concepts and methods to address the issues of sustainability?
633	Ghisellini P. (2016) J CLEAN PROD, V114, P. 11	Paulraj, Antony (2017) Motives and Performance Outcomes of Sustainable Supply Chain Management Practices: A Multi-theoretical Perspective
360	Green K.W. (2012) SUPPLY CHAIN MANAG, V17, P. 290	Simpson, Dayna (2010) Use of supply relationships to recycle secondary materials
249	Gimenez C. (2012) SUPPLY CHAIN MANAG, V17, P. 290	Green, Kenneth W. Jr. (2017) Impact of Radio Frequency Identification Technology on Environmental Sustainability

circles. According to the existing analyses, sustainability in manufacturing is a topic with underestimated academic value but broad radiation scope. Hence, the topic is worthy of further focus and deep discussion. Therefore, this study further analyzed Clusters 4, 7, 2, and 6 with citation burst. Tabs. 5–8 show cited literature at high frequency and literature of the four clusters (cited frequency derived from WOS, the search result on March 7, 2020).

The research topic of Cluster 4 was additive manufacturing, which focused on the product design and transformation of the manufacturing mode (Tab. 5). Cluster 4 included 23 pieces of literature. Hence, it was the largest cluster with the latest average citation time, and it represented the cutting edge of sustainability research of the manufacturing industry. Additive manufacturing has become one of the discipline orientations with the fastest development, the most active technical research, and the highest attention in the field of world-class advanced manufacturing. At present, additive manufacturing studies are mainly divided into two aspects: retrospective and qualitative studies, mainly being literature review. Duflou's works were publications with the highest cited frequency in this cluster, and he systemati-

TABLE 8. Cited references and citing articles of Cluster 6 on green information system (Top 5).

Cited References		Citing Articles
Cites	**Author (Year) Journal, Volume, Page**	**Author (Year) Title**
669	Vachon S. (2008) INT J PROD ECON, V111, P. 299	Eltayeb, Tarig K. (2011) Green supply chain initiatives among certified companies in Malaysia and environmental sustainability: Investigating the outcomes
375	Yang M.G. (2011) INT J PROD ECON, V129, P. 251	Tseng, Ming-Lang (2011) Green supply chain management with linguistic preferences and incomplete information
221	Dues C.M. (2013) J CLEAN PROD, V40, P. 93	Dao, Viet (2011) From green to sustainability: Information Technology and an integrated sustainability framework,
187	Joung C.B. (2013) ECOL INDIC, V24, P. 148	Gavronski, Iuri (2011) A resource-based view of green supply management
126	Faulkner W. (2014) J CLEAN PROD, V85, P. 8	Ageron, Blandine (2012) Sustainable supply management: An empirical study

cally reviewed how to improve the resource efficiency and technology of discrete parts manufacturing [55]. Kara discussed the relationship between energy consumption and process variable, and his article was also one of the articles with highly cited frequency [56]. Haapala summarized the sustainable manufacturing concept, method, and tool in the engineering field from two levels: system and operation in detail [57]. Ford highlighted the potential benefits and challenges in the practice of the additive manufacturing field through the case study method and discussed the influence of additive manufacturing on sustainability [51]. The other type is application-oriented quantitative research, which reaches sustainable goals mainly through technological and process innovation. Rajemi provided empirical evidence for the additive manufacturing industry, and he adjusted critical parameters to reduce energy use and energy cost and mitigate environmental impacts [58]. Additive manufacturing has become one of the most important technologies in the manufacturing field. In addition, cutting-edge literature pays significant attention to manufacturing technology and the comparison of the energy consumption of production processes [59], [60]. Although scholars have enriched studies on additive manufacturing from different angles, the practice and application of additive manufacturing remains limited, not to mention the exploration of systematization and digitalization.

The research topic of Cluster 7 was power consumption (Tab. 6). Regarding the writing articles with the highest cited frequency in this cluster, Jayal presented, in the form of literature review, the challenges encountered by the sustainable manufacturing industry in the aspects of modeling and optimization of products, processes, and systems; the author also provided an overall research perspective for this field [61]. Herrmann deemed that the power consumption of manufacturing enterprises could be reduced only by considering the mutual dependency of technical processes [62]. Garetti reformed the research paradigm of sustainable manufacturing industry and proposed that technology and education are also driving factors for sustainable manufacturing [48]. Jovane proposed the necessary steps from economic growth to sustainable development and explored actions taken by different stakeholders at macro-, meso-, and micro-levels [63]. Through the abovementioned literature, power consumption has become a non-negligible focus of attention in the optimization of the production process, improvement of enterprise efficiency, perfection of research paradigm, and strategic planning. As reflected by an analysis of citing articles, nowadays, scholars lay particular emphasis on production system optimization [64], [65] and energy consumption practice [65]–[67]. Given that only few studies have been carried out from the overall systematic perspectives, future studies can deepen the understanding of power consumption from a global angle.

The research topic of Cluster 2 was the green supply chain. By analyzing classical literature, we found that this cluster mainly includes two major fields, namely, supplier and product sustainability (Tab. 7). Seuring conducted a retrospective research on 191 literature published in 1994–2007, proposed strategies for supplier management and supply chain management of sustainable products, and summarized the main research direction for enterprises and researchers [31]. The literature review on green supply chain management by Sarkis provided a valuable theoretical foundation for subsequent profound studies [68]. The latest article with highly cited frequency was the research conducted by Ghisellini in 2006, who sought for the main characteristics and prospects of the circular economy field from micro-, meso-, and macro-levels, aiming to improve resource utilization efficiency [52]. Green paid close attention to the influence of green supply chain management practice on performance [69]. In a review of literature Giménez answered the influence of governance structure on sustainable performance and provided clarification and ideas for further studies from the aspect of management [70]. Based on the clustering results analysis, the enterprise is the main path to implement the green supply chain, and the product is the main object of the green supply chain. The existing studies are mainly dominated by scholar teams, lacking the participation of employees. Cutting-edge literature represents attention paid by scholars to sustainable consumption and production [71], planning method [72], and motivational influence [73], [74] as the practical application and extension of theoretical studies on classical literature.

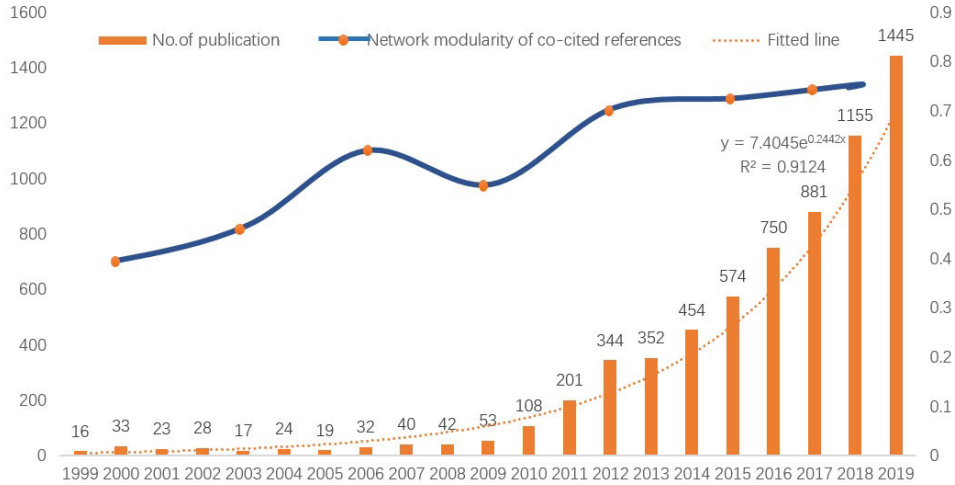

FIGURE 7. Number of publications and the modularity of the network in 1999–2019.

The research topic of Cluster 6 was green information system, and the average citation time was early, representing the research emphasis of the manufacturing industry in and before 2008 (Tab. 8). Vachon explored the relationship between environmental coordination and manufacturing performance in the supply chain, laid a theoretical foundation for their relationship, and empirically verified the influence of environmental cooperation on manufacturing performance [38]. Yang deeply analyzed the relationships of enterprise performance with lean production practice and environmental management. He believed that lean production experience was positively correlated with environmental management practice, whereas environmental management practice was negatively correlated with the financial performance [75]. Through a review of the existing literature regarding lean and green supply chain management, Dües thought that lean production was good for green practice, and green practice generated a positive influence on commerce [76]. Joung constructed a comprehensive index set including five sustainability dimensions, namely, environmental management, economic growth, social welfare, technological progress, and performance management to assess sustainability manufacturing initiatives of companies [77].Faulkner created a set of complete measurement methods and tools for sustainable value flow mapping to evaluate environmental and social sustainable performances of production lines [78]. Current studies have extended the application practice of green information system. However, confusion still exists over how to evaluate green information. Moreover, establishing a scientific and reasonable index system with strong operability and broad scope of application remains a difficulty.

VI. EMERGING TRENDS OF SUSTAINABILITY IN MANUFACTURING STUDIES

Discovering and mining the breakthrough changes and emerging trends of a research field helps to track the latest development of studies in this field in a timely manner. New changes in manufacturing can be captured by tracking the change of network modularity. The knowledge structure of sustainability in manufacturing can be expressed as a literature co-citation network, and new articles may result in the profound structural changes of this network. Fig. 7 is a summary of articles published in the sustainability research field of the manufacturing industry in 1999–2019. On the whole, the total number of published articles in this field increased yearly and presented an exponential growth trend. The orange dotted lines represent the fitted curve of the annual number of published articles, and its formula is presented below:

$$y = 7.4045e^{0.2442x},$$
$$R^2 = 0.9124,$$

where y is the annual number of published articles, and x is the year. R^2 value is 0.9124, indicating acceptable goodness-of-fit, meaning that sustainability in manufacturing has kept a the rapid growth trend in the next few years. The number of published articles was marginal and grew slowly before 2010. Since 2010, the number of published articles started increasing by a large margin year by year, meaning that sustainability in manufacturing has gradually become a research hotspot and has attracted increasing attention from scholars. This growth conforms to the notion that social development and environmental problems need urgent solutions. The diagram below displays the modularity change of the whole network, which presents an overall rising trend. However, modularity declined in 2006, reached the lowest point of 0.562 in 2009. Then, it started rising back to over 0.7 in 2012 and nearly remained unchanged and steady since then. The abovementioned evidence shows that studies on sustainability in manufacturing experienced some major structural changes in 2009 and 2012. Published literature in the two years was profoundly surveyed through citation burst. As a calculation technology used to discover events and other mutation types[79], citation burst detection usually

TABLE 9. Articles published in 2009 with citation bursts.

References	Title	Strength	Duration	Cluster	Range (1999–2019)
HERRMANN, 2009	Process chain simulation to foster energy efficiency in manufacturing	8.7718	2011–2016	7	
FINNVEDEN, 2009	Recent developments in life cycle assessment	8.3869	2014–2016	46	
ORTIZ, 2009	Sustainability in the construction industry: A review of recent developments based on LCA	7.9641	2014–2016	42	
PARK, 2009	Energy consumption reduction technology in manufacturing: A selective review of policies, standards, and research	6.4522	2012–2013	4	
GUTOWSK, 2009	Thermodynamic analysis of resources used in manufacturing processes	5.1156	2011–2013	7	

means attracting high attention in a potentially intriguing direction within a short time. Citation burst has two attributes: burst intensity and burst duration.

Through a comprehensive analysis of articles published in 2009, the declining modularity was manifested by the aggregation of previously disperse clusters in 2009. Tab. 9 lists five articles with citation bursts in 2009. The pioneering research by Herrmann in the aspect of energy efficiency had the highest citation burst, and the research lasted from 2011 to 2016 [62]. Park's article about energy efficiency started having citation bursts since 2012, which reached as high as 8.3869 [80]. This value was accurate because studies on sustainability in manufacturing emphasized energy efficiency in the early phase, and the two articles laid a foundation for early-stage studies on sustainability in manufacturing. Finnveden and Ortiz-Rodriguez investigated sustainable development and life cycle assessment, and their citation bursts continued from 2011 to 2016, lasting seven years [81], [82]. Gutowski deeply and comprehensively analyzed the influence degree of sustainability and energy conversion efficiency [83]. The above-mentioned observation can imply that the reason for the decline in the whole network modularity in 2009 was that studies centering on energy efficiency and life cycle assessment presented a centralized tendency.

Network modularity rebounded sharply in 2012, meaning that network clusters became loose. Tab. 10 lists 11 pieces of literature with citation bursts, where five came from Cluster 4, accounting for 45% of the whole network. This number shows that an increasing number of scholars have turned their eyes on additive manufacturing, thus influencing the modularity of the whole network. In this cluster, Kellens creatively applied the life cycle method to system inventory research [84]. Hu first proposed an online efficiency detection system with the aim of lowering the cost [85]. Cluster 7 also generated a remarkable effect on the change of network modularity in 2012. As a research scholar, He raised a classical modeling method in March to measure energy consumption [86]. He was the most active scholar within this field in 2012 and published two articles with high citation bursts. His other thesis was published in October wherein he proposed an energy consumption estimation method on the basis of the relationship between digital code and energy-consuming components [87]. Bruzzone from Cluster 7 brought forward an energy-saving, consciousness scheduling, nonmixed integer model [88]. Tab. 10 shows that the articles with high citation bursts in 2012 paid joint attention to modeling, tool, and method improvement and other problems in the manufacturing sustainability field. In addition, the 3D printing of additive manufacturing became a new trend [89]. Recent studies have paid more attention to the process modeling, development, and application of manufacturing sustainability [48], [90]. Gunaseraran analyzed a sustainable business model by combining the manufacturing and service industries and achieved great progress in solving environmental problems. The four citation bursts lasted until 2019, exerting the greatest effect on research fronts of manufacturing sustainability [91].

VII. RESEARCH CONCLUSIONS AND EXPECTATIONS

A. MAIN RESEARCH CONCLUSIONS

This study used the scientific bibliometrics method centering on science mapping to conclude the research characteristics and basic information of sustainability in the manufacturing field and depict its evolution course based on which the future development direction of sustainability was explored. This study used CiteSpace software to analyze core journals, core authors, core countries, discipline distribution, keyword co-occurrence, and literature co-citation knowledge maps of 6,591 articles with regard to sustainability in manufacturing in 1999–2019. The main results are presented as follows:

High-quality research results are generated in this field. Core journals with highly cited frequency lay different particular emphasis on theoretical foundation, empirical method, policy research, and practical application. Academic exchange between core authors is not that close, and no large-scale authorities are formed. As prominent high-citation authors, ISO, EU, UN, and OECD exert enormous influence in sustainability research. The main research areas and research institutions are distributed in North America, Europe, and Asia. This field centers on engineering science, environmental science, and science and technology

TABLE 10. Articles published in 2012 with citation bursts.

References	Title	Strength	Duration	Cluster	Range (1999–2019)
KELLENS, 2012	Methodology for systematic analysis and improvement of manufacturing unit process life–cycle inventory (UPLCI)—CO2 PE! Initiative	11.7828	2014–2016	4	
HE, 2012	A modeling method of task-oriented energy consumption for machining manufacturing system	10.5066	2014–2016	7	
HU, 2012	An online approach for energy efficiency monitoring of machine tools	9.6576	2014–2016	4	
BERMAN, 2012	3D printing: The new industrial revolution	9.3201	2017–2019	6	
SMITH, 2012	Steps towards sustainable manufacturing through modelling material, energy, and waste flows	9.3201	2017–2019	4	
DUFLOU, 2012	Towards energy and resource efficient manufacturing: A processes and systems approach	9.2369	2014–2017	4	
BRUZZONE, 2012	Energy-aware scheduling for improving manufacturing process sustainability: A mathematical model for flexible flow shops	9.2336	2014–2016	7	
GARETTI, 2012	Sustainable manufacturing: trends and research challenges	8.8858	2017–2019	7	
HE, 2012	Analysis and estimation of energy consumption for numerical control machining	7.9641	2014–2016	4	
GUNASEKARAN, 2012	Sustainability of manufacturing and services: Investigations for research and applications	7.4581	2016–2019	7	
GIMENEZ, 2012	Sustainable operations: Their impact on the triple bottom line	3.3679	2014–2015	2	

with increasingly evident interdisciplinary fusion attributes and pluralistic development trends.

Under the four stages of the theoretical framework of discipline development, studies on sustainability in manufacturing have formed the main blueprint, following the logic thread of concept definition, tool construction, and application phases. According to keyword co-occurrence results, research hotspots in the last 20 years stay at enterprise and industry levels with the main attention paid to sustainability theory and practical development, factors influencing enterprise or industrial performance, and the realization method of system modeling. Furthermore, the research perspectives of scholars undergo evident changes in the application phase. They have transformed from influence generation, optimization, and simulation in the previous second phase into the current additive manufacturing, circular economy, 3D printing, and Industry 4.0, and so on. This change, to a certain degree, reflects the epochal, cutting-edge, and evolutionary characteristics of research topics.

Based on the literature co-citation results, the research results related to sustainability in manufacturing can be subdivided into 11 mainstream research fields. Four clusters—additive manufacturing, energy consumption, green supply chain management, and green information system—attract the attention of many scholars in the recent period. Through further analysis of knowledge structures of the four clusters, the development track of core fields related to sustainability in manufacturing has been determined, thus laying a solid foundation for probing the emerging development direction.

The number of literature regarding sustainability in manufacturing presents exponential growth. Literatures published in 2009 and 2012 generated marked influences on the overall network modularity. The modularity in 2009 was changed because of two research topics: life cycle assessment and energy efficiency. Clusters 4 and 7 had the greatest contributions to rebounding modularity in 2012. On the grounds of citation burst intensity and duration, 3D printing, manufacturing industry and service industry fusion, process modeling, development tracking, challenge prediction, and practical application may become emerging trends in the field of sustainability in manufacturing.

B. EXPECTATIONS

This study comprehensively and clearly mastered the bibliometrics method used, the research status, research fronts, research hotspots, and research trends regarding sustainability in manufacturing over the 20 years through a quantitative analysis of literature characteristics and cited data. The above findings have important implications for developing sustainability in manufacturing which will be a long-term and complex process. In the near future, the business model of production will gradually make changes to

reach the sustainability targets from society and regulations. Accordingly, the manufacturing practices will transform step by step to adapt the rules of the new business models. Products, operations, organization, and business models will be explored to conform to the new constraints and goals of sustainability.

The comprehensive framework of this study offers valuable insights to practitioners for better understanding the influence of sustainability in manufacturing. Those topics are to be discovered further, especially for engineering, environmental science, materials science, chemistry, business, and economics researchers who are interested in multidisciplinary issues related to sustainability in manufacturing. For practitioners, this study reveals the existing or potential threats and problems for practice. The governmental officials, stakeholders, employees, employers, entrepreneurs can aim to explore the ways to take responsibility for sustainability in manufacturing. The research also points out the direction for relevant practitioners in this field, for example, improving the technology of additive manufacturing, encouraging the policies for power consumption, adapting green information technologies appropriately, advocating green consumption, and so on. Therefore, researchers and practitioners can understand the current research gaps and best practices from our analysis.

Although outstanding progress has been achieved in the field, a large research gap remains. Additional attention must be paid to the following aspects. First, theory construction and verification should take root in the current complex global perspectives and diversified cultural background. Second, multitime-point and multilevel research methods should be developed for the sake of innovation, and case studies should be enhanced and complementary empirical systems should be formed. Third, the problem-solving mechanisms for sustainability in manufacturing remain underexplored, and the transformation from ''problem recognition and parsing'' into ''design of effective solutions and system strategies'' should be realized. This study holds certain deficiencies. It only selected data in core datasets from peer-reviewed journals in Web of Science, which might have resulted in the omission of some research literature. Furthermore, data size was enormous, which could describe the complete picture of the field of sustainability in manufacturing. However, it could hardly achieve an in-depth analysis of variable and parameter adjustments in each cluster. In the future, scholars can focus on various types of articles, such as conference papers, proceedings, theses, and book chapters, to obtain more literature data, which will make the research coverage more extensive. A further study with more focus on the evolution of these latest insights and opinions related to sustainable development in the country-level is therefore suggested.

REFERENCES

[1] W. Naudé and A. Szirmai, ''The importance of manufacturing in economic development: Past, present and future perspectives,'' United Nations Univ. Maastricht, Maastricht, The Netherlands, UNU-MERIT Working Papers, 2012.

[2] G. H. Brundtland, ''Our common future, report of the world commission on environment and development,'' World Commission Environ. Develop., Oslo, Norway, Tech. Rep., 1987. [Online]. Available: http://www.un-documents.net/our-common-future.pdf

[3] C. Madu, *Handbook of Environmentally Conscious Manufacturing*. New York, NY, USA: Springer, 2001, p. 488.

[4] I. International Trade Administration. (2017). *How Does Commerce Define Sustainable Manufacturing*. Accessed: Feb. 3, 2020. [Online]. Available: http://www.trade.gov/competitiveness/sustainablemanufacturing/how_doc_defines_SM.asp

[5] C. Yuan, Q. Zhai, and D. Dornfeld, ''A three dimensional system approach for environmentally sustainable manufacturing,'' *CIRP Ann.*, vol. 61, no. 1, pp. 39–42, 2012.

[6] M. Garetti, G. Mummolo, and M. Taisch, ''Special issue on 'sustainable manufacturing,'" *Prod. Planning Control*, vol. 23, nos. 2–3, pp. 79–82, Jan. 2012.

[7] P. Glavič and R. Lukman, ''Review of sustainability terms and their definitions,'' *J. Cleaner Prod.*, vol. 15, no. 18, pp. 1875–1885, Dec. 2007.

[8] L. Ocampo and E. Clark, ''A sustainable manufacturing strategy framework: The convergence of two fields,'' *Asian Acad. Manage. J.*, vol. 20, no. 2, pp. 29–57, Jan. 2015.

[9] Y. Moon, ''Simulation modelling for sustainability: A review of the literature,'' *Int. J. Sustain. Eng.*, vol. 10, no. 1, pp. 2–19, Aug. 2016.

[10] F. Chan, N. Li, S.-H. Chung, and M. Saadat, ''Management of sustainable manufacturing systems-a review on mathematical problems,'' *Int. J. Prod. Res.*, vol. 55, no. 4, pp. 1210–1225, Sep. 2016.

[11] M. Gerner, ''Assessing and managing sustainability in international perspective: Corporate sustainability across cultures–towards a strategic framework implementation approach,'' *Int. J. Corporate Social Responsibility*, vol. 4, no. 1, p. 5, Jun. 2019.

[12] M. Benlemlih and L. Cai, ''Corporate environmental performance and financing decisions,'' *Bus. Ethics: A Eur. Rev.*, vol. 29, no. 2, pp. 248–265, Apr. 2020.

[13] P. E. Karlsson Niklas, H. Laurell, J. Lindgren, T. Pehrsson, S. Andersson, and G. Svensson, ''A cross-country comparison and validation of firms' stakeholder considerations in sustainable business practices,'' *Corporate Governance: Int. J. Bus. Soc.*, vol. 18, no. 3, pp. 408–424, 2018.

[14] M. J. Sanchez-Bueno, F. Muñoz-Bullón, and J. I. Galan, ''Socially responsible downsizing: Comparing family and non-family firms,'' *Bus. Ethics: Eur. Rev.*, vol. 29, no. 1, pp. 35–55, 2020.

[15] M. Tran and E. Beddewela, ''Does context matter for sustainability disclosure? Institutional factors in southeast asia,'' *Bus. Ethics: Eur. Rev.*, vol. 29, no. 2, pp. 282–302, Apr. 2020.

[16] R. Ojstersek, B. Acko, and B. Buchmeister, ''Simulation study of a flexible manufacturing system regarding sustainability,'' *Int. J. Simul. Model.*, vol. 19, no. 1, pp. 65–76, Mar. 2020.

[17] A. Martinez-Sentana, S. Valero-Verdu, and C. Senabre-Blanes, ''Energy sustainability: Macroeconomic indicators and productive sectors,'' (in Spanish), *Dyna, Editorial Mater.*, vol. 95, no. 2, pp. 139–143, Mar. 2020.

[18] R. Henao, W. Sarache, and I. Gómez, ''Lean manufacturing and sustainable performance: Trends and future challenges,'' *J. Cleaner Prod.*, vol. 208, pp. 99–116, Jan. 2019.

[19] C. M. Chen, Z. Hu, S. Liu, and H. Tseng, ''Emerging trends in regenerative medicine: A scientometric analysis in CiteSpace,'' *Expert Opinion Biol. Therapy*, vol. 12, no. 5, pp. 593–608, Mar. 2012.

[20] Liu, Zhao, and Xin, ''Analysis on the evolution path and hotspot of knowledge innovation study based on knowledge map,'' *Sustainability*, vol. 11, no. 19, p. 5528, Oct. 2019.

[21] C. Chen, ''Science mapping: A systematic review of the literature,'' *J. Data Inf. Sci.*, vol. 2, no. 2, pp. 1–40, Mar. 2017.

[22] L. Zhao, Z.-Y. Tang, and X. Zou, ''Mapping the knowledge domain of smart-city research: A bibliometric and scientometric analysis,'' *Sustainability*, vol. 11, no. 23, p. 6648, Nov. 2019.

[23] S. J. Deogratias Kibira and C. McLean, ''A system dynamics modeling framework for sustainable manufacturing,'' presented at the 27th Annu. Syst. Dyn. Soc. Conf., Albuquerque, NM, USA, 2009. [Online]. Available: https://www.nist.gov/publications/system-dynamics-modeling-framework-sustainable-manufacturing

[24] S. Hashimoto, S. Sugino, T. Fujita, Q. Zhu, and E. Nagasawa, ''Factors Affecting Resource Circulation And Environmental Behavior At The Level Of Manufacturing And Production Establishment,'' *Environ. Syst. Res.*, vol. 36, pp. 173–180, Jan. 2008.

[25] Q. Zhu, J. Sarkis, and K.-H. Lai, "Confirmation of a measurement model for green supply chain management practices implementation," *Int. J. Prod. Econ.*, vol. 111, no. 2, pp. 261–273, Feb. 2008.

[26] Q. Zhu, J. Sarkis, K.-H. Lai, and Y. Geng, "The role of organizational size in the adoption of green supply chain management practices in China," *Corporate Social Responsibility Environ. Manage.*, vol. 15, no. 6, pp. 322–337, Nov. 2008.

[27] Q. Zhu, J. Sarkis, J. Cordeiro, and K.-H. Lai, "Firm-level correlates of emergent green supply chain management practices in the Chinese context," *Omega*, vol. 36, no. 4, pp. 577–591, Aug. 2008.

[28] Q. Zhu, J. Crotty, and J. Sarkis, "A cross-country empirical comparison of environmental supply chain management practices in the automotive industry," *Asian Bus. Manage.*, vol. 7, no. 4, pp. 467–488, Dec. 2008.

[29] L. M. Meade and J. Sarkis, "Analyzing organizational project alternatives for agile manufacturing processes: An analytical network approach," *Int. J. Prod. Res.*, vol. 37, no. 2, pp. 241–261, Feb. 1999.

[30] S. Talluri, R. C. Baker, and J. Sarkis, "A framework for designing efficient value chain networks," *Int. J. Prod. Econ.*, vol. 62, no. 1, pp. 133–144, Feb. 1999.

[31] S. Seuring and M. Müller, "From a literature review to a conceptual framework for sustainable supply chain management," *J. Cleaner Prod.*, vol. 16, no. 15, pp. 1699–1710, Oct. 2008.

[32] S. Seuring, "A review of modeling approaches for sustainable supply chain management," *Decis. Support Syst.*, vol. 54, no. 4, pp. 1513–1520, Mar. 2013.

[33] S. Gold, S. Seuring, and P. Beske, "Sustainable supply chain management and inter-organizational resources: A literature review," *Corporate Social Responsibility Environ. Manage.*, vol. 17, no. 4, pp. 230–245, 2009.

[34] A. Shneider, "Four stages of a scientific discipline; four types of scientist," *Trends Biochem. Sci.*, vol. 34, no. 1, pp. 217–223, May 2009.

[35] S. Parkin, "Sustainable development: The concept and the practical challenge," *Proc. Inst. Civil Eng.-Civil Eng.*, vol. 138, no. 6, pp. 3–8, Nov. 2000.

[36] D. Maxwell and R. van der Vorst, "Developing sustainable products and services," (in English), *J. Cleaner Prod.*, vol. 11, no. 8, pp. 883–895, 2003.

[37] R. J. Calantone and C. A. Di Benedetto, "Performance and time to market: Accelerating cycle time with overlapping stages," *IEEE Trans. Eng. Manag.*, vol. 47, no. 2, pp. 232–244, May 2000.

[38] N. U. Ukidwe and B. R. Bakshi, "Thermodynamic accounting of ecosystem contribution to economic sectors with application to 1992 US economy," (in English), *Environ. Sci. Technol.*, vol. 38, no. 18, pp. 4810–4827, Sep. 2004.

[39] P. E. Waggoner and J. H. Ausubel, "A framework for sustainability science: A renovated IPAT identity," *Proc. Nat. Acad. Sci. USA*, vol. 99, no. 12, pp. 7860–7865, Jun. 2002.

[40] A. Goodman, "Implementing sustainability in service operations at scandic hotels," *Interfaces*, vol. 30, no. 3, pp. 202–214, Jun. 2000.

[41] S. Vachon and R. D. Klassen, "Environmental management and manufacturing performance: The role of collaboration in the supply chain," *Int. J. Prod. Econ.*, vol. 111, no. 2, pp. 299–315, Feb. 2008.

[42] H. ElMaraghy, G. Schuh, W. ElMaraghy, F. Piller, P. Schönsleben, M. Tseng, and A. Bernard, "Product variety management," *CIRP Ann.*, vol. 62, no. 2, pp. 629–652, 2013.

[43] S. K. Chandrasegaran, K. Ramani, R. D. Sriram, I. Horváth, A. Bernard, R. F. Harik, and W. Gao, "The evolution, challenges, and future of knowledge representation in product design systems," *Comput.-Aided Des.*, vol. 45, no. 2, pp. 204–228, Feb. 2013.

[44] B. Ageron, A. Gunasekaran, and A. Spalanzani, "Sustainable supply management: An empirical study," (in English), *Int. J. Prod. Econ.*, vol. 140, no. 1, pp. 168–182, Nov. 2012.

[45] D. B. Dittenber and H. V. S. GangaRao, "Critical review of recent publications on use of natural composites in infrastructure," *Compos. A, Appl. Sci. Manuf.*, vol. 43, no. 8, pp. 1419–1429, Aug. 2012.

[46] R. S. Blissett and N. A. Rowson, "A review of the multi-component utilisation of coal fly ash," *Fuel*, vol. 97, pp. 1–23, Jul. 2012.

[47] Q. Zhu and J. Sarkis, "The moderating effects of institutional pressures on emergent green supply chain practices and performance," *Int. J. Prod. Res.*, vol. 45, nos. 18–19, pp. 4333–4355, Sep. 2007.

[48] M. Garetti and M. Taisch, "Sustainable manufacturing: Trends and research challenges," *Prod. Planning Control*, vol. 23, nos. 2–3, pp. 83–104, Feb. 2012.

[49] V. Dao, I. Langella, and J. Carbo, "From green to sustainability: Information technology and an integrated sustainability framework," *J. Strategic Inf. Syst.*, vol. 20, no. 1, pp. 63–79, Mar. 2011.

[50] C. Labuschagne, A. C. Brent, and R. P. G. van Erck, "Assessing the sustainability performances of industries," *J. Cleaner Prod.*, vol. 13, no. 4, pp. 373–385, Mar. 2005.

[51] S. Ford and M. Despeisse, "Additive manufacturing and sustainability: An exploratory study of the advantages and challenges," *J. Cleaner Prod.*, vol. 137, pp. 1573–1587, Nov. 2016.

[52] P. Ghisellini, C. Cialani, and S. Ulgiati, "A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems," *J. Cleaner Prod.*, vol. 114, pp. 11–32, Feb. 2016.

[53] J. M. Müller, D. Kiel, and K.-I. Voigt, "What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability," (in English), *Sustainability*, vol. 10, no. 1, p. 24, Jan. 2018.

[54] C. Chen, F. Ibekwe-SanJuan, and J. Hou, "The structure and dynamics of cocitation clusters: A multiple-perspective cocitation analysis," *J. Amer. Soc. Inf. Sci. Technol.*, vol. 61, no. 7, pp. 1386–1409, Jul. 2010.

[55] J. R. Duflou, J. W. Sutherland, D. Dornfeld, C. Herrmann, J. Jeswiet, S. Kara, M. Hauschild, and K. Kellens, "Towards energy and resource efficient manufacturing: A processes and systems approach," *CIRP Ann.*, vol. 61, no. 2, pp. 587–609, 2012.

[56] S. Kara and W. Li, "Unit process energy consumption models for material removal processes," *CIRP Ann.*, vol. 60, no. 1, pp. 37–40, 2011.

[57] K. R. Haapala, F. Zhao, and J. Camelio, "A review of engineering research in sustainable manufacturing," *J. Manuf. Sci. Eng.*, vol. 135, no. 4, pp. 599–619, 2013.

[58] M. F. Rajemi, P. T. Mativenga, and A. Aramcharoen, "Sustainable machining: Selection of optimum turning conditions based on minimum energy considerations," *J. Cleaner Prod.*, vol. 18, nos. 10–11, pp. 1059–1065, Jul. 2010.

[59] H.-S. Yoon, J.-Y. Lee, H.-S. Kim, M.-S. Kim, E.-S. Kim, Y.-J. Shin, W.-S. Chu, and S.-H. Ahn, "A comparison of energy consumption in bulk forming, subtractive, and additive processes: Review and case study," *Int. J. Precis. Eng. Manuf.-Green Technol.*, vol. 1, no. 3, pp. 261–279, Jul. 2014.

[60] G. Ingarao, H. Vanhove, K. Kellens, and J. R. Duflou, "A comprehensive analysis of electric energy consumption of single point incremental forming processes," *J. Cleaner Prod.*, vol. 67, pp. 173–186, Mar. 2014.

[61] A. D. Jayal, F. Badurdeen, O. W. Dillon, and I. S. Jawahir, "Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels," *CIRP J. Manuf. Sci. Technol.*, vol. 2, no. 3, pp. 144–152, Jan. 2010.

[62] C. Herrmann and S. Thiede, "Process chain simulation to foster energy efficiency in manufacturing," *CIRP J. Manuf. Sci. Technol.*, vol. 1, no. 4, pp. 221–229, Jan. 2009.

[63] F. Jovane, H. Yoshikawa, L. Alting, C. R. Boër, E. Westkamper, D. Williams, M. Tseng, G. Seliger, and A. M. Paci, "The incoming global technological and industrial revolution towards competitive sustainable manufacturing," *CIRP Ann.*, vol. 57, no. 2, pp. 641–659, 2008.

[64] T. Tolio, D. Ceglarek, H. A. ElMaraghy, A. Fischer, and S. J. Hu, "SPECIES—Co-evolution of products, processes and production systems," *CIRP Ann.*, vol. 59, no. 2, pp. 672–693, Aug. 2010.

[65] Y. Liu, H. Dong, N. Lohse, S. Petrovic, and N. Gindy, "An investigation into minimising total energy consumption and total weighted tardiness in job shops," *J. Cleaner Prod.*, vol. 65, pp. 87–96, Feb. 2014.

[66] T. Peng and X. Xu, "Energy-efficient machining systems: A critical review," *Int. J. Adv. Manuf. Technol.*, vol. 72, nos. 9–12, pp. 1389–1406, Jun. 2014.

[67] F. Shrouf, J. Ordieres-Meré, A. García-Sánchez, and M. Ortega-Mier, "Optimizing the production scheduling of a single machine to minimize total energy consumption costs," *J. Cleaner Prod.*, vol. 67, pp. 197–207, Mar. 2014.

[68] J. Sarkis, Q. Zhu, and K.-H. Lai, "An organizational theoretic review of green supply chain management literature," *Int. J. Prod. Econ.*, vol. 130, no. 1, pp. 1–15, Mar. 2011.

[69] K. W. Green, P. J. Zelbst, J. Meacham, and V. S. Bhadauria, "Green supply chain management practices: Impact on performance," *Supply Chain Manage., Int. J.*, vol. 17, no. 3, pp. 290–305, Apr. 2012.

[70] C. Gimenez and E. M. Tachizawa, "Extending sustainability to suppliers: A systematic literature review," *Supply Chain Manage., Int. J.*, vol. 17, no. 5, pp. 531–543, Aug. 2012.

[71] M. A. Ülkü and J. Hsuan, "Towards sustainable consumption and production: Competitive pricing of modular products for green consumers," *J. Cleaner Prod.*, vol. 142, pp. 4230–4242, Jan. 2017.

[72] D. Stindt, "A generic planning approach for sustainable supply chain management–How to integrate concepts and methods to address the issues of sustainability?" *J. Cleaner Prod.*, vol. 153, pp. 146–163, Jun. 2017.
[73] A. Paulraj, I. J. Chen, and C. Blome, "Motives and performance outcomes of sustainable supply chain management practices: A multi-theoretical perspective," *J. Bus. Ethics*, vol. 145, no. 2, pp. 239–258, Oct. 2017.
[74] K. Green, P. Zelbst, V. Sower, and J. Bellah, "Impact of radio frequency identification technology on environmental sustainability," *J. Comput. Inf. Syst.*, vol. 57, no. 3, pp. 269–277, Sep. 2016.
[75] M. G. Yang, P. Hong, and S. B. Modi, "Impact of lean manufacturing and environmental management on business performance: An empirical study of manufacturing firms," *Int. J. Prod. Econ.*, vol. 129, no. 2, pp. 251–261, Feb. 2011.
[76] C. M. Dües, K. H. Tan, and M. Lim, "Green as the new lean: How to use lean practices as a catalyst to greening your supply chain," *J. Cleaner Prod.*, vol. 40, pp. 93–100, Feb. 2013.
[77] C. B. Joung, J. Carrell, P. Sarkar, and S. C. Feng, "Categorization of indicators for sustainable manufacturing," *Ecol. Indicators*, vol. 24, pp. 148–157, Jan. 2013.
[78] W. Faulkner and F. Badurdeen, "Sustainable value stream mapping (Sus-VSM): Methodology to visualize and assess manufacturing sustainability performance," *J. Cleaner Prod.*, vol. 85, pp. 8–18, Dec. 2014.
[79] J. Kleinberg, "Bursty and hierarchical structure in streams," in *Proc. ACM SIGKDD Int. Conf. Knowl. Discovery Data Mining*, vol. 7, Jul. 2002, pp. 373–397.
[80] C.-W. Park, K. S. Kwon, W. B. Kim, B. K. Min, and S. J. Park, "Energy consumption reduction technology in manufacturing—A selective review of policies, standards, and research," *Int. J. Precis. Eng. Manuf.*, vol. 10, pp. 151–173, Dec. 2010.
[81] G. Finnveden, M. Z. Hauschild, T. Ekvall, and J. Guinée, "Recent developments in life cycle assessment," *J. Environ. Manage.*, vol. 91, no. 1, pp. 1–21, Oct. 2009.
[82] O. Ortiz, F. Castells, and G. Sonnemann, "Sustainability in the construction industry: A review of recent developments based on LCA," *Construct. Building Mater.*, vol. 23, no. 1, pp. 28–39, Jan. 2009.
[83] T. Gutowski, M. Branham, J. Dahmus, A. Jones, and A. Thiriez, "Thermodynamic analysis of resources used in manufacturing processes," *Environ. Sci. Technol.*, vol. 43, no. 5, pp. 1584–1590, Apr. 2009.
[84] K. Kellens, W. Dewulf, M. Overcash, M. Z. Hauschild, and J. R. Duflou, "Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)—CO_2PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description," *Int. J. Life Cycle Assessment*, vol. 17, no. 1, pp. 69–78, Jan. 2012.
[85] S. Hu, F. Liu, Y. He, and T. Hu, "An on-line approach for energy efficiency monitoring of machine tools," *J. Cleaner Prod.*, vol. 27, pp. 133–140, May 2012.
[86] Y. He, B. Liu, X. Zhang, H. Gao, and X. Liu, "A modeling method of task-oriented energy consumption for machining manufacturing system," *J. Cleaner Prod.*, vol. 23, no. 1, pp. 167–174, Mar. 2012.
[87] Y. He, F. Liu, T. Wu, F.-P. Zhong, and B. Peng, "Analysis and estimation of energy consumption for numerical control machining," *Proc. Inst. Mech. Eng., B, J. Eng. Manuf.*, vol. 226, no. 2, pp. 255–266, Feb. 2012.
[88] A. A. G. Bruzzone, D. Anghinolfi, M. Paolucci, and F. Tonelli, "Energy-aware scheduling for improving manufacturing process sustainability: A mathematical model for flexible flow shops," *CIRP Ann.*, vol. 61, no. 1, pp. 459–462, 2012.
[89] B. Berman, "3-D printing: The new industrial revolution," *Bus. Horizons*, vol. 55, no. 2, pp. 155–162, Mar. 2012.
[90] L. Smith and P. Ball, "Steps towards sustainable manufacturing through modelling material, energy and waste flows," *Int. J. Prod. Econ.*, vol. 140, no. 1, pp. 227–238, Nov. 2012.
[91] A. Gunasekaran and A. Spalanzani, "Sustainability of manufacturing and services: Investigations for research and applications," *Int. J. Prod. Econ.*, vol. 140, no. 1, pp. 35–47, Nov. 2012.

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