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An Overview of Decade-Long Product Design Sustainability Studies: Region al Overviews Through a Bibliometric Lens

Abstract: - The integration of product design across diverse sectors has fueled technological innovation and progression throughout various industries. Recognizing this trend, academia has revisited its approach to product design education and research. This paper presents a bibliometric analysis of product design literature published between 2011 and 2020, utilizing data from the Scopus database. The analysis identifies key terms, countries, sources, and research clusters, providing insights into prevailing trends within the field. The paper further discusses these findings through an examination of publication patterns. The bibliometric analysis uncovers annual publication volumes, contributing nations, source expansion rates, predominant keywords, and collaborative efforts. The research topics are categorized into three primary domains: product design models, sustainable design, and design methodologies/evaluation strategies. The qualitative analysis segment provides a comprehensive review of the most frequently referenced articles.

Keywords: Product Design, Model Application, Sustainability, Methodology and Evaluation, Bibliometrics, Research Productivity

INTRODUCTION

Product design, encompassing aspects like drawing, modelling, material selection, and market research, is integral to contemporary design (Chandrasegaran, et al., 2013). Its application across finance, agriculture, and chemistry necessitates diverse design methodologies (Antle et al., 2017). To navigate these challenges, suitable tools and techniques are required (Lutters et al., 2014). It must balance environmental conservation, societal expectations, and profitability - the triple bottom line (Lacasa et al., 2016).

Two prominent tools employed in sustainable product design testing are SPD and P-SPD. SPD focuses on sustainability's three pillars, whereas P-SPD targets earlier design phases. P-SPD tools are more established and uniform compared to SPD (Ahmad et al., 2018). Environmental design (DFE) tools, particularly their user-friendliness, aid designers in addressing EoL performance (de Aguiar et al., 2017). The cutting-edge toolset includes Virtual Reality (VR) systems, enabling scenario simulations and reducing design wastage, enhancing product life cycle value, and mitigating irreversible energy loss (Chandrasegaran, et al., 2013; Charter, and Tischner 2017).

Validation factor analysis and structural equation modelling verify how product design influences consumer affinity towards the product, facilitating the enhancement of various design research values (Kumar et al., 2015). A theoretical model exists for understanding customer preference bias, business strategy, and governmental policy (Homburg et al., 2015). Lifecycle-based product design models, incorporating assembly, disassembly, recycling, maintainability, and environmental processes, are widely applied for design performance evaluation (Sy and Mascle, 2011). Ecological product design, currently under development globally, aims to achieve sustainability and mitigate environmental pollution (Hartmann and Germain, 2015).

Currently, sustainability within product design has emerged as a prominent topic, propelling the advent of sustainable design for goods (DFS), and urged researchers to address consumers' interests, reflected in sustainability-focused research (Ceschin, and Gaziulusoy 2016; Iqbal and Ahmad, 2021; de Aguiar et al., 2017). To produce sustainable goods, material selection is critical, facilitated by life cycle engineering (LCE) (Iqbal, Ahmad and Li., 2021a; Zarandi, et al., 2011). The product's lifecycle reflects its sustainability, which can be categorized across design stages, each addressing unique sustainability needs (Ahmad et al., 2018; Chen et al., 2012; Iqbal, Ahmad, Li, and Li., 2021). For instance, early product design necessitates cost reduction and quality enhancement for sustainable development. Designers should devise checklists for new sustainable product development and collaborate with production personnel to ensure product performance and quality (Chen et al., 2012). To optimize sustainability throughout the lifecycle, companies must recognize that sustainability is not solely about technological advancement, but also about its impact (Antle et al., 2017; Iqbal, Ahmad, and Li., 2021b).

Comparatively, sustainable product design prioritizes environmental, resource, and usage considerations over

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traditional design. Design efficiency, a metric of sustainability, can be evaluated via the two-stage Data Envelopment Analysis (DEA) model (Chen et al., 2012). Consumers consider practical, aesthetic, and symbolic design dimensions when evaluating sustainability. They employ a consumer information processing model to gauge design tendencies based on emotional responses (Candi et al., 2017). Life cycle assessment and ecological design principles are integral during product design, necessitating a decision-making model for sustainability and environmental conservation (Kulatunga et al., 2015). Sustainability in product design can mitigate energy consumption, utilizing the industrial energy consumption model to analyze product design system energy consumption (Bonvoisin et al., 2013).

Sustainable product design encompasses diverse fields like finance, agriculture, and chemistry, aiming to ameliorate their inherent drawbacks (Iqbal and Piwowar-Sulej., 2021). Various models can be employed to assist in resolving design issues, particularly those in chemistry, where they form a decision framework for sustainability and utilize computer-aided design tools and information and communication technology models (Antle et al., 2017; Heintz et al., 2014). Literature on sustainability research provides comprehensive insights into the application of sustainable models in product design research, enhancing design precision and efficacy at every stage (Ma and Kremer, 2016). This paper employs bibliometric analysis, enabling readers to discern research trends and summarize current research topics (Wang et al., 2020; Chen et al., 2019; Chen et al., 2019). Unlike traditional knowledge transmission and scholarly experiences, bibliometric analysis aids researchers in gaining macroview insights (Wang et al., 2020; Chen et al., 2019). Bibliometrics, defined as scholarship measurement based on metrics like literature volume, citation count, and author collaboration, is utilized in quantitative studies (Li et al., 2020). Bibliometric analysis of published literature facilitates understanding of academic field knowledge and framework theories, assessing publication trends (Ponce, and Lozano, 2010; Akhavan et al., 2016). A bibliometric study analyzes publication author country, keywords, citations, and research trends to quantitatively examine the research domain (Ebrahim, et al., 2019).

Bibliometric analysis finds application across diverse fields, encompassing business strategies within the circular economy (Bocken et al., 2016), competitive supply chains (Zhu and He 2017), two-phase supply chains and procurement tactics (Dey et al., 2019), prospective environmental strategies and performance (Li et al., 2016), global supply chain enhancement initiatives (Marsillac and Roh 2014), resource council effectiveness surveys (Khor, and Udin, 2013), among others. Similarly, sustainability models have been employed in areas like sustainable waste management (Krystofik et al., 2015), sustainable product design bottom lines (Melles, et al., 2011; Iqbal, Ahmad and Halim., 2021), product design sustainability evaluations (Reuter, 2016), environmental design assessments (He et al., 2018), low-carbon product design objectives (Kuo et al., 2014), energy efficient product designs (Moon et al., 2013), lightweight product design methodologies (Carruth et al., 2011). Notably, sustainability modeling offers comprehensive solutions to product design issues, comparable to modular product design (Bonvoisin et al., 2016). While previous literature overlooked sustainability models in product design, this presents opportunities for exploration. However, bibliometric findings should not replace qualitative peer review (Boons and Roome, 2005). Consequently, scholars should interpret bibliometric outcomes independently (Boons and Roome, 2005). A balanced approach combining qualitative and quantitative bibliometric analysis is optimal for understanding a research domain (Maghami et al., 2015; Elaheh et al., 2018). This paper employs both methods to analyze sustainability research in product design models from 2011-2020. The study provides insights into the current research landscape, highlighting key focuses and emerging trends in product design.

I. METHOGOLOGY

The recognized literature databases include Scopus and Web Of Science (WoS). While WoS is highly regarded, Scopus offers broader journal coverage. For our topic, "product design", we queried the two databases: Scopus yielded 5265 publications while WoS returned 3119. This count represents all documents containing "product design" in their title, abstract, or keywords across all years. Given the volume, we limited our data collection to Scopus on October 15, 2020.

To capture recent references, we focused on publications post-2011, reducing the initial count to 2682. This reflects the total number of "product design" publications from 2011 to 2020, excluding pre-release records for 2021. Thus, the Scopus database identified 2681 "product design" publications from 2011 to 2020. The annual publication count, top 20 publishing nations, and top 50 contributing authors can be conveniently displayed via VOS software. VOS viewer is a tool for generating distance-based maps clustering keywords from document titles and abstracts (Ebrahim et al., 2020). The resulting literature metrics visualization map comprises linked nodes, each denoting a keyword, nation, institution, or author. The final refinement of 2681 publications to 283 utilized search terms "model" and "sustainability" (Ebrahim et al., 2020).

Like other literature search studies, ours has potential limitations. Data were primarily sourced from Scopus, with "product design" appearing in article titles for accurate collection. Despite covering over 95% of literature from WoS and Scopus, specific WoS content might be overlooked. In conclusion, this study presents a metric analysis of numerous Scopus articles demonstrating product design trends via models (Ebrahim et al., 2020).

Bibliometrix package, an RTool for comprehensive scientometric and bibliometric analysis, enables importing bibliographic data routines from WoS and Scopus. The data collection process is illustrated in Figure 1, aligning with PRISMA guidelines for systematic reviews and meta-analyses. It facilitates integrating bibliometric outcomes with qualitative content analysis (Ebrahim et al., 2020).

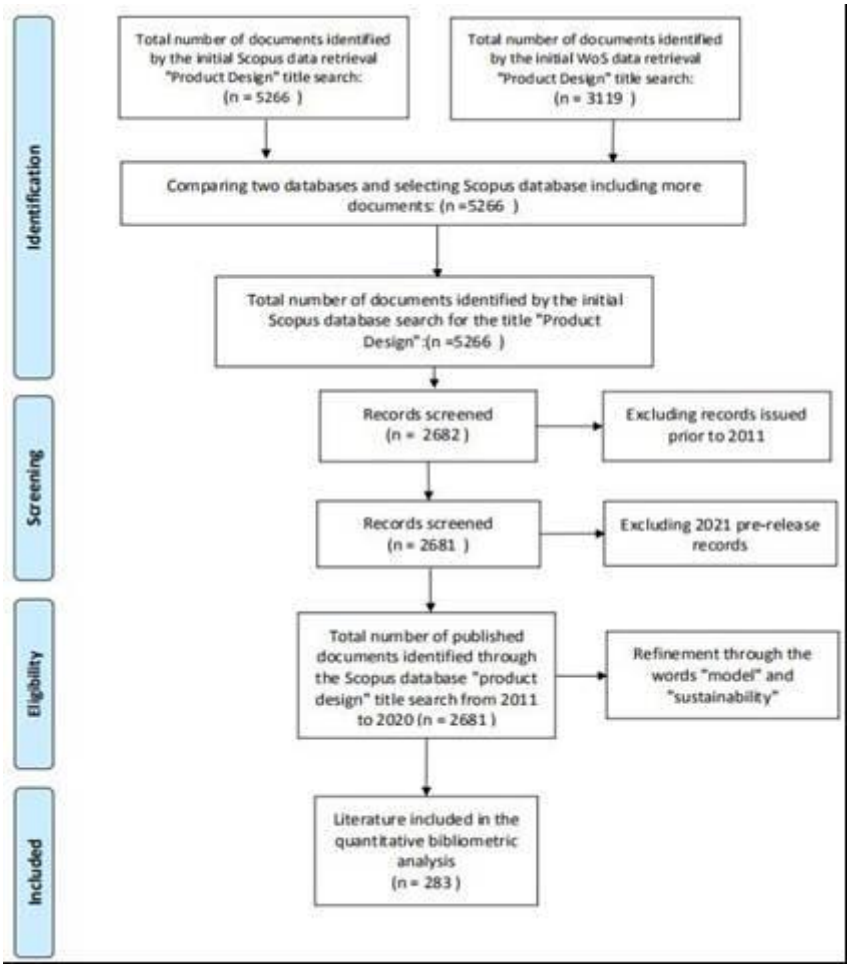

Figure 1. The PRISMA flow diagram for the bibliometric analysis on Product Design using Sustainability Models

QUANTITATIVE ANALYSIS

From 2011 through 2020, 2682 articles were published in product design, as illustrated in Fig. 2 where an initial surge to 332 in publications occurred in 2011, followed by a dip until 2015, subsequently increasing to reach 317 publications in 2019 signifying renewed academic focus. Together, these studies represent over half of the total output during this time span.

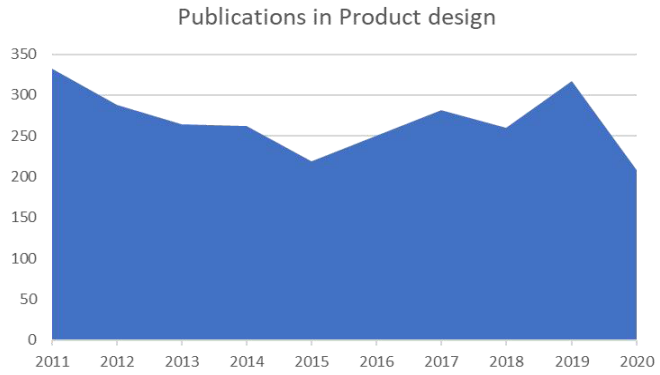

FIGURE 2. Analysis of publication years in using Sustainability Models from 2011 to 2020

Fig. 3 presents the 20 premier nations in product design research. Their combined contributions comprise 98.35% of global output volume based on bibliographic data. Asian and Western regions equally contribute, led by China's 717 records (world no. 1), U.S.'s 445 (no. 2) and UK's 192. These countries span diverse locations: (1) China ranks highest in Asia; (2) the U.S. represents North and South America; and (3) the UK remains Europe's predominant contributor. Consequently, each continent boasts national presence in product design research, with China emerging as a critical hub in this discipline (Ebrahim et al., 2020).

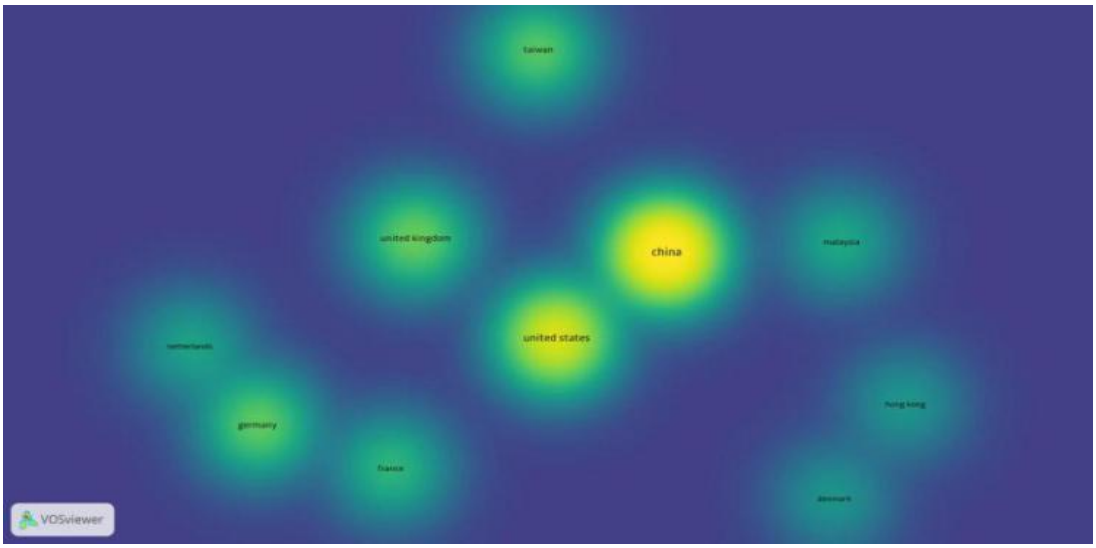

FIGURE 3 Density visualization map of 10 countries collaboration in using Sustainability Models bibliometric analysis

A comparative evaluation was conducted employing author keywords identified in Scopus, with a focus on those appearing over 20 times. The analysis encompassed a total of 8,885 indexed keywords, among which only 99 surpassed the minimum frequency. Fig. 4 illustrates the top 50 most frequent keywords along with their interrelationships. Keywords differing in color represent their earliest publication year while connecting lines signify shared connections. Product design publications, dating back to 2016, primarily concentrate on ongoing research and advancement within the field.

Subsequent to the co-occurrence analysis of author keywords in Scopus, the most prevalent keyword networks identified via VOS software were sustainable product design, modular product design, product development, and product design models. To uncover less frequently used but recent keywords, we revisited the publication keywords from 2017 to 2018. These revealed the emerging hotword networks including sustainability, sustainable design, and model ecological design. Hence, our study focuses on sustainability-oriented product design

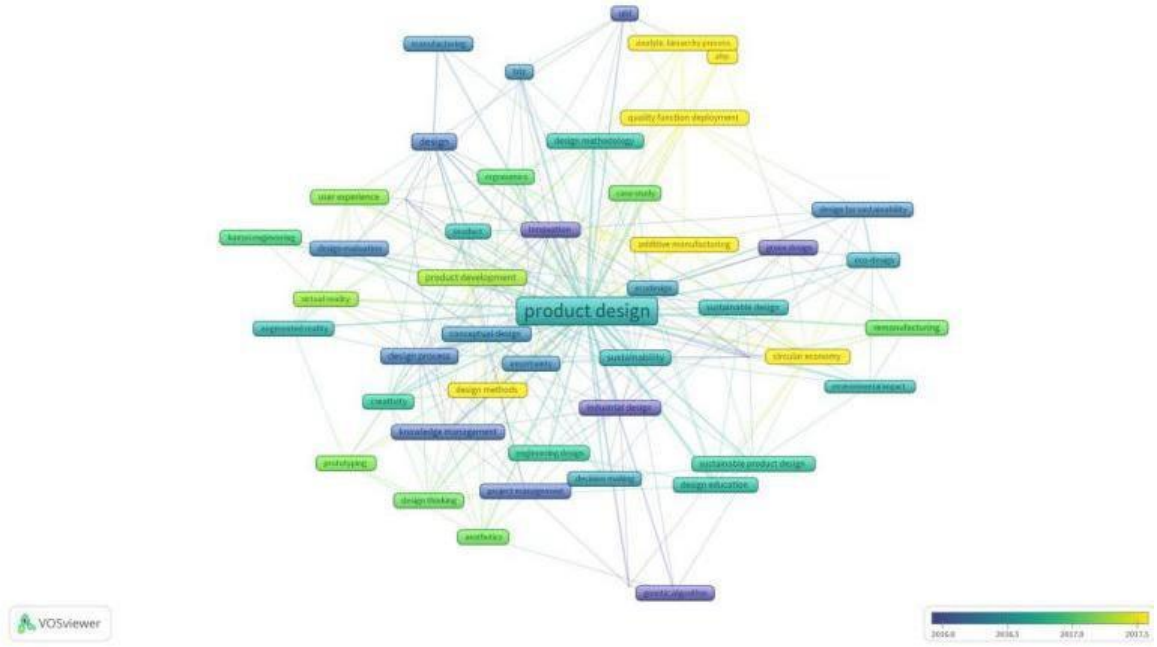

FIGURE 4. The network structure of top 50 keywords (author's keywords and keywords index) in using Sustainability Models bibliometric analysis.

A total of 283 documents were procured via the Scopus platform after refining the original 2682 papers with sustainability and modeling aspects. A comprehensive snapshot of these results is depicted in Table I. This reports 815 researchers utilizing sustainability models for product design investigations. The average number of contributors per paper stands at 2.879 indicating collaborative efforts amongst scholars. Data analysis revealed that 23 of these papers were authored solely by individuals while 260 were collaboration efforts. Each publication boasted an average citation count of 14.37, signifying a significant number of highly regarded academic works.

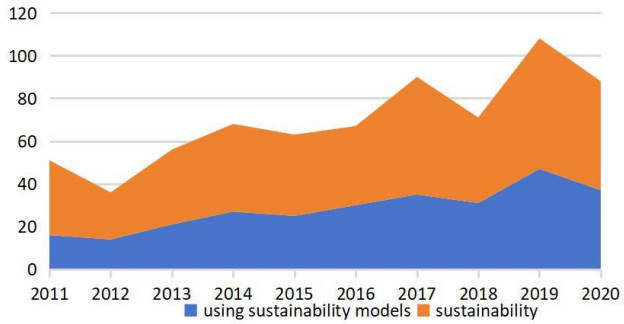

FIGURE 5. A cumulative graph of publication years in Product Design research field limited to Use Sustainability Models from 2011 to 2020

Graphic 5 illustrates the dynamic trend of sustainability-focused product design publications. It reveals that the field witnessed a peak of 47 publications in 2019, marking the highest output within the past decade. The table further highlights a gradual increase in sustainability model utilization publications from 2012 to 2017, followed by a dip in 2018. Remarkably, a resurgence occurred in 2019, marking the highest publication count in the last decade. This suggests a renewed emphasis on sustainability in product design research.

Figure 6 elucidates the correlation network amongst the top 20 nations examined under the sustainability paradigm in product design. Collaborative alliances are portrayed via colorcoded lines, with line width indicating intensity of cooperation (Ebrahim et al., 2020). Within this domain, the U.S. emerges as the leading nation, contributing a total of 64 articles, primarily in conjunction with China, India, Sweden, Denmark, and Hong Kong. Since 2011, China has ascended to second place with 49 publications, representing over 17% of the discipline. The correlation network reveals an increased partnership between China and Switzerland. During the same period, the UK contributed 25 articles and Taiwan, 22. Other

participating nations include Germany, Malaysia, the Netherlands, and Canada. The diverse color scheme in Figure 6 denotes distinct international research collaborations: (1) The U.S., China, Taiwan, and Canada group; (2) Germany, France, the Netherlands, and Portugal. This interconnected framework facilitates global scholarly interaction, fostering collaborative efforts towards enhanced research outcomes.

FIGURE 6. The network structure of of top 20 countries collaboration in Product Design using Sustainability Models bibliometric analysis

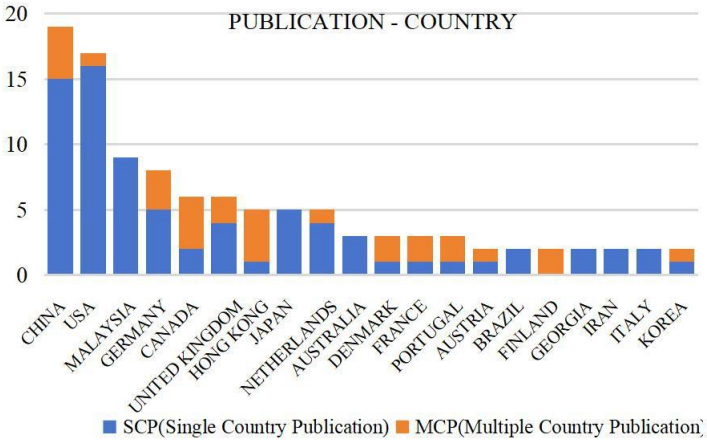

FIGURE 6. The network structure of of top 20 countries collaboration in Product Design using Sustainability Models bibliometric analysis

Figure 7 displays the distribution of multiple versus single publications within product design sustainability models. A selection of the top 20 nations based on publication quantity reveals China's high ranking. Its top contributor, with 19 publications inclusive of
4 multinational and 15 single-nation contributions, places it at the pinnacle. likewise, Malaysia stands amidst these top 3 contributors, boasting 9 solitary-author papers. Also contributing solely are Japan, Australia, Brazil, Iran, and Italy, accounting for over 29% of all sustainability model product design research fields. Consequently, Figure 7 indicates a predominant trend of domestic collaboration, signifying authors' national affiliations.

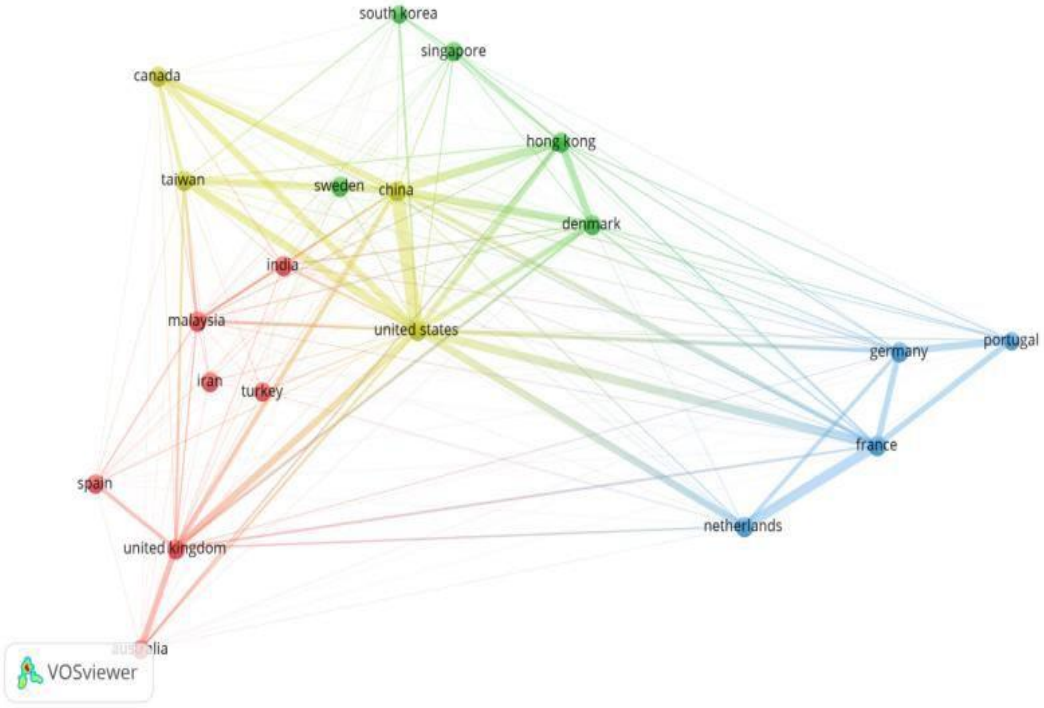

FIGURE 7. Total number of publications in (multiple country publications and single country publications) by 20 corresponding author's countries Product Design using Sustainability Models

Figure 8 elucidates the decade-long progression of the sustainability model's product design exploration

sphere. It underscores the disparity in article output from the top ten prolific contributors from 2011 to 2020. Consequently, the INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH is concentrating on sustainable product design studies, providing a pivotal resource. Although it currently ranks foremost amongst peers, its publication rate remained consistent from 2018 to 2020. Despite an existing body of literature on sustainable product design, the number of articles in this specific research domain decreased slightly during 2019 and 2020.

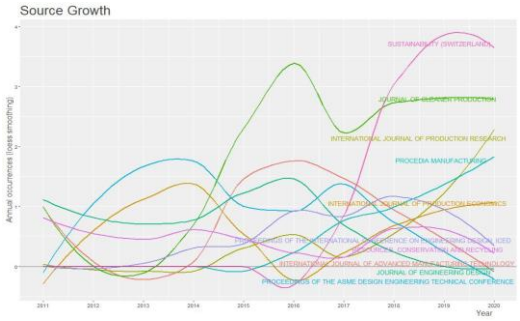

FIGURE 8. Annual occurrences (with Loess Smoothing) of top 10 sources Product Design using Sustainability Models

Design for sustainability	6
Ecodesign	6
TRIZ	5
Product design	5
Design for sustainability	5
Sustainable product development	5
Supply chain	5
quality function deployment	5
Green design	5

Table II reveals a trend in the writers' preferred keywords in the product design literature concerning the continuity model from 2011 to 2020. It exclusively displays those keywords appearing at least five times across all relevant publications, yielding a total of 838 unique author keywords. Consequently, 20 keywords surpass the threshold. Notably, "product design" emerged as the predominant keyword with 63 occurrences, making it an effective search term. Analysis of these publications revealed recurring keywords such as "sustainability", "sustainable design", and "sustainable product design". As illustrated in Table 2, these keywords consistently revolved around sustainability and green eco-development in product design (Ebrahim et al., 2020).

TABLE II THE OCCURRENCE OF TOP AUTHOR'S KEYWORDS PRODUCT DESIGN

Author's Keywords	
Occurrences Product design	63
Sustainability	25
Sustainable product design	20
Sustainable design	13
Life cycle assessment	12
Circular economy	9
Circular economy	8
Sustainable manufacturing	7
Green product design	7
Remanufacturing	6
New product development	6

Refer to Figure 9, illustrating keyword indices sourced from Scopus and arranged via Conceptual Structure Map - Method: MDS in biblioshiny for bibliometric application. Fundamental assessments reveal product design publications involving continuity models during the years 2011 to 2020 comprise two distinct clusters. The predominant red cluster encompasses all indexed keywords within the study's scope, featuring 26 high-occurrence terms including sustainability, eco-design, and new product development (NPD). The secondary blue cluster, comprising four keywords, includes sustainable, green product design, environmental management, and environmental performance. These findings underscore a notable trend among product design researchers towards environmental preservation and sustainable progression.

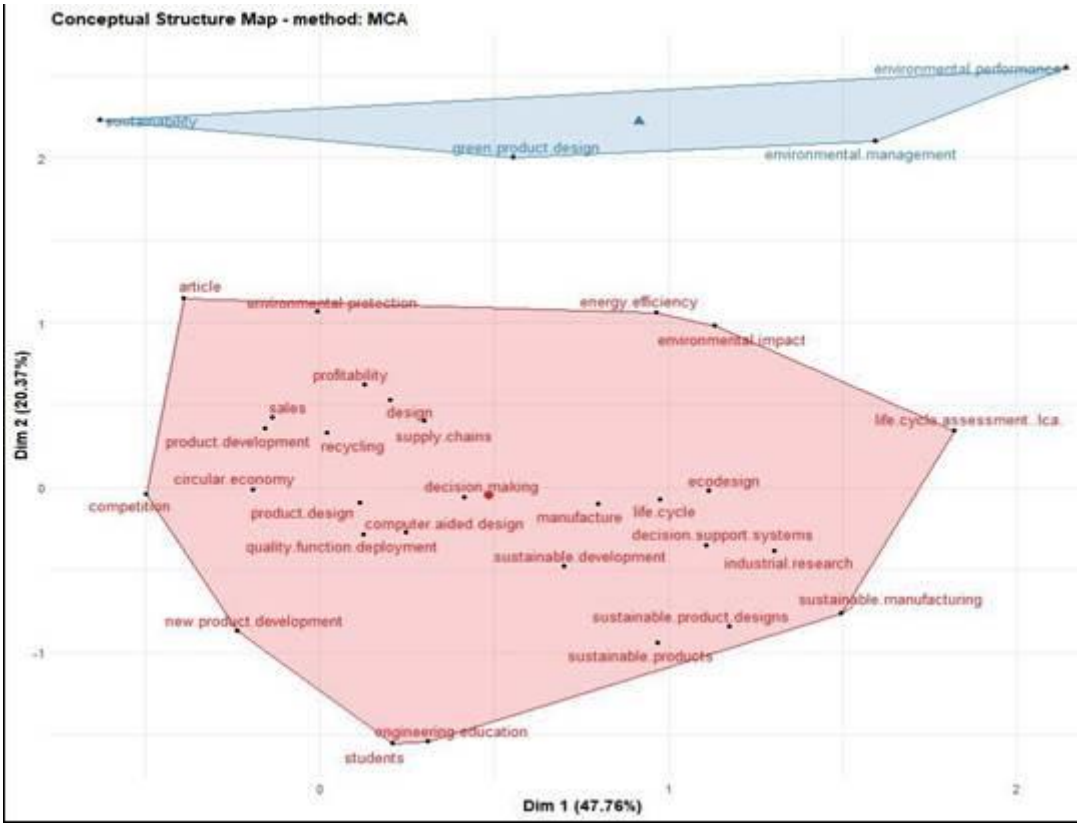

FIGURE 9. Conceptual structure map (with multidimensional scaling) of tip 30 Scopus keywords index Product Design using Sustainability Models bibliometric analysis

II. QUALITATIVE ANALYSIS

Sustainability models are employed in product design research trend aggregation, indexing key phrases extracted from publications to highlight research trajectories. Partially, bibliometric analysis identified significant research clusters, which were further examined by combining automatic keyword clustering with qualitative content analysis (Ebrahim et al., 2020).

Scopus database search revealed all publications utilizing the persistence model were arranged based on their average annual citation rate. This metric, calculated by dividing a paper's citation count by its post-publication age, aids in identifying crucial research areas. Statistical analysis of VOS, Biblioshiny For Bibliometrix, Qiqqa, and similar tools resulted in categorization of the top 50 highly cited papers (Ebrahim et al., 2020).

From this list, the literature with the highest average annual citation count was chosen for thorough examination. Articles citing at least 10 times annually out of 50 papers averaging 223.5-10.16 citations were included. The initial 14 articles satisfying these criteria underwent detailed qualitative analysis due to their subsequent average annual citation rate falling below 9.7.

A. Application models and methods for sustainable product design

In modern manufacturing, sustainable design objectives encompass cost minimization and resource conservation/recycling. However, for effective execution, models and methodologies are needed to comprehend consumer and market demands. Environmental protection tools like Quality Function Deployment (QFDE), consisting of consumer, environmental, and quality perspectives, play pivotal roles. Models such as QFDLE, Fuzzy Decision Experimentation and Evaluation Lab, and Fuzzy Analysis Network Process (FANP) assist firms and designers in establishing optimal design procedures for environmental sustainability. Incorporating QFDE within FANP yields a prioritization technique applicable at the initial design phase, benefiting Life Cycle Engineering (LCE; de Aguiar et al., 2017). This model has been implemented in real-world businesses and is gaining traction in R&D.

The selection of sustainable product design methodology involves familiarity with dry transformers and average methods. For successful integration of QFDE and FANP, understanding the significance of technical requirements is crucial due to the lengthy development process associated with matrix series. Thus, researchers should prioritize cost, product quality, and environmental pollution, key elements of sustainable

design. To ensure accurate matrix series, a queue is necessary, posing challenges for experts and scholars. The MMDE algorithm can represent matrices with a relational graph of queue values or binary. Currently, Professors Li and Zeng (2020) propose a method for constructing influence relation graphs and binary matrices.

Understanding the matrix approach to sustainable product design models provides clarity about the practicalities of DFS. Integrating QFDE methodology enhances focus on cost, product quality, and environmental criteria throughout the product design process, aiding designers or enterprises in making informed decisions. QFDE can also be utilized alongside other models to aid manufacturers across various industries in their sustainable product design journey.

While social considerations are vital in sustainable product design, QFDE's modeling framework lacks comprehensive coverage, considering solely the entire product lifecycle. Moreover, QFDE requires goal planning models to mitigate unforeseen variations in the manufacturing process.

B. Evolving systems for sustainable product design

Sustainable product design can adopt chronological organization, likely dividing it into four timelines encompassing product, product service system, spatial society, and socio-technical system (de Aguiar et al., 2018). Despite complexity, effective design requires precise goal definition for systematic progression. Understanding DFS evolution aims to discern its framework and methodology shift from product-centric to systemic transformation. Presently, product design has enhanced significantly in knowledge acquisition and articulation. Reviewing past studies and integrating them with contemporary ones can expedite product research advancement.

Understanding product design's essence is crucial, as its research domain adapts to environmental shifts and evolving comprehension. Product production varies across companies or teams. Generally, product design intertwines engineering and design contexts. Design directed towards purpose is product design, as teleology pertains to engineering design. Design process concepts like conceptual design, function mapping, modeling, and simulation, along with ontology and net semantics, evolve over time. Present day product design initiates with conceptual sketching, progressing through design decision-making, exploration, computational aid, and culminating in VR-assisted final designs. Regardless of changes, product design revolves around a lifecycle.

Thus, examining evolving systems for sustainable product design translates into future research trends. We currently stand at the brink of product design method implementation and knowledge extraction. Specific influences have already impacted DFS, potentially influencing future research directions including: 1. wiki database proliferation; 2. AI problem solvers; 3. bio-sensing design technologies; 4. large-scale collaborative product shelving; 5. naturalized interactive interfaces; and 6. sustainable systems. Currently, product conception and democratization are imperative trends, influenced by designing user-friendlier products and wireless manufacturing/supply chain expansion. Thus, sustainable product design is an irrefutable global research trend, necessitating incorporation of the DFS platform into business model design.

III. CONCLUSION

This article examines a comprehensive quantitative and qualitative analysis of product design literature published during 2011-2020. The Scopus database was queried for Moamen products, revealing key trends such as sustainability. Refining the data set via a deep dive into publication year, country, source, keywords, and themes produced insights regarding a rise in sustainability-focused product design publications. It shows potential for continued growth following a slower initial phase in the last decade. The study assessing collaborative efforts among scholars across nations serves as an ideal guidance tool for emerging scholars interested in global partnerships. According to international publication records, China leads in terms of both publications and international collaborations, followed by the US. Author keywords and indexed keywords spanning a decade reveal research hotspots, primarily centered around sustainability and its associated methodologies. The analysis of author keywords indicates that sustainability in product design research primarily revolves around sustainability, sustainable product design, sustainable design, life cycle assessment, Circular economy, circular economy, sustainable manufacturing, design for sustainability, sustainable product development, etc. The factor analysis of keyword indices and qualitative content examination of the most frequently utilized publications reveals a consistent emphasis on sustainability and model/method utilization. This paper aims to illustrate the evolving nature of sustainability-oriented product design research during the 2011-2020 period. It provides critical insights into the evolution of product design, sustainability concept applications, and future research trajectories within the field. Consequently, a surge in researchers focusing on contemporary sustainable product design issues and the development of sustainability concepts can be anticipated, leading to a significant increase in publications.

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