sustainability

Review

A Bibliometric Analysis of Sustainable Product Design Methods from 1999 to 2022: Trends, Progress, and Disparities between China and the Rest of the World

Meng Gao [1,*], Ke Ma [1], Renke He [1], Carlo Vezzoli [2] and Nuo Li [3]

[1] School of Design, Hunan University, Changsha 410000, China
[2] Design Department, Politecnico di Milano, 20158 Milan, Italy
[3] School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK
* Correspondence: meng_gao@hnu.edu.cn

Abstract: Effective product design strategies play a crucial role in promoting sustainable production, consumption, and disposal practices. In the literature, many such practices have been proposed by various researchers; however, it is challenging to understand which is more effective from the design point of view. This study employs bibliometric analysis and visualization software, CiteSpace, to comprehensively assess the literature on sustainable product design methods (SPDMs) from two major citation databases, namely, China National Knowledge Infrastructure and Web of Science, covering the period between 1999 and 2022. The objective of this review is to identify the latest research trends, progress, and disparities between China and the rest of the world in the field of SPDMs. The findings reveal that the development of SPDMs is characterized by a combination of multi-method integration and expansion, as well as qualitative and quantitative hybrids. However, research processes differ between China and other countries. Chinese studies focus on digital-driven development, rural revitalization, and system design, while research from other countries emphasizes a circular economy, distribution, additive manufacturing, and artificial intelligence. Nevertheless, both Chinese and international studies lack quantitative research methods in relation to socio-cultural sustainability. Future research should aim to deepen sustainable design methods and standards for specialized products, as well as to incorporate quantitative methods that address cultural and social sustainability dimensions. Open-source and shared SPDMs should be encouraged to promote methodological innovation that prioritizes multidimensional and systematic sustainable benefits, leveraging the strengths of new technologies.

Keywords: sustainability; design method; product design; CiteSpace; bibliometric analysis; comparative study

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1. Introduction

The global population has significantly increased from three billion in 1960 to approximately eight billion in 2022, leading to an enhanced human impact on the ecosystem in pursuit of products and services necessary for production and life [1]. The unprecedented use of natural resources during this process exerts enormous pressure on the ecosystem, pushing the planet to its limits. Furthermore, the recent environmental and climate crisis, increasingly severe regional conflicts, complex and volatile international market, and the outbreak of COVID-19 have heightened the volatility and vulnerability of the socio-economic system that supports people's lives and development. Consequently, achieving sustainable socio-economic development has become a critical concern for academia. Sustainable design, first proposed during the environmental movement in the 1980s, has emerged as an effective strategic solution to this challenge [1]. Over the past four decades, scholars, designers, and engineers across the world have widely used sustainable design to guide the design of various products, services, buildings, environments, and social systems [2]. According to research, approximately 80% of sustainability is determined at the product design stage [3]. Therefore, designing and producing sustainable products is a critical strategy for achieving the sustainable development goals outlined in *Transforming our World: The 2030 Agenda for Sustainable Development* [4].

Product sustainability refers to the ability to maintain a product's sustainable service life while minimizing environmental impacts and providing socio-economic benefits for stakeholders. Sustainable product design methods (SPDMs) play a crucial role in achieving sustainability goals [5]. The widely accepted definition of sustainability is the triple-bottom-line approach, which assigns "equal importance to economic stability, ecological compatibility, and social equilibrium" [6]. The World Design Organization (WDO) updated its definition of industrial design in 2015 to emphasize its role in creating a better world through sustainable development, addressing socio-economic, environmental, and ethical issues. Sustainable design methods broadly address these issues and have become vital and increasingly focused on social innovation and cultural inheritance projects [7]. Tsinghua University, Tongji University, and Hunan University have made significant contributions in this regard [7]. In recent years, numerous research projects have been launched to explore how to guide, improve, and optimize the production and supply of sustainable products and services. Sustainable design methods are critical and involve all sectors, fields, and disciplines. To better understand these methods, we must therefore thoroughly understand past methods, which is possible only through a comprehensive literature assessment. In line with this, some researchers have already conducted literature assessments, and to move forward, we must understand how these past review assessments were done to set a path for this research.

Recent literature reviews on sustainable product design methods (SPDMs) conducted by scholars in China and beyond have identified several areas for improvement. Firstly, previous reviews have primarily focused on introducing theoretical progress in sustainable design research rather than systematically presenting the evolving trends and dynamic processes of SPDMs in recent years. Secondly, the existing research scope does not incorporate knowledge graphs or visualization regarding SPDMs from the China National Knowledge Infrastructure (CNKI) database search results, while qualitative research has been conducted on relevant literature in the Web of Science (WOS) database regarding sustainable design and relevant systems. Although some scholars have conducted bibliometric analyses and literature reviews considering WOS-based data samples on sustainable product design and production systems [8,9], the latest analysis of sustainable product design tools was performed in 2017 [10], failing to present the overall progress in SPDM research in China and around the world. Thirdly, existing review research has mainly focused on the impact of SPDMs on the environment, with little comprehensive analysis of the current status, focused topics, and dynamic evolving trends in design methods that influence environmental, socio-economic, and cultural sustainability.

In response to the above-highlighted challenges, this paper adopts a bibliometric analysis approach to visually analyze the SPDM literature from the WOS and CNKI databases over the past 24 years (1999–2022). This approach systematically explores the current status, focused topics, and research trends in China and around the world on product design methods that respond to multiple sustainability challenges. Moreover, this analysis identifies differences in research between China and other regions, providing a reference for future theoretical and practical research in sustainable design.

2. Methods and Data Sources

We used CiteSpace, a type of visualization software developed by Professor Chen Chaomei at Drexel University, to carry out a metric analysis of the scientific literature and visualize the knowledge structures [11]. The collaboration network and co-occurrence network modules in CiteSpace 5.8. and R3 were employed to conduct a visual metric analysis of global research on SPDMs. By creating the maps of collaboration networks of authors, institutes, and countries and the co-occurrence, burstness, clustering, and timeline evolution maps of keywords, the research content, movement, and focused topics in this field were comprehensively and directly presented, and relevant research progress was sorted out, which will lay a foundation of the literature and provide a methodological reference for research and practice in this field.

The Chinese literature used in this paper was sampled from CNKI, with three categories of keywords, namely, (product OR product design) and (method OR methodology OR tool OR approach OR theory OR framework OR guideline) and (sustainable OR sustainability OR green OR ecological) as the query pattern. Moreover, the Chinese literature sampled was mainly published between 1 January 1999 and 18 July 2022 in the Chinese Social Sciences Citation Index (CSSCI), Chinese Science Citation Database (CSCD), EI, and A Guided to the Core Journals of China. The literature irrelevant to this research was excluded by the following standards: (a) product design works; (b) literature with incomplete information and paper solicitation information of periodicals and magazines; (c) papers and interview articles; and (d) articles irrelevant to this research (including articles containing sustainable product design information but not design methods). Finally, a total of 531 papers was adopted. The reference in WOS was mainly sourced from the core datasets of WOS, and the time range for literature sampling was the same as that for the Chinese literature. Additionally, the language of the articles and reviews to be sampled was English, and the theme of the query was "sustainable product design method". It was ensured that the inclusion and exclusion criteria were consistent across the two databases. After the literature data were cleaned and deduplicated in CiteSpace, a total of 829 pieces of literature was sampled. This process is summarized and illustrated in an adapted PRISMA flow diagram for systematic reviews (see Figure 1).

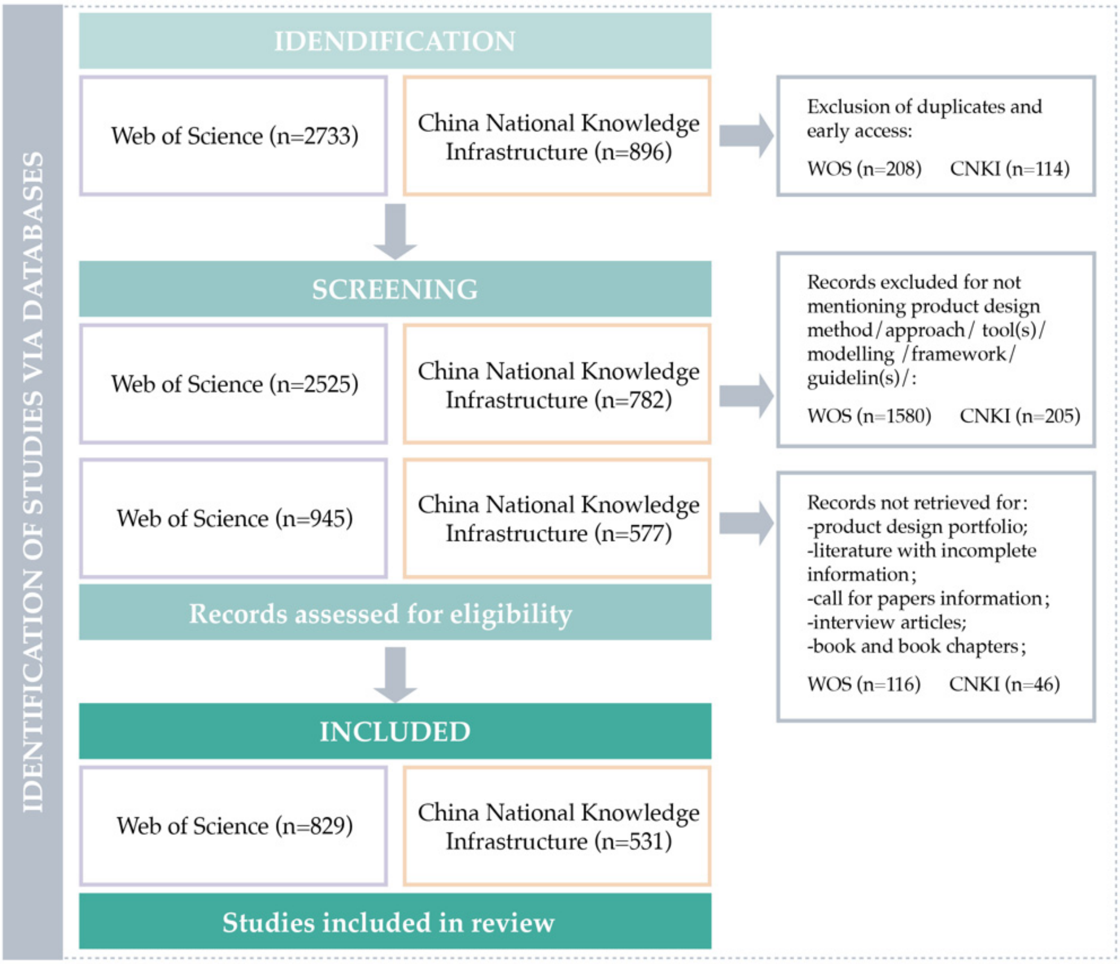


Figure 1. PRISMA flow diagram for systematic reviews.

3. Bibliometric Analysis

3.1. Analysis of Publication

3.1.1. Analysis of the Annual Number of Papers Published

A statistical graph of the number of papers published can present the dynamic evolving process of research in this field. According to the distribution and linear prediction of the publication year of the literature on SPDMs from WOS and CNKI (Figure 2), the annual number of both China and the rest of the word published in these years has leapt forward and can be divided into three phases. In the first phase, the number of annual publications in the two databases is similar between 1999 and 2007, averaging approximately eight every year, which is a preliminary exploration into this field. Then, between 2008 and 2014, this field witnessed rapid development and promotion. Accordingly, the annual number of worldwide publications increased dramatically, with the increase of the number of published papers in the WOS database being significantly higher than that of the CNKI. Statistically, the average annual number of CNKI and WOS paper s published during this period reached 21 and 32, respectively. Nevertheless, the annual number of papers published in this phase fluctuated significantly. In 2009, Ezio Manzini at the Polytechnic University of Milan established the "Design for Social Innovation and Sustainability Network (DESIS Network)" [12], which drives international cooperation and global promotion concerning research in this field. In the third phase, driven by the 17 sustainable development goals of the UN since 2015, the number of publications in these two databases has increased rapidly. Moreover, the number of WOS publications peaked in 2020, reaching 82, which surpassed the entire number of publications in these two databases in the first phase. Concurrently, the number of articles published gained constant and rapid growth in China. In December 2016, the State Council introduced the *Program for the Promotion of Extended Producer Responsibility System*, which specified that "the producer responsibility in resource consumption and environmental protection should be extended to product design [13]". Since then, the number of publications has soared in the CNKI database. In 2021, 66 references were published in CNKI, approximately eight times as many as the average annual number of papers published during the first phase. Overall, the research in this field both in China and the rest of the world is rich in content and plentiful in achievements, showing a booming trend.

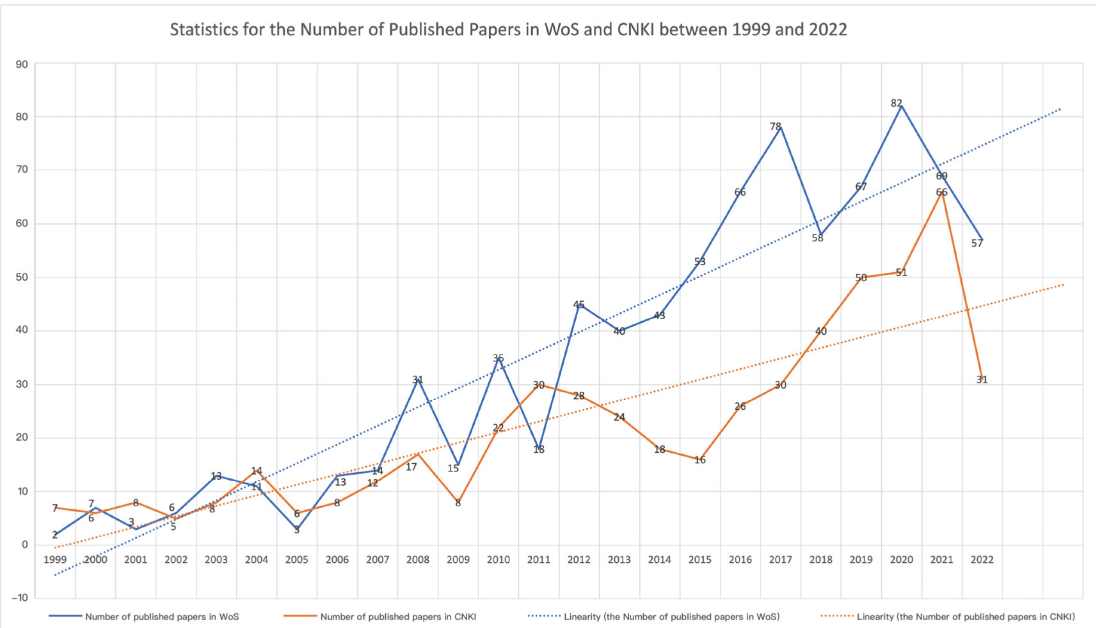
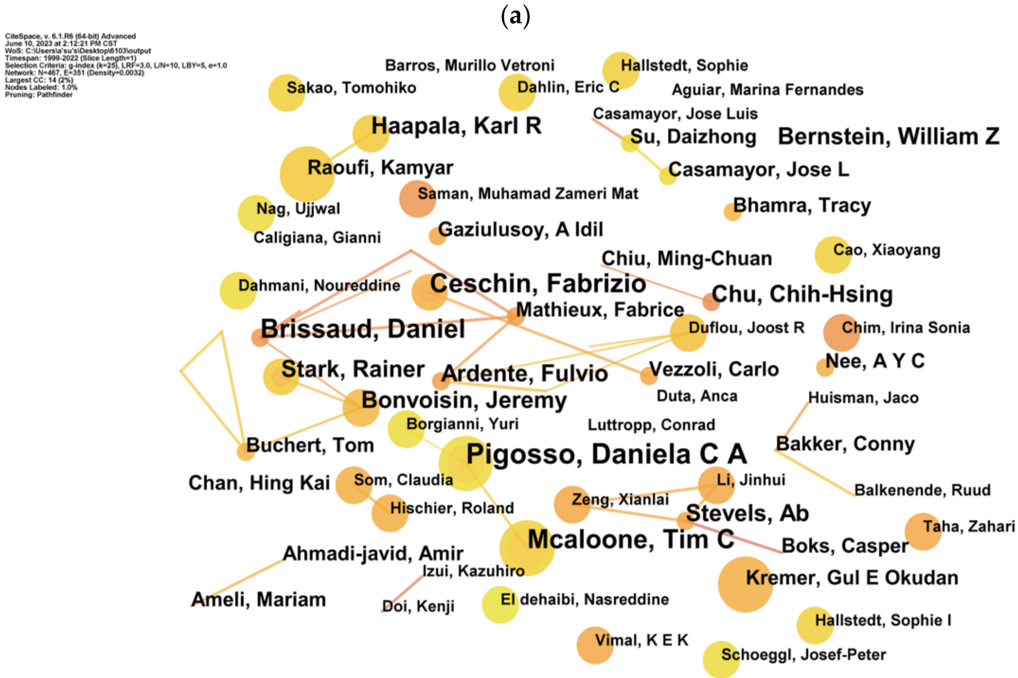


Figure 2. Distribution and linear prediction of the publication year of literature on SPDMs from WOS and CNKI.

3.1.2. Analysis of Author Collaboration Network Map

The author co-occurrence module in CiteSpace was used to create the author collaboration network maps (Figure 3) of these two databases, respectively. On the map, the nodes represent the number of published papers of authors, and the lines connecting the nodes imply the collaboration among authors. Moreover, the thickness of the lines means the degree of the collaboration, and the color indicates the time of the collaboration.

(**a**)



(**b**)

Figure 3. (**a**) Network map of collaboration among authors in CNKI. (**b**) Network map of collaboration among authors in WOS.

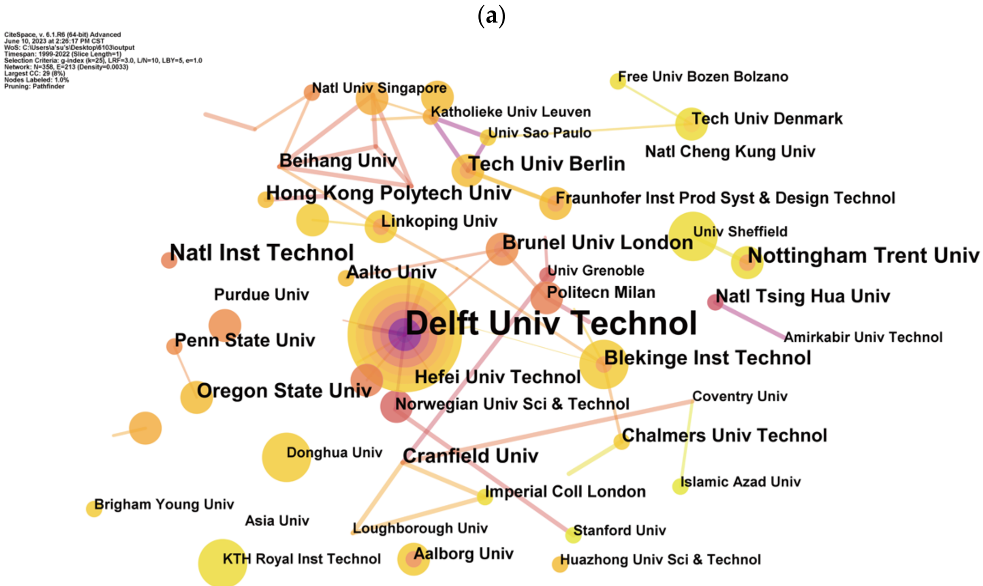
Among the collaboration networks of Chinese scholars, five were quite distinct (Figure 3a). The largest author base formed through the connection between the new collaboration network with Ji Tie at the core and the sub-network led by He Renke; the author base consisting of Zhou Daowei, Sun Gang, and Sheng Lianxi, who started their research earlier; the author base led by Yu Dongjiu, whose node is the biggest; and the author base consisting of Yu Senlin, Liu Xin, and Xia Nan, whose nodes are connected by only one line, indicating that though they have had quite a few published papers, the collaboration network is not formed, and the collaboration among them is not deep. There are many separate units on the map that are not connected by networks, implying that cross-unit, multidisciplinary collaboration is required for Chinese research in this sector. Scholars from the WOS database outperform CNKI scholars in terms of the number of collaboration networks. Moreover, the collaboration networks of scholars in WOS are distributed rather than centralized (Figure 3b). The author base led by Brissaud Daniel and Fabrizio Ceschin connecting nine nodes is the largest, followed by the author network with Stevels Ab at the core, and then the collaboration networks led by McAloone Tim C. and Pigosso Daniela, respectively. Except for the networks mentioned above, networks on the map connect mainly two or three nodes, indicating that despite the deep intra-base collaboration, the linkage among networks remains to be strengthened and that no large, stable author base has been formed.

Further investigation reveals that there are five scholars who have more than six publications, namely, Yu Dongjiu (15), Yu Senlin (10), Liu Xin (8), Karl Haapala (8), McAloone Tim C. (8), Pigosso Daniela (7), and Daniel Brissaud (7). Yu Dongjiu explored the application of strategies and methods for social value-oriented sustainable innovation [14] and design to the design of elderly-oriented [15] and children-oriented products [16]. Yu Senlin proposed that the focus of the methods for the innovation of sustainable product design should be extended from production to consumption, from physical products to product-service systems, and from material culture to spiritual culture [17]. Liu Xin emphasized the understanding of the sustainable design for products and services from a systematic perspective [18] and proposed creating a sustainable design assessment system based on Chinese conditions [19,20] and developing teaching tools for sustainable design of the product–service system. Karl Haapala focused on the relationship between product design and sustainable manufacturing [21] and developed a method for assessing the environmental factors behind the product design and manufacturing based on the life cycle approach [22,23] as well as a modeling method [24] that would facilitate decision-making regarding sustainable design. McAloone Tim C. and Pigosso Daniela have a tight close collaborative relationship regarding the development and implementation of multiple ecodesign tools and methods [25,26] to measure sustainability performance in product development [27], such as the ecodesign maturity model [28,29], guidelines for evaluating the environmental performance through life cycle assessment [30], and a generic process model for the early stages [31]. Daniel Brissaud, from the perspective of remanufacturing, brought forward the sustainable design method and practice [32] for redesigning products and developing new products, the product cycling strategy [33], and the multi-criteria assessment method [34] that take into consideration technological, economic, environmental, business, and social factors, and the method for the transformation [35] toward and creation [36] of a design value-driven and sustainable industrial product–service system. By Price's Law, authors with at least three papers published in this field can be defined as core authors, and when the total number of published papers of core authors represents 50% of the total number of papers in this field [37], a core author base is formed. According to the available statistics, there are 17 core authors in the CNKI database and 46 core researchers in the WOS database, and the total number of their published papers represents 17.1% (91) and 21.4% (177) of the total, respectively, neither of which has reached 50% of the total number of sampled papers published in this field. Therefore, no core author base has been formed in this field. Moreover, compared to Chinese authors, researchers contributing to WOS are more willing to carry out research through collaboration. Overall, worldwide research on this issue demonstrates the characteristics of a large number of researchers, scattered cooperative relations, and a lack of connectivity.

3.1.3. Analysis of the Academic Influence of Institutes with Papers Published

The Institution module in CiteSpace was used to illustrate the institutions that contributed to the research, and the institutions with no fewer than three published papers on this research are marked (with the threshold value being three) in Figure 4. Moreover, the top 10 institutes in China and around the world by the number of published collaborations are summarized (see Table 1). According to Table 1, the top 10 research institutes in China and around the world are dominated by universities, indicating that universities are the mainstay of global research on SPDMs. Nonetheless, the centrality values of universities are zero, which means no core team has been formed in this field worldwide.

(**a**)



(**b**)

Figure 4. (**a**) Network map of collaboration among institutes with published papers in CNKI. (**b**) Network map of collaboration among institutes with published papers in WOS.

Table 1. Summaries of the top 10 global institutes by the number of published papers.

Number	Institute	Number of Published Papers	Centrality	Publication Year of the First Paper
a. CNKI Database				
1	School of Art and Design, Guangdong University of Technology	21	0	2014
2	Academy of Arts and Design, Tsinghua University	17	0	2003
3	School of Design, Hunan University	16	0	2004
4	School of Design, Jiangnan University	15	0	2002
5	School of Art and Design, Wuhan University of Technology	11	0	2008
6	School of Art and Design, Nanjing University of Technology	10	0	2011
7	School of Arts, Nanchang University	10	0	2001
8	School of Art and Design, Hubei University of Technology	9	0	2016
9	School of Fashion, Beijing Institute of Fashion Technology	7	0	2019
10	College of Furniture and Industrial Design, Nanjing Forestry University	6	0	2016
b. WOS Database				
Number	**Institute**	**Number of Published Papers**	**Centrality**	**Publication Year of the First Paper**
1	Delft University of Technology (the Netherlands)	28	0.01	2001
2	Oregon State University (the US)	13	0	2012
3	Polytechnic University of Milan (Italy)	10	0	2010
4	Technical University of Berlin (Germany)	9	0	2008
5	Pennsylvania State University (the US)	8	0	2012
6	Blekinge Institute of Technology (Sweden)	8	0.01	2017
7	Hefei University of Technology (China)	7	0	2004
8	Brunel University London (Britain)	7	0	2014
9	National Cheng Kung University (Taiwan, China)	6	0	2003
10	Imperial College London (Britain)	6	0	2017

In terms of the number of published papers in Chinese institutes, as shown in Table 1 (a), the School of Art and Design, Guangdong University of Technology tops the table with 21 published papers. The school has designed green design-oriented curricula for undergraduates, such as Sustainable Design Overview, Methods for Sustainable Innovation, and Upcycling-Based Low-Carbon Design. The Academy of Arts and Design, Tsinghua University; the School of Design, Hunan University; the School of Design, Jiangnan University; and School of Art and Design, Wuhan University of Technology rank second, third, fourth, and fifth in the table, respectively. They have jointly established a core team, which developed the Learning Network on Sustainability-China (LeNS-China) in 2011. So far, 19 Chinese universities and research institutes have joined LeNS-China [38] to increase local awareness, information and resource exchange, and practical engagement around sustainable design.

Figure 4a is a map of the distribution of and collaboration among Chinese research institutes with 398 nodes, 148 lines, and a network density of 0.0019. According to the map, a total of 398 Chinese organizations conducted research on SPDMs between 1999 and 2022, during which the institutions collaborated with each other 148 times. Nevertheless, the collaboration network map also indicates that no clustering phenomenon has been formed in the Chinese sustainable product design field. Although a large inter-university collaboration network led by the School of Art and Design, Guangdong University of Technology; the Academy of Arts and Design, Tsinghua University; the School of Design, Hunan University;

and the School of Art and Design, Nanjing University of Technology has been created to explore the methods for designing a sustainable product-service system, develop relevant tools, and disseminate relevant knowledge, it has only a few light-colored lines, implying that the universities have not carried out frequent, long-term, and in-depth collaboration. Moreover, the Academy of Arts and Design, Tsinghua University; the School of Fashion, Beijing Institute of Fashion Technology; and the School of Mechanical Engineering, Beijing University of Science and Technology have jointly established a small, regional network and proposed strategies for sustainable design by learning from nature [39] and sustainable design approaches for culturally innovative products [40]. Moreover, an intra-university collaboration has been formed between the College of Furniture and Industrial Design and the College of Art and Design, Nanjing Forestry University, to propose a coupled approach for furniture and product packaging design based on sustainable use [41]. In addition to the above-mentioned collaboration networks, few networks have been created among other institutes, so the institutes are not obviously linked to each other. Moreover, as research is dominated by universities, there is much room for improving academic collaboration and exchange among research institutes in this field.

In terms of the number of published works of institutes from the WOS database, as shown in Table 1 (b), the Delft University of Technology in the Netherlands leads its peers with 19 published papers. Moreover, the Faculty of Industrial Design Engineering at Delft has made sustainability its top three design research topics. As a classic in the design research field, the *Delft Design Guide: Design Strategies and Methods*, published in 2013, has systematically clarified the design methods for products and other design-related fields. Oregon State University comes second in the table with 13 papers published, most of which are contributed by its College of Engineering and focus on the development of quantitative and modeling methods for sustainable product design and manufacturing. Polytechnic University of Milan in Italy ranks third with ten published papers, all from its School of Design. The Lab of Sustainable Design and Systems Innovation (Polimi-DiS) in 2002, the Learning Network on Sustainability (LeNS) in 2007, and the international Learning Network on Sustainability (LeNSin) [42] in 2015, which were all launched by the School of Design, have led 155 universities and institutes in Europe, Asia, Africa, and South America to participate in sustainable design-related research and practice, delivering a range of cases, methods, and tools about sustainable product design. Among the top 10 institutes in WOS by the number of published papers, 2 are from the US; 2 are from Britain; 1 each are from the Netherlands, Italy, Germany, and Sweden; and the remaining 2 are from China, namely, the Hefei University of Technology and the National Cheng Kung University, with seven and six published papers, respectively. Moreover, only the research carried out by the two Chinese universities was later than that by the Delft University of Technology.

On the collaboration network map of research institutes in WOS database (Figure 4b), there is a total of 411 institutes and 202 lines, and the network density is 0.0024. Among the networks, five are quite distinct. Specifically, there is a European university collaboration group consisting of only universities, including the Delft University of Technology, Polytechnic University of Milan, Blekinge Institute of Technology in Sweden, Brunel University London, Aalto University in Finland, and the Chalmers University of Technology in Sweden. Moreover, Imperial College London, Loughborough University, Cranfield University, and Coventry University have formed a British university collaboration network. Additionally, American universities, including Pennsylvania State University and Oregon State University, have jointly built a US collaboration group. There are another two research institute–university collaboration networks. One consists of the University of California, Berkeley; the National Institute of Standards and Technology; and the Indian Institute of Science; and the other comprises the Technical University of Berlin in Germany, KU Leuven in Belgium, and Fraunhofer Institute for Production Systems and Design Technology in Germany. Except for the above-mentioned collaboration networks, there are 12 distributed small collaboration teams, displaying the “overall dispersion and small concentration" feature that characterizes the institutes contributing to WOS that have been exploring SPDMs.

3.1.4. Analysis of the Distribution of Institutes in WOS by Country and Region and of Collaboration Networks

In the country co-occurrence map (Figure 5), there are 66 countries and regions, and they have collaborated 189 times. Moreover, the network density is 0.0881. Specifically, 14 countries and regions have at least 20 published papers. Table 2 is a ranking of the top 10 countries by the number of published papers, in which China (156 published papers) ranks first, followed by the US (124), Britain (80), and then Germany (57) and Taiwan, China (51). Although China has the most published papers, it comes fifth in terms of betweenness centrality (0.13). This indicates that even though China is internationally active in SPDMs, its academic influence remains to be improved. The US (0.53) and Britain (0.24) feature high centrality, indicating that their international academic influence is significant, so they serve as a medium and propel this field forward.

Figure 5. Network map of collaboration among countries in WOS.

Table 2. Summary of top 10 countries in WOS by the number of published papers.

Number	Country	Number of Published Papers	Centrality	Publication Year of the First Paper
1	China	156	0.13	2000
2	The US	124	0.53	1999
3	Britain	80	0.24	2000
4	Germany	57	0.09	1999
5	Italy	48	0.17	2003
6	Taiwan (China)	46	0.15	2008
7	India	36	0.09	2010
8	Brazil	30	0.01	2006
9	Sweden	30	0.06	2003
10	France	29	0.07	2007

3.2. Analysis of Research Trends and Frontiers

3.2.1. Analysis of Research Evolution Process

The temporal knowledge evolution process on SPDMs can be described as three-phase by the timeline map generated in CiteSpace's Keyword Co-occurrence Module. The horizontal axis of Figure 6 is the timeline, which is divided into multiple 1-year slices. Each slice indicates the keywords of the year, and the size of the keyword node is in direct proportion to each keyword's appearance frequency. However, the importance of the nodes in the research depends on the centrality. The higher the centrality value, the more important the nodes are. Keywords with high centrality values of no less than 0.1 represent the focused research issues in the field to some extent [43]. After the three subject terms for retrieval are excluded, in the CNKI database, "TRIZ (theory of inventive problem solving) (0.35)" is the supporting point of the keyword network and the main focused research issue concerning SPDMs, followed by "life cycle (0.34)", "innovative design (0.23)", "mechanical product (0.19)", "sharing economy (0.18)", "redesign (0.12)", "green manufacturing (0.11)", and "QFDE (0.11)", which play significant liaison and transition roles in the entire network. Specifically, keywords including "green design", "green product", and "environment" are the focused research issues appearing in the early stage, and the focus of research in recent years has shifted to "sustainable", "sharing economy", and "service design". Over the years, the focused research issues have changed significantly. The focused issues in the WOS database emphasize factors such as "environmental impact (0.19)", "barrier (0.17)", "consumption (0.16)", and "cost (0.15)" in the process of design of sustainable products, as well as the "integration (0.13)" methods employed, design "framework (0.12)" supporting sustainable strategies, the "QFD (0.11)" method, and the "LCA (0.10)" method. "Environment" is the earliest, followed by "ecodesign tool", and then "strategy", "sustainability", and "implementation".

The first phase, spanning from 1999 to 2007, is foundational for Chinese research on SPDMs. In this phase, keywords such as green design, product design, product packaging, green manufacturing, mechanical products, TRIZ, life cycle, and material selection were spawned. Research in the product design field back then mainly adhered to the green design methods and green manufacturing philosophy and focused on the R&D of green mechanical products, green mechatronic products, and green industrial products. Moreover, Chinese research between 1999 and 2007 paid attention to the environmental impacts and evaluation of the materials, structures, and functions of products, which has been a fundamental issue, namely, how to understand and cope with the influences of product design on the environment, facing the product design field since the theory of sustainable development was introduced into this field in 1987 [1].

Moreover, a review of the results of the WOS database shows that other regions of the world are also in their infancy in terms of academic research in this sector. It mainly concentrated on the analysis of environmental impacts, product performance, green product management, life cycle, and the efficiency and feasibility of product dismantling. Moreover, QFD and AHP began to be used in sustainable product design, and exploration into the tools used to support design decisions commenced.

The second phase, which lasted from 2008 to 2014, witnessed the rapid development of research interest in this field in China. In this phase, keywords such as service design, sharing economy, emotional experience, bionic design, and forms emerged. In terms of design objects, scholars paid more attention to the application of sustainable design methods in the design of shared products, furniture, children-oriented furniture, and tourism products. In terms of methodological innovation, Chinese scholars started their research from the perspectives of emotional factors, user experience, bionic appearance [44], and user-friendliness. On the other, they combined service design methods and SPDMs and explored sustainable product-service design. Nevertheless, the advancement of the rest of the world in this regard during this period was explosive. Specifically, high-frequency keywords constantly emerged and were densely connected, and focused research issues such as the LCA of products, product design, system, model, design framework, ecodesign, optimization, design decision, integration, material selection, and innovation kept emerging, deepening the research and broadening the themes.

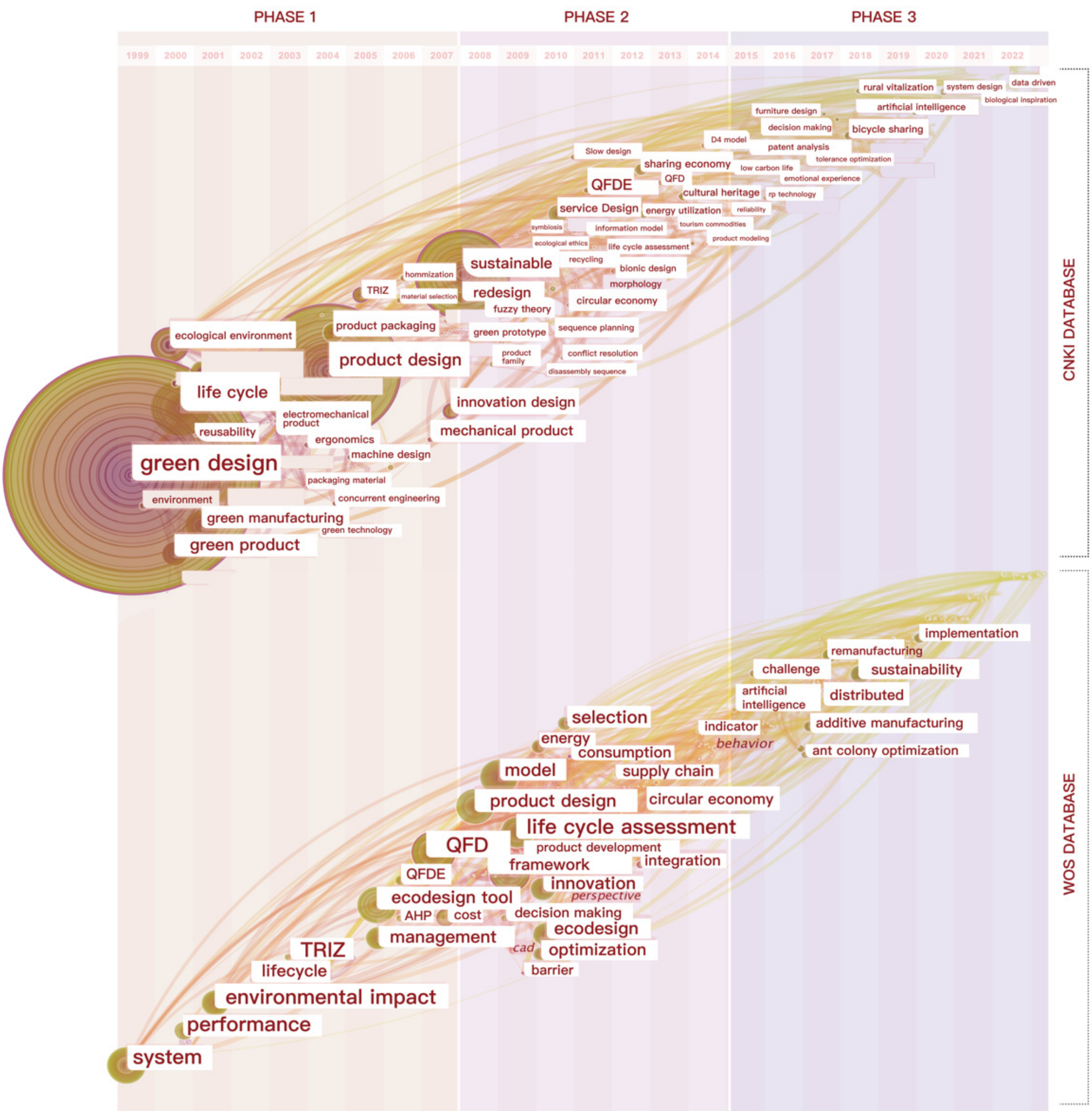


Figure 6. Keyword timeline map of research on SPDMs in CNKI and WOS databases.

Drawing on the cost–benefit analysis method after 2007, scholars developed the LCC method, improving the role of economic factors in SPDMs. Moreover, driven by the guide to the evaluation of social methods formulated by the UN Environment Program in 2009, keywords from both CNKI and WOS in the second phase demonstrated the rapid development and application of SPDMs in the economic and social dimensions. The design optimization of energy-saving products, shared products, and small household equipment, which are expected to achieve economic and social sustainability benefits in low and middle-income areas, was widely discussed.

The third phase, since 2015, is the booming period of Chinese research on SPDMs, during which the number of articles published gradually recovered. In this phase, the emerging research subjects in the second phase were explored in depth and thoroughly. China has been prioritizing the role of cultural confidence in developing a strong socialist culture since the 18th National Congress of the Communist of China. Accordingly, research on SPDMs laid great emphasis on carrying forward intangible cultural heritage and designing cultural and creative products. How to better incorporate cultural elements into sustainable product innovation became one of the principal research issues in this phase, and culture was introduced into SPDMs. Moreover, keywords including rural revitalization, system design, AI, data-driven, and bio-inspired emerged.

Research outputs available in WOS after 2015 appeared in the form of small and numerous nodes, and the number of publications rose significantly. This indicated that research in this phase was scattered and diversified and was in the phase of stable and deepening development. In this period, new, targeted hot topics such as circular economy, distributed, sustainable indicator, innovation tools, AM, AI, remanufacturing, and ant colony optimization (ACO) were spawned, in addition to the in-depth practice and research on the research themes that emerged in the second phase. The construction of sustainability standards gradually improved in more subdivided categories of products in the innovation of sustainable products, and more and more health and medical products, wearable products, personalized devices, smart products, and complex products were studied to maintain both environmental and economic and social sustainability.

3.2.2. Analysis of Method Clustering and Research Trends

To systematize the identified methods and enable their analysis, a classification framework including five main categories was iteratively developed through previous literature reviews, and especially the additional categories of purpose were derived from an inductive content analysis. Figure 7 shows how the sub-classification dimensions are related to one another; the classification has a transversal emphasis that does not typecast procedures in only one category, and it offers a spectrum of possibilities. The cultural sustainability dimension is identified separately based on the literature content analysis of the CNKI and WOS databases, on the basis of three pillars of sustainability, to further clearly understand the development of different attitudes and design methods of Chinese and foreign scholars in achieving the goal of cultural sustainability development. Analyzing the development level and nature of data allows it to be evident how the method is employed, as well as to identify the purpose of the focus when proposing the method.

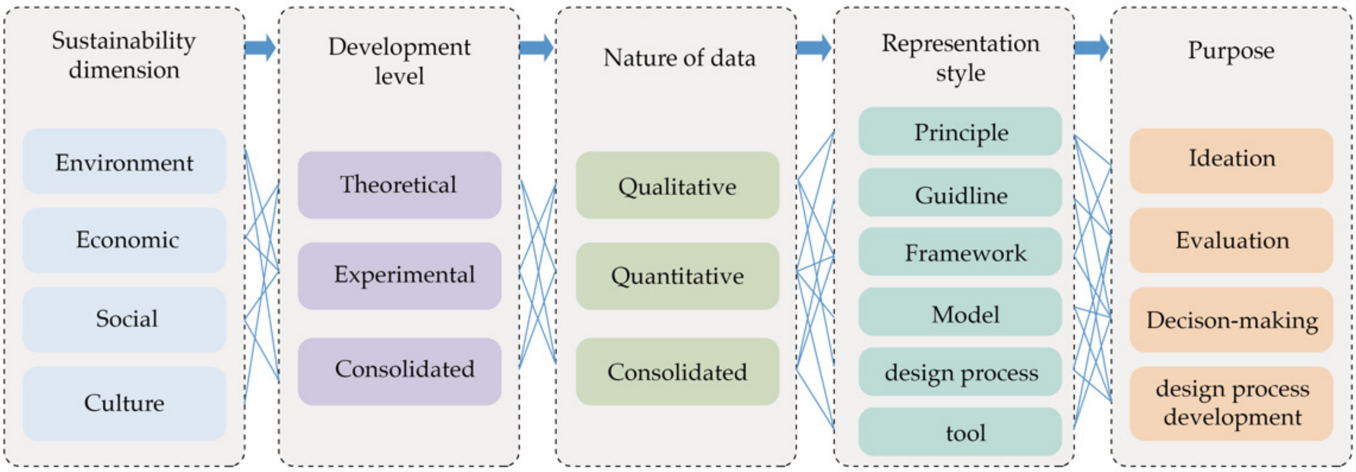


Figure 7. Framework for classifying data of methods (modified from Pigosso et al., 2011 [45], and Fernandes et al., 2020 [46]).

In particular, throughout the methodological analysis, the cases or specific product concerned are highlighted, which may enhance and optimize future design practice. The methods used in the articles were systematically reviewed according to the co-citation results of the literature and the keyword frequency and centrality. There are 79 representative methods from these two databases in total, which are listed and specified in Table 3.

Table 3. List of 79 representative sustainable product design methods based on the literature found in China National Knowledge Infrastructure and Web of Science databases between 1999 and 2022.

Sustainability Dimension	Representation Style	Methods	Development Level: Theoretical	Development Level: Experimental	Development Level: Consolidated	Nature of Data: Qualitative	Nature of Data: Quantitative	Nature of Data: Consolidated	Case/Example	Purpose: Ideation	Purpose: Evaluation	Purpose: Decision-Making	Purpose: Design Process Development	Time	Reference
Environment	principle	Principles and procedures for the eco-design	■			■			energy-using products	■				2009	[47]
		Ecological Packaging principle	■			■			energy-using products packaing	■				2013	[48]
	guideline	Ten Golden Rules			■	■			none	■	■			2006	[49]
		Environmentally conscious guidelines by combining reverse engineering with LCA			■			■	electric kettles	■			■	2010	[50]
		LCA guideline	■			■			digital products	■				2014	[51]
		bionic design method	■			■			sprinkling can	■				2014	[44]
		TRIZ-Based Guidelines for Eco-Improvement			■	■			mechanical ball	■	■			2020	[52]
		Sustainable design guidelines for additive manufacturing applications			■			■	none	■				2022	[53]
	framework	redesign method Based on Ecological Ethics	■			■			industrial product	■				2010	[54]
		An Integrated Approach for Eco-Design			■			■	LED Lighting	■	■	■	■	2020	[55]
	model	integration of ECQFD and LCA approaches				■			electronics switches			■	■	2010	[53]
		Ecodesign maturity model			■	■			eco-product				■	2013	[28]
		Resource Efficiency Assessment of Products method	■					■	liquid cristal display television		■			2014	[56]
		model of factors affecting environmental sustainability performance of PSS	■			■			ofo sharing bicycles	■	■			2019	[57]
		Green Product Optimization model Based on QFDE		■				■	mechatronic products/hobbing machine		■			2019	[58]
		F-MCDM			■		■		hot runner systems		■	■		2021	[59]
		life cycle impact assessment by openLCA		■			■		disposable face mask		■	■		2022	[60]
	tool	Fuzzy AHP and modularity analysis Method	■					■	discrete electromechanical product			■		2000	[61]
		comprehensive and simplified indexes developed based on a life cycle approach			■		■		energy-using products/washing machine	■	■	■		2014	[62]
		decision tables of green design knowledges by rough sets			■		■		mechanical product	■		■		2019	[63]
		PEP indicator			■		■		smartphones	■		■		2020	[64]
Environment-Economic	principle	TRIZ and case-based reasoning principles			■			■	dishwasher		■	■		2012	[65]
		design guidelines to meet the circular economy principles			■			■	small household electronic equipment	■	■	■		2018	[66]
		principles of 5R Based on the Fractal Structure	■			■			packaging	■				2018	[67]
		9R principles	■			■			none	■				2019	[68]
	guideline	guidelines based on Concept-Knowledge design theory supporting			■	■			automotive	■	■	■		2009	[69]
		design strategies for product life extension			■			■	electric and electronic products	■	■			2014	[70]
		ETRIZ matrix that compiled existing guidelines for remanufacturing and AM			■			■	remanufacturing product	■	■			2021	[71]
	framework	A framework of integration of LCA and LCC			■		■		diesel engine		■			2008	[72]
		a conceptual framework to assess energy consumption			■			■	mechanical part		■			2013	[73]
		A design framework for sustainable PSS customization			■			■	elevator	■			■	2017	[74]
		systematic methodology for data-driven product family green redesign	■			■			product family	■	■			2020	[75]
		7 Rs sustainable packaging framework			■	■			packaging	■				2022	[76]
	model	novel design methods of "Design for Energy Minimisation" approach							simple part/an elbow pipe	■	■	■		2010	[77]
		a mathematic energy model based systematic approach			■		■		energy-saving product/commercial blender			■		2010	[78]
		QFDE and Modular design			■			■	indoor air conditioner	■	■			2013	[79]
		innovative model Integration of ECQFD, TRIZ, and AHP			■			■	automotive parts	■		■		2014	[80]
		Integration of green quality function deployment and fuzzy theory			■			■	green mobile phone			■		2015	[81]
		a comprehensive evaluation model of LCC and environmental impacts based AHP			■			■	automotive door		■			2015	[82]

Table 3. *Cont.*

Sustainability Dimension	Representation Style	Methods	Development Level			Nature of Data			Case/Example	Purpose				Time	Reference
			Theoretical	Experimental	Consolidated	Qualitative	Quantitative	Consolidated		Ideation	Evaluation	Decision-Making	Design Process Development		
Environment-Economic		a hybrid optimizing method named chaos quantum group leader algorithm			■		■		drive device		■	■		2016	[83]
		an energy flow modelling approach based on Characteristics-Properties Modelling			■			■	hair dryer		■		■	2016	[84]
		QFD and Case-based Reasoning	■				■		air conditioner			■		2018	[85]
		AHP and Grey Relational Analysis Approaches			■		■		none			■		2019	[86]
		energy-aware digital twin model	■				■		energy-saving product			■		2020	[87]
		LCA and modular design			■	■			stroller	■				2020	[88]
		a user requirements-oriented method integrated fusing Kano, QFD and FAST			■			■	baby stroller	■		■		2020	[89]
	design process	process of sustainable product design based on QFDE			■			■	water purifier				■	2017	[90]
		design process based on TRIZ and lca analysis	■			■			furniture				■	2018	[91]
	tool	remanufacturable product profiles			■			■	remanufacturable product	■	■	■		2008	[32]
		Product design scenarios for ESFPs	■			■			energy-saving fashion products	■			■	2013	[92]
		concept circularity evaluation tool (CCET)			■			■	furniture/trampolines/ergonomic mobility aids/plastic components	■	■	■	■	2020	[93]
Environment-Economic-Social	principle	Design Principles of Resource Recycling Concept	■			■			sharing bicycles	■				2020	[94]
		Sustainable Design Strategy for Creative Products in Cultural Consumption			■	■			cultural and creative products	■				2022	[95]
	guidline	comprehensive scenario of sustainable dimensions	■			■			packaging	■				2015	[96]
		new classification system of PSS applied to Distributed Renewable Energy	■			■			energy product-service system	■	■			2016	[97]
		Evaluation Criteria of Design for Sustainability			■			■	sustainable living Lab		■			2017	[20]
		desgin theory base on Ecological Philosophical	■			■			furniture	■				2017	[98]
		guidelines for evaluating the environmental performance through life cycle assessment			■			■	bike-sharing system/lawnmower PSS/hull cleaning PSS	■	■	■		2018	[30]
	framework	Design directions to the empowerment of end users to become co-providers	■			■			smart energy system	■				2013	[99]
		system design method based on semiotics	■			■			furniture	■				2013	[100]
		A framework of a life-cycle focused sustainable new product development	■			■			none		■		■	2015	[101]
		a comprehensive set of process-related key performance indicators	■					■	none	■	■	■		2016	[27]
		4D system of product sustainable design	■			■			none	■				2020	[102]
		PSS model analysis		■		■			children's learning desk	■				2021	[103]
		framework Data-driven sustainable design		■		■			none	■			■	2021	[104]
		A trade-off navigation framework			■			■	furniture	■	■	■		2021	[105]
	model	fuzzy inference approach for evaluating sustainability			■			■	electrical power generation		■			2013	[106]
		a sustainable platform based grey relational analysis/ bayesian network/ Fuzzy			■			■	coffee makers	■	■			2017	[107]
		a Decision flow chart for bio-based products designed to be recirculated	■			■			bio-based products				■	2017	[108]
		Additive manufacturing/3D printing			■	■			automotive components	■	■			2022	[109]
	design process	design strategy based on LCA	■			■			intangible cultural heritage product	■			■	2020	[110]
		a generic process model	■			■			none	■			■	2023	[31]
	tool	Sustainable design-oriented product modularity combined with 6R concept			■			■	rotor laboratory bench	■	■	■		2014	[111]
		A Metrics-Based Methodology for Establishing Product Sustainability Index	■					■	electronics component		■	■		2014	[112]
		The Checklist for Sustainable Product development			■	■			automotive	■	■	■		2017	[113]
		a social impact checklist table			■			■	corrugated cardboard	■	■	■		2020	[114]
		an AHP-based ELECTRE I method			■			■	furniture		■	■		2021	[115]
		an Open-Source Tool for Social Impacts Assessment			■		■		none	■	■	■		2022	[116]
		product sustainability assessment tool (PSAT)			■			■	wind turbine generator	■	■	■		2023	[117]

In summary, sustainability in the environmental and economic dimensions shows the characteristics of easy measurement of quantitative data and mature application of methods, which have been widely implemented in a large number of practical cases. For example, a typical hair dryer is used to demonstrate the systematic approach via energy flow modelling to reduce epistemic uncertainty in the design process in the early stages of a design [84], lowering the managing complexity for designers. Duran et al., proposed a new sustainability index, namely, "potential embedded power (PEP)", determining the influences of product disposal on the product design life. By doing so, the environmental impacts of resource waste resulting from design decisions can be evaluated [64]. However, the impact of environmental sustainability is frequently associated with economic sustainability indicators, for instance, products with higher energy efficiency are better for the environment. Diverse design approaches help lessen the drawbacks of existing products' energy intensity and help achieve the objective of energy conservation and emission reduction (ESER). Ardente and Mathieux presented the Resource Efficiency Assessment of Products method for liquid crystal display televisions [56] and introduced a general index and a simplified index tested for the environmental assessment of durability of energy-using products, such as washing machines [62]. However, the contradictions and trade-offs between the impacts of environmental and economic sustainability will hinder designers from producing more sustainable solutions; certain design principles can help investigate how a product may be both economical and environmentally friendly through creative design, for example, guidelines based on Concept–Knowledge design theory [69]; enhanced TRIZ matrix [71] support solving the contradiction between environmental and economic factors; principles of sustainable energy-saving fashion products [92]; design strategies for product life extension of electric and electronic products [70]; and a conceptual framework to aid in the derivation of realistic energy consumption values from a product design perspective, allowing for an improvement of product manufacturing energy efficiency at both design and manufacturing stages [73]. Bovea and Pérez-Belis identified design guidelines for small household electrical and electronic equipment that allow for an improved product design from a circular economy perspective and convert it into a circular product design [66].

The analysis of social sustainability is mostly manifested by qualitative guidelines in the early stages of product development and design, such as eco-philosophical ideas [98], modular analysis [118], data-driven sustainable design frameworks [104], packaging design dimensions [96], principles of resource recycling design [94], and systematic frameworks for children's product [119]. The toolkit involved 15 archetypal models of PSS applied to distributed renewable energy [97] that were created to support innovative design in the energy sector while taking into account environmental, economic, and social benefits. Furthermore, methods covering quantitative and qualitative questionnaires have been gradually implemented recently, such as the checklist tool of PSAT [117], a checklist table involving eleven social impact categories [112] and tested in the automotive industry [113]. In general, social sustainability is linked to how the system benefits customers [107], with customer rights and satisfaction as essential measures that may have a beneficial impact on social sustainability. Three design directions are suggested in regard to the empowerment of end users to become co-providers as an addition to complement the ongoing development of products and services in smart grid deployment [99]. The product sustainability index (ProdSI) [114] was used to evaluate the quantitative sustainability indices of the environment, economy, and society at the product design and manufacturing stages. However, social sustainability is primarily measured by employee-related indicators such as working conditions, health, safety, training, and education [120], and applications measuring social sustainability performance in the context of various products and industrial manufacturing lack consistency [121]. For example, Kim selected the easily measurable indicator of toxic substances to represent worker health status in measuring the social sustainability of coffee machines [104], and Shin selected sedentary behavior and physical activity to analyze human-powered products [105]. Simultaneously, uncertainty of what data to utilize for social sustainability assessment and data quality [122] adds to the complexity of sustainable product design, evaluation, and decision-making. Although social sustainability indicators have been enriched and expanded in different fields and applications in recent years, such as green buildings [123] and food supply-chains [124], there is still a lack of clear definition of quantitative indicators that can be used to perform social sustainability assessment [125].

Achieving cultural sustainability is an important goal of product design. Among CNKI scholars, cultural sustainability is seen as a crucial fourth perspective for assessing product sustainability in order to support the sustainable design of intangible cultural heritage. Mou et al. analyzed the path to sustainable development of Chinese intangible cultural heritage with the life cycle method [110] and held that the incorporation of cultural factors was critical to improvements in the sustainability of intangible cultural heritage brands. Zhou proposed the 4D systematic view of sustainable product design [102], which consisted of load reduction design, persuasive design, fair design, and cultural and creative design. In recent years, China has seen a significant increase in research and practice on the cultural sustainability of product design as a response to how to shift from "going global culturally" to "cultural confidence" in the face of the contradiction between endemicity and globalization [126]. Design can serve as a vehicle and means of achieving cultural sustainability. Through design works, it can dynamically, specifically, and sustainably carry forward and internationally promote excellent traditional Chinese cultures and intangible cultural heritage, aiding in China's progress toward the establishment of a socialist culture. However, the literatures included in WOS demonstrate that the cultural sustainability dimension tends to be regarded as a minor subset of the social dimension in the field of sustainable product design [8,127]. Although Moalosi et al. proposed a culture-oriented product design method [128], they did not extend it to sustainable design methods. Ji and Lin proposed six design strategies to improve the emotional durability and lead consumer behavior toward more sustainable use of products [129], but the impact of the design practice guided by such design strategies on the ecological environment is difficult to estimate precisely. Through the analysis of sustainable design models discussed in the literature between 2000 and 2009, Rocha et al. pointed out that research on the social sustainability of sustainable design was far behind that of environmental and economic sustainability [130]. After analyzing the policies for material cultural heritage utilization, regional development of culture, and participation in art performances, Sabatini argued that culture could be fully deemed the fourth pillar of sustainable development [131], on which, however, researchers in the field of product design have not reached a consensus.

Moreover, the proposing trends can be represented visually and can be seen in Figure 8; it shows the precision and depth of the methodological development in the vertical dimension, suggesting a more accurate consolidated approach for inspiring, detailing, evaluating, and optimizing sustainable solutions. It also shows the integration and extension of the method in the horizontal dimension, signaling broader implementation and multilateral efforts between academics and industry. SPDMs are also trending toward an increasingly systematic, open-source, and sharing approach.

SPDMs are becoming more systematic, as evidenced by the expansion and deepening of sustainable design standards, such as the expansion of environmental indicators [10]; 5R [67], 6R [111], 7R [76], and 9R [68] sustainability principles; guidelines such as the top 10 golden rules [49]; and a more perfect product design process [50,132]. On the other hand, it emphasizes multi-method integration. TRIZ [65], LCA [72], LCC [82], QFD [85], QFDE [79,90], ECQFD [53], fuzzy inference [106], AHP [61], the data packet network, KANO, gray relational analysis (GRA), MCDM, F-MCDM [59], and other quantitative methods are increasingly used. They can be used to aid in design comparison, function and structural optimization, material evaluation, and decision-making. To attain more accurate environmental, economic, and social sustainable benefits, it is essential to systematically develop and employ many of the strategies mentioned above concurrently. The integration of the QFD-based method into the KANO model and function analysis system technique could bring a more sustainable stroller design [89]. Applying the combination of ECQFD, TRIZ, and AHP in automotive parts design could lead to innovative and sustainable product design [80]. The incorporation of ECQFD into the fuzzy theory reduced the semantically subjective judgments on user demand at the product design stage [81], thereby making product design environmentally and economically sustainable. Considering environmental benefits and market value, Tan et al. used GRA and AHP [86] to optimize their decisions on the implementation of sustainable plans during the design of new products. Energy consumption is a key factor in the design of sustainable products [87], which necessitates the use of multiple strategies to calculate both environmental and economic benefits. The novel design methods of the "Design for Energy Minimization" approach [77], a systematic approach with an energy factor [78], and an energy-aware digital twin model [87] have been proposed to optimize energy-saving product design within entire product life cycles. Moreover, a hybrid optimizing method named chaos quantum group leader algorithm [83] is designed to obtain an optimal energy-consumption solution in designing products with various complexity, such as the drive device.

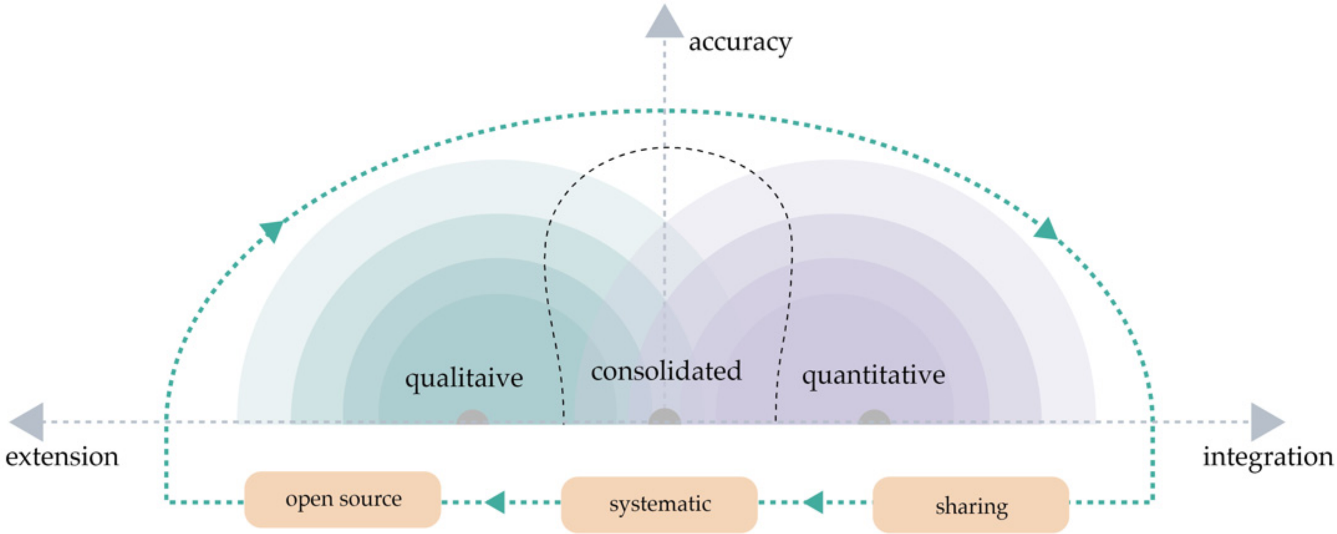


Figure 8. Graphic for proposing the trends of SPDMs.

Additionally, current research separates product sustainability evaluation and product design [5]. It is vital to develop holistic methods and tools that enable product design and sustainability evaluation simultaneously in an effort to produce more sustainable design concepts across the entire design stage. Covering a wide range and inconsistency of environmental, economic, and social sustainability assessment indicators is expected to be resolved by increasing accessibility and the sharing of methods and tools. Open data and open-source make it possible for anybody to freely duplicate research results, and the open-source philosophy holds that communities of study and practice should collaboratively construct and share tools rather than developing individual ad hoc scripts that produce incomparable indications [133]. For example, an open-source tool for social impact assessment [116] can be freely accessible to support open sharing with consistent data standards, allowing consistent measures to be produced and evaluated over time with little obstacles to participation. Simultaneously, collaboration between academics and industry is encouraged to promote the development and application of consistent indicators through multiple stakeholder participation.

In the hybrid design approach, the systematic framework that integrates multiple design tools and methods has positive significance in realizing interdisciplinary collaboration, developing holistic tools, and promoting the dialogue between designers and people from multiple industries. The systematic framework that incorporates various design tools and processes has an effective impact on realizing multidisciplinary collaboration, to generate holistic tools, and facilitate dialogue between designers and individuals from other industries. A customized design framework included ten various techniques and tools that were put to the test in elevator design [74]. Sherwood et al. presented a decision flow chart for bio-based products designed to be recirculated [108], promoting the rational circulation and utilization of biomass energy. The integrated product life cycle framework [101], comprehensive utilization of product life cycle management, LCA, social life cycle assessment (S-LCA), and LCC covering the environmental, economic, and social dimensions can realize more accurate and efficient design process management. Moreover, additive manufacturing (AM) has been increasingly leveraged to produce human-centered products in different fields to minimize material and energy spent to realize sustainability [134], such as sustainable automotive components [109], orthoses and prostheses, as well as therapeutic helmets, finger splints, and other personalized devices [135].

4. Conclusions

A bibliometric analysis of the SPDM literature indexed by CNKI and WOS from 1999 to 2022 reveals that Chinese academic interest in this field primarily focuses on TRIZ, green design, redesign, green products, sustainable philosophy, shared products, and service design. Additionally, numerous research issues and extensive themes reflect academic interest in this area. Articles indexed by WOS concentrate on environmental impacts, eco-design tools, sustainable barrier analysis, cost estimates, integration methods, QFD, and LCA. Furthermore, the centralized focused research hotspots and in-depth themes suggest a steady and advanced research stage in this field. However, SPDM research is marked by a constant expansion and enrichment of sustainable design principles, sustainability indices, and sustainable frameworks, with the integration of QFD, AHP, LCA, TRIZ, fuzzy inference, and MCDM. A single quantitative approach is no longer sufficient to adapt to increasingly complex and broadening sustainability indicators. As a result, researchers are using combined qualitative and quantitative analytic approaches and exploring how to incorporate more specific, readily quantifiable, and comprehensive sustainability indicators.

To facilitate more detailed, deep, and long-term research and provide methods and theoretical guidance for practice in the field of SPDMs, collaboration and communication between researchers and institutes in China and worldwide should be strengthened. Furthermore, researchers should widen their research subjects, construct more effective sustainability criteria, and investigate improved design approaches for various products. For example, a product design characteristic-oriented energy-accounting methodology could be developed to achieve more effective sustainability benefits, contributing to design improvement and the sustainable promotion of household and distributed energy products, such as distributed solar equipment, drip irrigation planting equipment, and water filter purifiers [136]. In the sector of health-oriented and medical care products, sustainable design guidelines and approaches have not received timely attention, and sustainable standards, methods, and design tools for diverse groups have not been successfully identified and tailored. Alfarisi et al. [60] offer a new perspective on a product's life cycle impact and highlight the nature of efforts to improve the eco-design of future facemask designs by analyzing the disposable facemask production process. Multidisciplinary and multi-stakeholder design approaches can be created and utilized to produce more systematic sustainability advantages. As the social and cultural sustainability of sustainable design methods is not well-proven, more attention should be paid to suggestions and conceptual frameworks proposed. Additionally, more quantified, practical, and standard design methods that enable sustainability across all dimensions will be needed in the future. For instance, design methods for developing culturally sustainable products based on design computation may provide designers with a new perspective. Finally, a broader and more diverse output of sustainable design solutions can be encouraged by enhancing the systematic, open-source, and sharing of design approaches in the promotion of SPDMs.

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