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REVIEW ARTICLE

Sustainable design for users: a literature review and bibliometric analysis

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Abstract

Due to the environmental impact associated with the products' use, sustainable design has extended consideration of products' production to consumption. This study puts forward the concept of sustainable design for users (SDfUs). Using related keywords of sustainable design and user-centered design, we identify a total of 447 usable articles published during 1992–2019 from Scopus. Results of bibliometric analysis show that the number of SDfUs articles has generally continuously increased since 2007. The most productive scholars are from the USA, the UK, and China, while the top three organizations are Loughborough University, Norwegian University of Science and Technology, and Delft University of Technology. Different focuses of SDfUs appear among developed and developing countries. Green building design has emerged as one key area that uses the concept of SDfUs in developed countries such as the USA and the UK. SDfUs studies in developing countries such as China focus on design for end-of-life products' treatment and disposal. Most SDfUs studies examine how design can contribute to environmental performance through emission reduction and energy saving during products' use, and articles in one of five clusters from co-word analysis explore users' behaviors for sustainable design in the textile industry. This paper is the first study that systematically reviews the literature on SDfUs. It provides valuable insights for scholars in the SDfUs-related fields to identify their research directions and partners. Results on clusters from network analysis also offer practical implications for enterprises to learn from the construction and textile industries.

Keywords Sustainable design · User · Literature review · Bibliometric analysis · Co-citation analysis · Co-word analysis · Trend

Introduction

Due to the increasing resource scarcity and environmental pressure, sustainable design (or eco-design) has been promoted as an important approach to alleviate or even eliminate the negative environmental impacts generated from production and consumption (UNEP 1997). The sustainable design integrates environmental concerns into design processes with an aim to reduce resource consumption and environmental pollution of products through their whole life cycle (Sun et al. 2017). Initially, sustainable design focused only on production, and it has extended to consideration of products' consumption and end-of-life treatment only in recent years (Ahmad et al. 2018). To promote sustainable consumption, designers need to integrate users' preference and consider users' behaviors in product design (Lockton et al. 2008; Cor and Zwolinski 2015). Unfortunately, due to its originality, sustainable design mainly considers from the level of systems or objects (products) with limited consideration on the side of users (Armstrong et al. 2015; Withanage et al. 2016).

It has been realized that it is essential to consider users' perception and behaviors during the design process (Cor and Zwolinski 2015). Particularly, user-centered design, using an iterative design process with focuses on consideration of users' needs, is becoming more and more popular (Goodman-Deane et al. 2010; Shluzas and Leifer 2014; Uva et al. 2019). Most of the previous publications studied on either sustainable design or user-centered design, while very few covered both (Wever et al.

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2008; Selvefors et al. 2017). A few fields use the concept of SDfUs or cover the related aspects. For example, the U.S. Green Building Council leads a Leadership in Energy and Environmental Design (LEED) program, which has made efforts to promote sustainable design for buildings and communities, considering users' (residents') health and living conditions[1]. An emerging field called design for sustainable behaviors is a user-centered approach that tries to change users' behaviors to a more sustainable way through design (Wever et al. 2008; Daae et al. 2016). However, the importance of considering both sustainable design and user-centered design simultaneously has not been sufficiently highlighted.

This paper aims to explore if and how sustainable design studies have considered users. It first contributes to putting forward the concept of sustainable design for users (SDfUs). In this paper, sustainable design mainly focuses on product design. As for users, they can be not only individual consumers but also companies. Using 447 related publications from 1992 to 2019 and based on results of bibliometric analysis, this paper further contributes to revealing the origin and history of SDfUs studies. Third, this paper can help scholars to identify future directions and partners. Key authors in the SDfUs-related fields and their institutions are identified. Moreover, different focuses on SDfUs show that developed and developing countries have different challenges and experiences. Besides, co-citation and co-word analysis reveal different clusters for SDfUs studies, which can help scholars in a certain discipline to pursue collaboration with scholars from other fields. The interdisciplinary partnership is needed for more in-depth future studies to develop methods and tools, which can also facilitate practical applications of SDfUs.

To achieve our research goal, the "Data collection and research methods" section introduces data collection and research methods. The "Results of initial statistics and discussion" section presents initial results from the bibliometric analysis, examining author influence, and affiliations statistics, as well as keywords and citations statistics. Network analysis is further conducted in the "Results of network analysis and discussion" section, including co-citation analysis and co-word analysis. The "Conclusions" section summaries the whole paper with conclusions.

Data collection and research methods

Data collection

After an initial search in Google Scholar, we identified keywords for sustainable design with consideration of users. Keywords related to sustainable design are "eco-design" and "sustainable design." Keywords that reflect users include "user", "consumer," and "customer." We also include keywords related to users' purchasing behaviors such as "awareness," "behavior," and "purchase." To guarantee our reasonable selection of these keywords, we discussed with two leading scholars in sustainable design and user-centered design, respectively.

In the end, we used the following keywords and their combinations: ("eco-design" OR "design for environment" OR "sustainable design" OR "green design" OR "environmental design" OR "design for sustainability" OR "environment-friendly design") AND ("user" OR "behavior*" OR "awareness" OR "intention" OR "purchase" OR "procurement" OR "perception" OR "consumer" OR "customer"). For each keyword, we also considered basic variations (e.g., for "purchase," we also searched for "purchasing") by using "wildcards" (e.g., searching for "purchas*," where * is the wildcard indicator). We searched the above keyword combinations from the Scopus database due to its broadness.

Initially, 1698 relevant publications were extracted from Scopus. Then, publications meeting the following rules were deleted: (1) duplicated articles; (2) articles with incomplete information such as keywords, journals, or authors' names; (3) conference articles or articles that published in commercial magazines as they are not rigidly scientific articles; (4) books, book sections, and series. After filtering, 447 journal articles were chosen for the following analyses.

Research methods

A literature review aims to identify, specify, map, and evaluate the existing body of the relevant literature using a systematic, objective, and reproducible way, which highlights a reasonable scope for collecting papers (Tranfield et al. 2003). A structured literature review can handle a broad diversity of publications and methodologies, which provides a thorough and in-depth analysis considering clear contextual relationships (Raghuram et al. 2009). Bibliometric analysis was applied in this study due to three reasons. First, compared with other text analysis methods such as content analysis, bibliometric analysis is easier and more reliable to handle several hundred articles. Second, bibliometric analysis can deeply analyze relationships among articles, citations, co-citations, and keywords, and thus, the results can provide comprehensive information. The final reason is that the strong visualization ability of bibliometric analysis, which helps readers easily and clearly identify clusters of research interests in the field.

Initial statistics of bibliometric analysis

For initial statistics, we first examined the publication trend in the SDfUs field with a focus on sustainable design considering users according to the number of articles in each year. Then,

[1] https://www.usgbc.org/

according to a previous study (Fahimnia et al. 2015), we used a series of quantitative measures such as papers per author, citations per paper, and the place of publications to assess the quality and impact of research. Bibexcel, a software package, was used to analyze the bibliometric data due to its high flexibility in data inputting and manipulating, as well as its excellent compatibility with other databases such as Scopus and visual tools such as Gephi or VOSviewer that were adopted in this study.

The authors marked with high citations are regarded as influential scholars in the field. To depict the authors' influence in SDfUs, we extracted the authors' information for all selected publications and recorded their appearance frequencies as the indicator. The affiliations of the authors were extracted into Bibexcel to analyze the top organizations and their countries where the organizations are located.

To understand the research focuses on the field, we conducted a keyword analysis by identifying the most frequently used keywords in all publications of our sample. Tracking citations and understanding the relations of all citations among articles are critical to the evaluation of the impact and areas of the research domain (Nicolaisen 2007). The citation of one publication reflects its acceptance degree by academia, which is one of the critical indicators to measure the research impact of this publication. We calculated the cited time of one publication by others in our sample articles as the local citation frequency. The cited time of one publication in the broader perspective is named as the global citation, and it is calculated considering references from the Google Scholar database, which covers key academic databases such as Web of Science, Scopus, and Essential Science Indicators. Technically, the difference between the local citation and the global citation of one paper reflects the degree of attention from its own and other research fields.

Network analysis

After a direct statistics description of the sample publications, we conducted a more in-depth examination of the inner relations among these studies to reveal more results. Network analysis was applied based on the bibliometric data to describe the network structure of the SDfUs field by using visual tools such as Gephi and VOSviewer. The network relation strength between two publications could be explained by their co-occurrence of the same keywords or co-citation of the same study (Zupic and Čater 2014).

Co-citation analysis was put forward by Small (1973). If two articles cite at least one common reference, both these two articles have one co-citation. The co-citation frequency calculates the time that one article has co-citations with other articles. Co-citation analysis assumes that the higher frequency of one article, the higher probability that this paper is related to other articles in the sample. Co-citation analysis is based on references of each article in the sample to identify the clusters. We use this method to map and classify the articles in the SDfUs field.

The output file from Bibexcel could be imported into the visual tool, Gephi, for co-citation analysis. Several steps were used to generate the co-citation clusters map. Before being imported to Gephi, bibliometric data needs to be pre-processed. A threshold of the co-citation frequency should be appropriately set. An article with the co-citation frequency below the threshold is excluded in the following co-citation analysis. A too high threshold would lead to overfiltering, so that too few articles are kept in co-citation analysis to provide the research structure of the field; a too low threshold would result in underfiltering so that too many clusters are generated. For better visualization in the layout in Gephi, the Force Atlas algorithm suggested by the previous studies (Fahimnia et al. 2015; Feng et al. 2017) was used in our study due to its simplicity and readability. Each node represents an article, and each edge between two nodes represents the co-citation relation. After manual adjustment on the repulsion strength, speed, node size, and other parameters (Fahimnia et al. 2015), the most connected modes are formed as a cluster in the network.

For a more detailed examination of the research field, the co-word analysis was conducted. Similar to co-citation analysis, co-word analysis generates clusters that represent diverged research focuses on a field (Ding et al. 2001). Different from co-citation analysis, which is based on the connectivity according to cited references, co-word analysis extracts information of keywords in each article in the field and analyzes their frequency of co-occurrence (Ding et al. 2001). Two keywords have higher closeness if they are found in the same articles more frequently. Co-word analysis enables researchers to directly analyze the content of articles from used keywords to depict the structure of the field. Similar steps for co-citation analysis, we used the VOSviewer software package, which has good compatibility with Bibexcel, to generate a co-word network. Density can be also used to measure the strength of the interaction between keywords (An and Wu 2011; Feng et al. 2017). VOS mapping in VOSviewer enables users to generate a diagram of nodes for keywords and the distance between each couple of keywords based on density (Cobo et al. 2011). The algorithm is based on the sum of squared Euclidean distance between each couple of two nodes in an iterative process (Feng et al. 2017). A large density value means a small distance between two nodes. Based on the density values, a heap map can be generated from VOSviewer to reflect research focuses on the field.

Results of initial statistics and discussion

Descriptive analysis of collected articles

Figure 1 shows a continuously growing trend since 1992. A tremendous growth started from 2006–2007, and about 94%

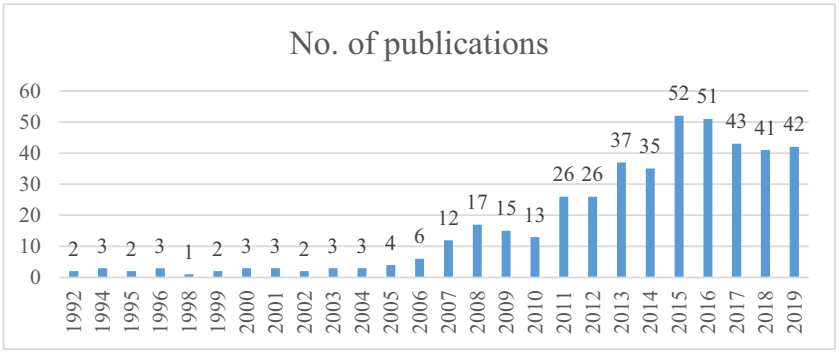

Fig. 1 The publication trend of the SDfUs field

of the articles were published after 2006. The peak year that published the most articles was 2015, with 52 publications. The earliest two papers in 1992 focused on eco-design and life cycle analysis. Another key finding is that more papers have been published since 2015, and over half (229 out of 447, 51.23%) of the articles were published after 2015. Such results indicate that SDfUs has attracted increasing attention from researchers, especially in the recent 5 years, which reveals that SDfUs has become an emergent and important research field.

The top ten journals that published articles about SDfUs are shown in Table 1. These ten journals published 134 articles, which is nearly 30% of the total of 447 publications. The remaining 70% of the articles were dispersedly published in other journals. The *Journal of Cleaner Production* published 62 articles, accounting for about 46.3% and 13.9% of the articles published in the top ten journals and all articles in the sample, respectively. Notably, there were four special issues in the *Journal of Cleaner Production*. The special issue of "Eco-design: what's happening" in volume 14, issues 15–16, 2003, covered studies considering the combination of eco-design and user benefits with the attempt to gain a win-win situation by using clean energy systems (Karlsson and Luttropp 2006). Another special issue in 2012 published papers on "sustainable product-service systems (PSS)" to explore possible tools and methods that could enhance the implementation of PSS to satisfy customers/users (Vezzoli et al. 2012). The special issue in 2013 of "Sustainable consumption and production for Asia: sustainability through green design and practice" published papers addressing sustainability through green supply chain management, design, and practices in Asia (Tseng et al. 2013). Later in 2013, another special issue on "Sustainable innovation and business models" published papers to explore the design of new management tools to stimulate sustainable innovation (Boons et al. 2013). The second top journal discussing issues on SDfUs is *Sustainability* with 14 publications, followed by the *International Journal of Sustainable Engineering* with 13 articles.

Table 1 shows that most articles were published in journals related to either sustainability or design, such as the *Journal of Design Research*, the *Journal of Cleaner Production*, and the *International Journal of Design*. Despite the increasing attention in other fields in recent years, the main attention to SDfUs is still from the fields of sustainability and design. It might take more years to attract broader attention from other related fields. Papers appearing in the *International Journal of Production Economics* prove that SDfUs has attracted scholars in the field of operations management and production economics. Due to the nature of SDfUs, more interdisciplinary research is needed.

Table 1 Top ten journals in terms of number of SDfUs publications

Journal name	Total number	Percentage (%)
Journal of Cleaner Production	62	46.27
Sustainability	14	10.45
International Journal of Sustainable Engineering	13	9.70
Journal of Design Research	8	5.97
International Journal of Design	7	5.22
Design Journal	7	5.22
International Journal of Sustainability in Higher Education	6	4.48
Resources, Conservation and Recycling	6	4.48
Journal of Industrial Ecology	6	4.48
International Journal of Production Economics	5	3.73
The total number of top ten journals	134	100

Authors influence and affiliations statistics

Table 2 describes the top ten authors who contribute the highest number of papers, including both first-authored and co-authored papers.

As shown in Table 2, Boks C published 11 papers, ranking as the top 1 author with the highest number of publications. Among these 11 papers, four were co-authored by Deea J. Both Lilley D. and Bhamra T. published 7 papers, and two were co-authored by these two scholars. Similarly, Lockton D. and Stanton NA co-authored most of their papers. Moreover, the majority of these researchers are from product or technology design backgrounds. Three researchers (Kuo, Zhang L, and Zhang J) are from industrial engineering, which is close to operations management/operational research. Most of these researchers applied empirical methodologies such as case study, experiment, and survey. Boks C, for example, did a literature review and case analysis in his studies. The business model design is another highly used method by these top researchers.

Table 3 presents the top organizations that contribute more than two publications, as well as their geographic locations and the number of publications. Researchers at Loughborough University published the highest number of papers. Compared with the top ten authors in Table 2, it can be seen that Norwegian University of Science and Technology, Delft University of Technology, and Loughborough University are represented by authors of Boks, Lilley, and Bhamra, respectively.

Table 4 depicts the top ten geographic locations of the organizations that contribute to the field. Totally, 342 of 447 papers in our samples are from the top ten countries/regions. Among these ten countries/regions, scholars in the USA and the UK published the highest numbers of papers, 101 and 62, respectively. China ranks as the third with 61 publications, including 35 from the mainland of China and 26 from Taiwan but excluding those from HK. Specifically, the number of publications from China has increased rapidly over recent years, which indicates that SDfUs has become popular in China. This echoes the position of China as the world factory, and thus, China has realized the importance of SDfUs, bringing more related efforts. The rest 105 papers in our sample were contributed by scholars from the rest countries of Europe such as Germany, the Netherlands, France, and other countries or regions such as Hong Kong and Singapore. Overall, scholars in the SDfUs field disperse globally. Asia contributes less than North America and Europe, and no contribution is from Africa and Russia.

Keywords and citations statistics

Table 5 lists the top 20 used keywords. There are 6128 keywords generated from 447 articles in total. Table 5 shows that "eco-design" is the keyword with the highest frequency, which indicates that SDfUs has been mostly studied from the eco-design perspective. The keyword of "life cycle assessment" is interesting to appear as the equally second frequently used to "sustainable development." Such a result reveals that SDfUs is closely connected to the life cycle thinking of products. Besides, "building" also appears in the list, which implies that one important application of SDfUs is about the building and construction industry. The US LEED program has been implemented successfully and diffused to other countries such as China. Experiences in the building and construction industry can be summarized and then learned by other industries.

The initial citation analysis in Gephi reveals that 447 studies cite each other. The top ten papers based on the times of citations are listed in Table 6. Lilley (2009) has the highest

Table 2 Top ten authors with the highest number of publications in the SDfUs field

Author name	Authors' organizations	Number of publications	Percentage (%)
Boks C	Norwegian University of Science and Technology	11	22
Lilley D	Delft University of Technology	7	14
Bhamra T	Loughborough University	7	14
Daae J	Norwegian University of Science and Technology	4	8
Lockton D	Carnegie Mellon University	4	8
Stanton NA	University of Southampton	4	8
Millet D	SUPMECA Toulon	4	8
Kuo TC	Chung Yuan Christian University	4	8
Zhang L	Liverpool John Moores University	3	6
Zhang J	University of Vermont	3	6
The total number of publications for Top ten authors		51	100

Table 3 Organizations with over two publications in the SDfUs field

Organizations	Number of publications	Location
Loughborough University	14	UK
Norwegian University of Science and Technology	12	Norway
Delft University of Technology	10	Netherlands
Aalto University	9	Finland
University of California	8	USA
University of Manchester	7	UK
Brunel University	6	UK
Chalmers University of Technology	6	Sweden
Chung Yuan Christian University	5	Taiwan
University of Florida	4	USA
University of Toronto	4	Canada
Colorado State University	4	USA
University of New South Wales	4	Australia
University of Hong Kong	3	Hong Kong
National Cheng Kung University	3	Taiwan
Purdue University	3	USA
Michigan State University	3	US
Georgia Institute of Technology	3	US
University of South Australia	3	Australia
National Taipei University of Technology	2	Taiwan
Total	113	

citation among all papers. Five scholars as top contributing authors shown in Table 2 also have publications in the list of Table 6 as expected, such as Boks, Lilley, Lockton, Stanton, and Bhamra. Such results further provide evidence of their strong impact in the field. Surprisingly, two papers receive extremely high global citations, they are Steg and Vlek (2009) with 2454 citations and Abrahamse et al. (2005) with 2442 citations, but their local citations of 7 and 6 are not high. These two articles are review papers on environmental

Table 4 Geographic locations of organizations that contribute to the field

Country	Number of publications	Percentage (%)
USA	101	29.53
UK	62	18.13
The Mainland of China	35	10.23
Taiwan	26	7.60
Canada	25	7.31
Australia	23	6.73
Netherlands	20	5.85
Italy	18	5.26
Sweden	17	4.97
Norway	15	4.39
Total among ten top countries	342	100

Table 5 Top 20 frequently used keywords in the field

Keywords	Frequency
Eco(-)design(s)	151
Sustainable Development	142
Life Cycle Assessment/Analysis (LCA)	142
Product design	112
Environmental impact assessment(s)	98
Design	90
Sustainability	80
Sustainable design	69
Building(s)	38
Product development	37
Design for sustainability/(sustainable behavior)	36
Energy efficiency	36
Recycling	31
Article	30
Decision making	29
Environmental design	28
Green building(s) design	28
Quality function deployments (QFD)	28
Environmental protection	27
Design for environment (DfE)	26

behaviors. Such results indicate that they have laid the foundation for the later studies in broader fields related to SDfUs.

A closer check found that the contributing authors for two publications in Table 6, Steg, Vlek, Abrahamse, and Rothengatter, have backgrounds of psychology or behavior studies, which may explain the high global citations that are from the related fields such as behavior research. Researchers for the rest of 8 publications in Table 6 are from the field of sustainable design. Such results also indicate that despite SDfUs interacts with two fields of sustainable design and human behavior research, the majority of scholars in the SDfUs field mainly study sustainable design without enough consideration from the users' perspective. Last, examining the overall research topics and adopted methodologies of these highly cited papers, we can see that most of the articles are exploratory studies and aim to develop a conceptual or research framework of SDfUs by using qualitative methods or case studies. Such results indicate that the SDfUs field is in the emerging stage, which further urges for research cooperation on SDfUs among researchers, especially for designers and psychologists.

Results of network analysis and discussion

Co-citation analysis

Learning from previous studies (Zupic and Čater 2014; Feng et al. 2017), we used the threshold of 4 for the co-citation frequency. Based on this principle, our co-citation data have 332 articles, deleting 105 from the original 447 articles. Table 7 shows the values of parameters for the co-citation network. The density measures the co-citation strength of the overall network, and it ranges from 0 (means no co-citation) to 1 (means each article in the network having co-citation with other articles). The density value of 0.02 shows a relatively weak co-citation among all articles, which indicates limited cooperation among scholars in the field of SDfUs. The average path length is 3.454, and the number of shortest paths (which is one-unit length) is 5993. Considering the network with 332 nodes, the number of 5993 is a reasonable shortest path number.

Table 6 Top ten publications with the highest local citations

Publications	Local citations	Global citations
Lilley (2009)	16	300
Wever et al. (2008)	14	284
Jelsma and Knot (2002)	10	125
Pettersen and Boks (2008)	8	74
Lockton et al. (2010)	8	376
Steg and Vlek (2009)	7	2454
Tang and Bhamra (2012)	7	51
Zachrisson and Boks (2012)	6	68
Redström (2006)	6	419
Abrahamse et al. (2005)	6	2442

Table 7 Values of parameters of the co-citation network

Index	Value
Density of the network (0, 1)	0.02
Number for a group of fastest nodes	12
Average path length	3.454
Number of shortest paths	5,993
Modularity	0.602

Given that closely connected articles have similar characteristics, a cluster with strong co-citation relations could be considered as a subject research area (Hjørland 2013). An in-depth examination of the papers in the same cluster helps to draw the research focus of the sub-field. The co-citation analysis generates 7 clusters (shown in Table 8 and Fig. 2). Six of 7 clusters, excluding cluster 6, have tens of articles in each cluster, and thus, we ranked articles by their PageRank[2] values of co-citation. We further conducted the content analysis for the top ten articles for each cluster (4 articles for cluster 6) to determine the sub-areas in the SDfUs field by labeling clusters. Table 8 summarizes the sub-areas for all 7 clusters considering their research focuses.

According to the contents of articles, especially those with high PageRank values, we label all seven clusters. Cluster 1 is labeled as theoretical, exploratory, and conceptual development. For example, Hart (1995) extended the resource-based theory to propose a natural resource-based view of firms. Based on 650 articles from the engineering, management, and policy studies, Baumann et al. (2002) suggested that a systems perspective is necessary to optimize resource use and minimize emission for green product development. Daae and Boks (2015) explored how techniques and experience applied in design for sustainable behavior can help to deal with uncertainties in the use phase for life cycle assessment. The existing studies provide a theoretical foundation, but a clear conceptual model of SDfUs is still underexplored.

For clusters 2–6, articles in each one focus on one specific industry or area. We label them as green building design (cluster 2); packaging, recycling, and reverse supply chain (cluster 3); consumers' perception, willingness, and behavior on

[2] "Co-citation PageRank" has been accepted as an effective indicator for determining the top articles in a given co-citation cluster (Ding et al., 2009; Yan and Ding, 2011). The PageRank algorithm gives higher weights to papers that are (1) co-cited with different papers and (2) co-cited with highly co-cited papers (Fahimnia et al. 2015).

Table 8 Publications in co-citation clusters

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
Daae and Boks (2015)	Abrahamse et al. (2005)	Koenig-Lewis et al. (2014)	Abdul-Muhmin (2007)	Burgess and Nye (2008)	Hanson (2013)	Mehta and Wang (2001)
Fogg (2002)	Geelen et al. (2013)	Lindh et al. (2016)	Buchanan et al. (2014)	Elias et al. (2008)	Sauer et al. (2003)	Jin Gam (2009)
Hart (1995)	Kneifel (2010)	Magnier et al. (2016)	Gulbinas and Taylor (2014)	Fischer (2008)	Sauer et al. (2004)	Kahraman et al. (2004)
Makower (1993)	Magnier and Haghighat (2010)	Nordin and Selke (2010)	Jain et al. (2013)	Fitzpatrick and Smith (2009)	Thatcher (2013)	Kwong and Bai (2002)
Stern et al. (1999)	Wang et al. (2005)	Pires et al. (2015)	Wever et al. (2008)	Jelsma and Knot (2002)		May-Plumlee (1998)
Baumann et al. (2002)	Sharifi and Murayama (2013)	Scott and Vigar-Ellis (2014)	Lilley (2009)	Löfström and Palm (2008)		Nissen (1995)
Clark et al. (2009)	Heinonen and Junnila (2011)	van Birgelen et al. (2008)	Lockton et al. (2010)	Maan et al. (2011)		Waage (2007)
Grund (1996)	Paul and Taylor (2008)	Yang et al. (2011)	Polizzi di Sorrentino et al. (2016)	McCalley et al. (2010)		Lamb and Kallal (1992)
Klassen and Angell (1998)	Newsham et al. (2009)	Niinimäki and Hassi (2011)	Guerra Santin (2011)	Solli et al. (2009)		Marchand and Walker (2008)
Jeurissen (2000)	Matisoff et al. (2014)	Yenipazarli (2016)	Steg and Vlek (2009)	van Dam et al. (2010)		Ornetzeder and Rohracher (2006)

sustainable design (cluster 4); products' energy consumption design (cluster 5); and green ergonomics (cluster 6). Cluster 6 only has four articles, which indicates that green ergonomics gains less attention from academia. Related studies on SDfUs are fragmented, and comprehensive studies are needed.

Cluster 7 includes articles discussing methods or business models in the field, and thus, we label it as methods and tools for analyzing research questions in the SDfUs field. Nissen (1995) introduced a methodology with two phases for the development of ideal eco-products. Mehta and Wang (2001) developed green quality function deployment III, which integrates life cycle impact assessment into the Green House and uses the Analytic Hierarchy Process (AHP) for selecting the best product concept. Jin Gam (2009) developed the first apparel design and production model that emphasizes sustainability in addition to functional, expressive, and aesthetic considerations, cradle to cradle apparel design (C2CAD), which provides guidelines for apparel designers and manufacturers to solve sustainability problems related to apparel production. Qualitative methodologies such as literature review (Waage 2007) and case study (Ornetzeder and Rohracher 2006), as well as quantitative methods such as AHP (Kwong and Bai 2002; Kahraman et al. 2004), are used. Only four articles use analytical models or optimization methods. Thus, opportunities for future research in modeling exist, which can help to reveal mechanisms for the successful implementation of SDfUs, especially when multi-stakeholders are involved in sustainable design.

Co-word analysis

As shown in Fig. 3, gradually warmer colors and density values are used to show the importance of a concept in the network. A concept with warmer color (red) and a higher density value indicates that the concept is more frequently used and gains higher attention from researchers in the field than a concept with cold color (green). Three main concepts could be easily identified from the heat map in Fig. 3, which are "environmental impact," "product design," and "sustainable development."

Similar to co-citation analysis, a threshold of the minimal times that a keyword appears in the article should be set (Zupic and Čater 2014). We have a total of 6128 keywords from 447 articles, which could be difficult to generate clear clustering results according to the previous studies (Chai and Xiao 2012). A reasonable size for clustering keywords in network analysis should be between 200 and 500 (Fernandez-Alles and Ramos-Rodríguez 2009). For this reason, we kept keywords that appear more than 3 times (including 3), and totally, 494 keywords were analyzed in the co-word analysis.

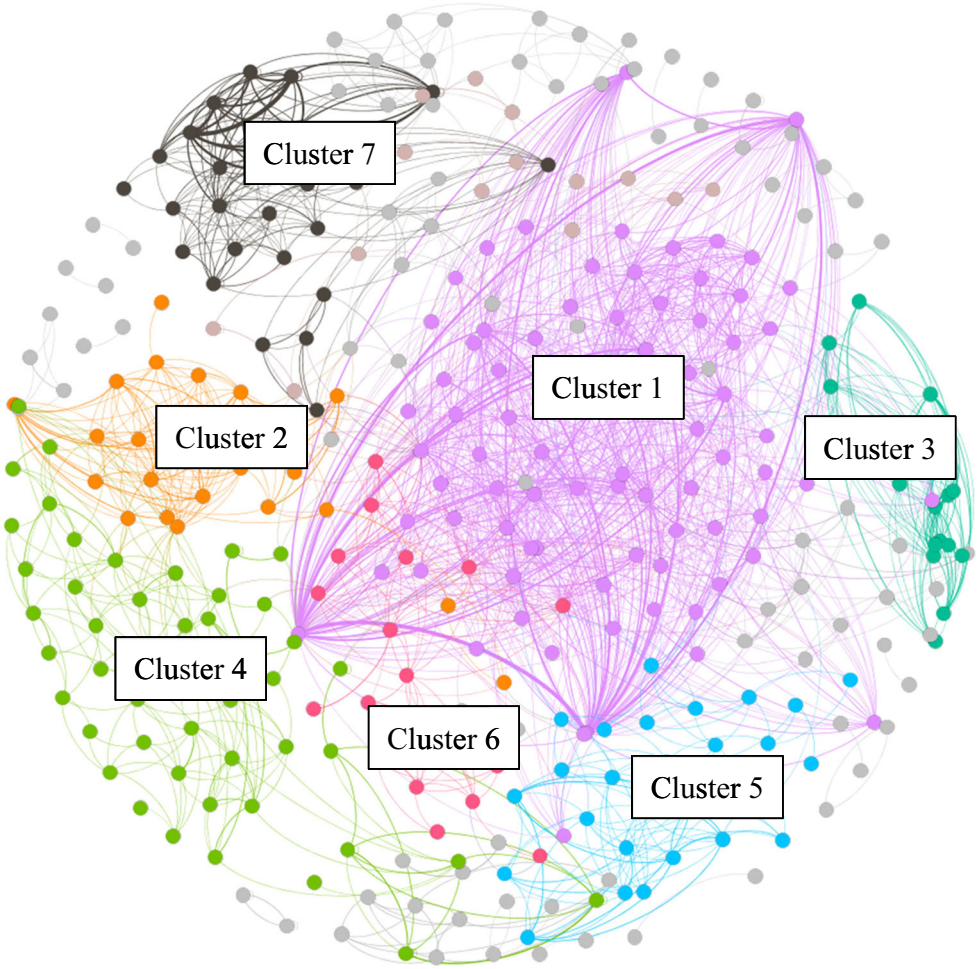

Fig. 2 Clustering map for co-citation analysis

The algorithm in VOSviewer generates five clusters. We listed the top-ranked keywords in terms of the weights in each cluster (shown in Table 10). The weights are calculated from the sum of squared Euclidean distance. We also visualized the five clusters as groups of nodes in five colors (see in Fig. 4). Each node in Fig. 4 represents a keyword, and the size of the node is proportional to the co-occurrence frequencies of each keyword. We then conducted the cluster labeling process for the keywords, and the labels of five clusters are also included in Tables 9 and 10.

Table 10 shows that cluster 1 focuses on the issues of end-of-life products, post-use treatment, and waste management, and thus, we label it as sustainable design for treatment and disposal of end-of-life products. The most relevant keywords in this cluster are "human," "recycling," "waste management," "circular economy," etc. One of the objectives of sustainable design is to reduce the environmental impact in the phase of product use. Researchers have studied this issue by developing "extended producer responsibility," "green packaging," or "recycling." Interestingly, "developing countries" and "china" appear in the cluster (see in Fig. 3), which implies that this issue received significant attention from developing countries such as China. Such a result may link to the reality that developing countries such as China have experienced increasing pressure for waste management (Wang et al. 2017; Shi et al. 2019).

Cluster 2 discusses energy conservation, and thus, we label it as a sustainable design for energy efficiency of product use. As a typical practice of SDfUs, green building design aims to achieve environmental performance and decrease energy consumption without sacrificing users' experience. Words such as "architectural design," "energy efficiency," "energy conservation," and "green building" are included in the cluster. Despite the fewer frequencies, "intelligent buildings," "human engineering," and "indoor air" appear in this cluster, which are closely related to the sustainable design of buildings. Compared with environmental aspects of the sustainable design, the social design of buildings, which highlight users' preference for a better living environment beyond energy saving, receives less attention from researchers. Due to the growing importance of social aspects in sustainability, user-centered design considering more users' preferences besides environmental performance can be another research direction.

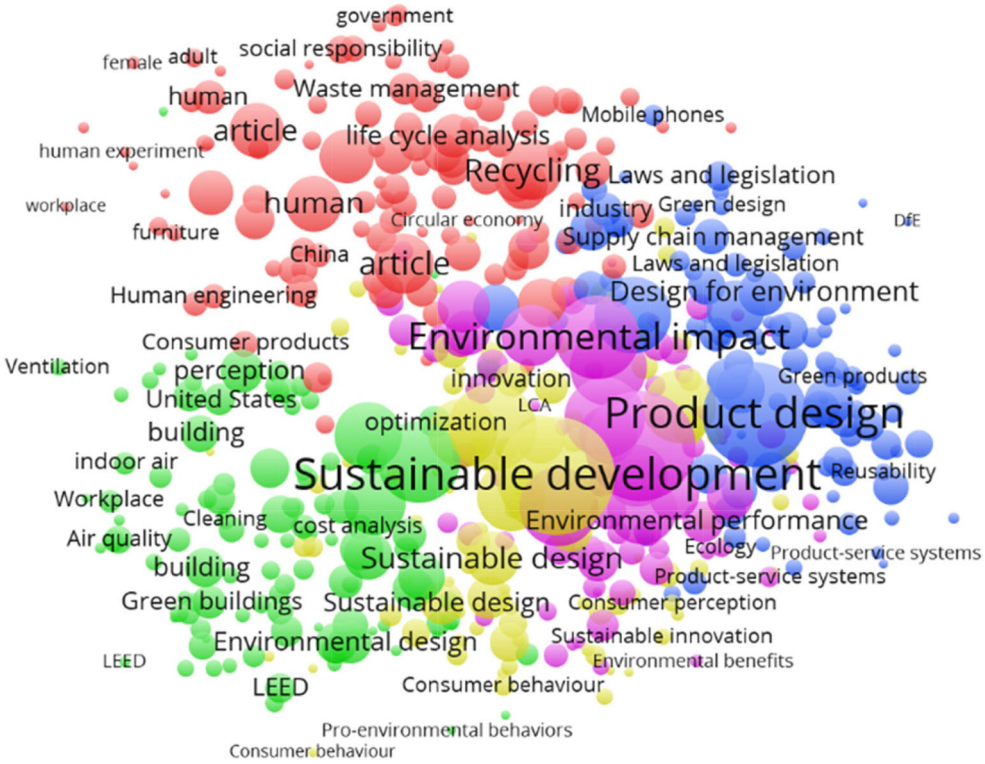

Fig. 3 Clustering results for co-words analysis

Another research focus in the field of sustainable design is related to sustainable supply chain management considering different stakeholders, which forms cluster 3. We label this cluster as a sustainable design considering stakeholders' involvement for products' use. SDfUs requires collaboration among firms and their stakeholders, especially among suppliers and customers. With more stakeholders involved in the product design stage, better performance can be achieved from the product life cycle perspective. Empirical works considering "economic and social effects" of sustainable design at the supply chain level are incorporated in this cluster. A small number of articles using analytical models or optimization tools and methods in this cluster, such as "optimization," "simulation," and "fuzzy logic," appear with relatively low frequencies (3, 12, and 2, respectively). Such a result indicates that more in-depth quantified studies are worthwhile.

Table 10 Top-ranked keywords based on cluster weights for co-word analysis

Cluster 1 (sustainable design for treatment and disposal of end-of-life products)	Cluster 2 (sustainable design for energy efficiency of product use)	Cluster 3 (sustainable design considering stakeholders' involvement for products' use)	Cluster 4 (sustainable design considering consumers' behaviors)	Cluster 5 (sustainable design for broader environmental and economic performance)
Human (s)	Sustainable development	Product design/development	Product design	Environmental impact
Recycling	Sustainability	Supply chain management	Surveys	LCA
Circular economy	Architectural design	Design for environment	Behavioral research	Decision making
Waste management	Energy efficiency	Green design	Consumer behavior	Climate change
Environmental sustainability	Green buildings	Manufacture	Planning	Cost-benefit analysis
Waste disposal	Energy utilization	Sustainable products	Design strategies	Gas emissions
Extended producer responsibility	Environmental design	Economic and social effects	Corporate social responsibilities (CSR)	Carbon footprint
Packaging	Energy conservation	Customer satisfaction	Textile industry	Global warming
Environmental regulations	United States	Fuzzy logic	Ethics	Product-service systems
Developing countries	United Kingdom	Small and medium-sized enterprise	Feedback	Eco-innovation

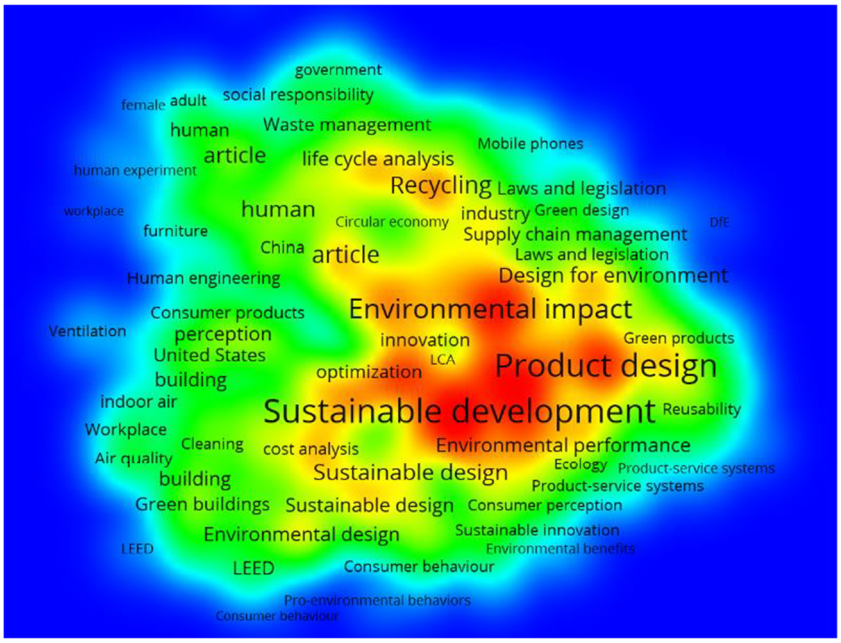

Fig. 4 The heat map for co-word analysis

Cluster 4 focuses on consumers' behaviors in the field of SDfUs, which is in line with the results of cluster 4 from co-citation analysis. We label this cluster as a sustainable design considering consumers' behaviors. "Consumer behaviors" and "behavioral research" are critical to SDfUs, highlighting understanding of consumers' intention, perception of products. Articles in this cluster mainly conduct survey-based or experiment-based empirical studies. Another finding from this cluster is that keywords related to practical applications of sustainable design such as "planning," "design strategy," and "textile industry" are included. Empirical studies on understanding consumers' consciousness, perception, and behaviors in sustainable design help firms in turning business strategies to practices. Experiences in the textile industry have been examined, which can be diffused to other industries.

Cluster 5 examines the field with a broader view beyond firms, supply chains, and stakeholders. We label this cluster as a sustainable design for broader environmental and economic performance. For example, articles in this cluster examine products' environmental impact from the "life cycle" view and explore the role in the products' design stage. SDfUs can also serve to the environmental performance improvement in ways of decreasing "gas emission." "Eco-innovation" is explored, and new business models such as "product-service systems" have been discussed by an increasing number of researchers. With more data available associated with technologies, it can be expected that effective approaches and tools can be developed.

Conclusions

Sustainable design, as the fundamental approach to alleviating environmental impact through the product life cycle, mainly focuses on the stage of product production. With the increasing awareness of sustainable consumption, studies on sustainable design have been extended to the stage of product use. This study puts forward the concept of SDfUs and reveals the trends and features of SDfUs study through a bibliometric

Table 9 Research focus areas and numbers of publications for clusters in co-citation analysis

Cluster	No. of publications	Research focus area
1	77	Theoretical, exploratory and conceptual development
2	45	Green building design
3	27	Packaging and recycling
4	81	Consumers' perception, willingness, and behavior on the sustainable design
5	42	Products' energy consumption, sustainable technology
6	4	Green ergonomics
7	56	Methods and tools for analyzing research questions in the field
Total	332	

analysis. Totally, 447 SDfUs-related articles published during 1992 and 2019 in Scopus were selected for this analysis. SDfUs gained limited attention before 2007, but it has become increasingly popular in recent 10 years. The majority of influential journals that publish SDfUs studies are environmental journals such as the *Journal of Cleaner Production, Sustainability, Resources, Conservation and Recycling*, and the *Journal of Industrial Ecology*. Meanwhile, three design journals (*Journal of Design Research*, *International Journal of Design*, and *Design Journal*) and one operations management journal (*International Journal of Production Economics*) also published several articles. More in-depth interdisciplinary studies are needed.

Both developed countries such as the USA and the UK and developing countries such as China have paid attention to SDfUs, but their focuses are different. The construction industry is the key area of SDfUs for developed countries. One typical example is the US LEED program. Developed countries outsource their manufacturing and even dump their wastes to developed countries, and thus, the construction industry is the key industry that brings environmental impact, especially for energy consumption. Sustainable design can help to significantly reduce the energy consumption of buildings when they are used. Differently, developing countries such as China suffer from the high burden of wastes, and they mainly focus on the reclaimable use of end-of-life products through sustainable design. Meanwhile, with an understanding of associated issues from waste treatment and disposal, China has strictly restricted the import of used products. Thus, developed countries have also met big challenges of waste disposal. Therefore, design for reuse, recycling, and remanufacturing needs more in-depth research all over the world.

Researchers realize the importance of links between sustainable design and considerations of users. SDfUs-related studies examine environmental impact during product use. However, more studies are needed to further link sustainable design to users' psychological and habit aspects. Some experiences in the textile industry can be diffused to other industries. Usually, users are not willing to sacrifice the traditional advantages of products such as low prices and convenience for use unless they understand the environmental performance of sustainable products or have high environmental awareness. Thus, in-depth studies on SDfUs are also needed based on the understanding of users' awareness and purchase intention for sustainable products. Moreover, user's behaviors can affect the environmental performance of products when they are used. Designers need to understand users' behaviors and try to adapt designed sustainable products to such behaviors.

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