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Contour crafting in architectural applications: A comprehensive bibliometric analysis

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ABSTRACT

In recent years, automated systems have been widely adopted in construction to reduce labor costs and increase productivity with high accuracy. This article presents a bibliometric analysis of contour crafting (CC) research published from January 1, 1996, to December 31, 2022. The analysis aimed to uncover connections among researchers, institutions, publication sources, and other aspects of CC research. The study reveals a significant uptick in CC articles published across various journals in recent years. Notably, researcher Khoshnevis from the United States has made substantial contributions to CC, publishing approximately 35 articles with 2,323 citations. The United States, China, Australia, and India stand out as influential countries in CC research and development. This article's findings provide encouragement and inspiration for young researchers to explore new opportunities in this field.

Keywords: contour crafting; bibliometric analysis; VOSviewer; network visualization; architecture

1. INTRODUCTION

In recent years, India's construction sector has played a crucial role in driving the country's economic growth, contributing significantly to GDP expansion. Despite India's abundant labor force, the construction industry confronts challenges such as high labor costs and limited adoption of technological advancements. To tackle these issues, many construction firms are increasingly adopting advanced technologies to automate manual processes. The use of robots in various construction applications has grown, alongside other technological innovations. Studies indicate that robots can handle tasks like material handling and constructing intricate structures, underscoring their role in efficiently building complex edifices with constrained resources. While advanced robotic solutions are gaining traction, there remains a critical need to identify automated methods that achieve comparable outcomes with fewer resources and less labor.

A cutting-edge technology closely related to 3D printing, namely, contour crafting (CC), has increased in popularity for architectural applications (Khoshnevis, 2004). Developed by Behrokh Khoshnevis in the early 2000s, CC aims to automate construction processes, significantly cutting labor costs and construction time while enhancing precision and minimizing waste (Rouhana, 2014; Akhnoukh, 2021). Notably, CC can construct a 200-square meter, two-story house in an incredibly short timeframe (Zhang and Khoshnevis, 2010). By utilizing a robotic arm to extrude building materials in layers, CC offers a promising alternative to traditional methods, employing computer-controlled machinery to deposit a variety of materials. This capability provides architects with increased design flexibility, enabling exploration with innovative forms and materials such as thermoplastics, thermosets, ceramics, clay, and concrete.

In architecture, CC facilitates the creation of complex geometries that are often difficult or impossible to achieve with conventional techniques (Hwang and Khoshnevis, 2005). CC's automation revolutionizes traditional layer-by-layer construction, seamlessly constructing entire houses complete with integrated electrical, plumbing, drywall, and insulation systems. This approach ensures precision and pollution-free construction. Within the architectural sphere, CC holds vast potential to revolutionize building design and construction, addressing critical issues such as sustainability and affordable housing. The integration of CC into architectural practice is transforming building design and construction methods. Construction robots are increasingly utilized in CC, promising significant reductions in labor costs without compromising product quality. Furthermore, researchers are actively optimizing machine operation planning for CC, unveiling its potential for further automation in construction (Zhang and Khoshnevis, 2013).

CC is an additive fabrication technology primarily used for creating complex architectural profiles. Automation in CC is increasingly emphasized by researchers for its potential to reduce raw material wastage, enhance accuracy, and lower labor costs. This technology combines computer-aided design (CAD) and computer-aided manufacturing (CAM) to streamline the construction process (Kwon, 2002; Khoshnevis et al., 2016). CC constructs large-scale structures using materials such as concrete, polymer, ceramic, or sulfur concrete, deposited layer by layer through a nozzle, and controlled trowel mechanisms that manage angle and orientation (Huthman, 2017), as shown in Figure 1.

As CC continues to advance, comprehensive analyses are crucial to understanding its current status, emerging trends, and future prospects. Examining the current state of CC provides valuable insights into its potential to reshape the architecture and construction industries.

This bibliometric analysis aims to offer a detailed overview of the research landscape on CC in architectural applications. By analyzing publication trends, key authors, influential publications, and primary research themes, this study aims to underscore the development and impact of CC technology in architecture. The analysis will encompass a review of publication countries, affiliations, citation metrics, and collaborative networks to illuminate the collaborative dynamics of research in this field. The primary objective of this article is to guide future researchers by summarizing the insights gleaned from existing literature on CC.

Figure 1. CC robot (Zhang and Khoshnevis, 2013)

2. MATERIALS AND METHODS

This study aims to conduct a thorough bibliometric analysis of CC in five sequential stages, as depicted in Figure 2. Initially, search criteria are defined to identify relevant published articles. Articles are then collected based on these criteria, followed by a refinement stage to ensure the inclusion of articles specifically related to CC. The retrieved results are meticulously analyzed to uncover trends and insights within the CC literature. Finally, the findings are synthesized and presented comprehensively, providing a detailed overview of research patterns and highlighting areas for future exploration and development in CC technology.

In conducting this bibliometric analysis, the selection of appropriate keywords is critical. Utilizing databases such as Scopus and Web of Science (WoS), which host multidisciplinary articles with significant citation impacts, ensures comprehensive coverage. This study specifically focuses on the application of robots in CC. Initially, the search concentrated on articles related to robots in architecture using the keywords "Robot" OR "Architecture". Subsequently, the search expanded to include keywords "Robot" OR "Contour" OR "Crafting" OR "Architecture" to capture relevant literature on CC. Articles were retrieved from Scopus using these keywords without quotation marks and with asterisks to broaden the search. Scopus was chosen over WoS due to its larger database and detailed bibliographic information, including author details, publication year, volume, issue numbers, and more, facilitating a comprehensive analysis in this study.

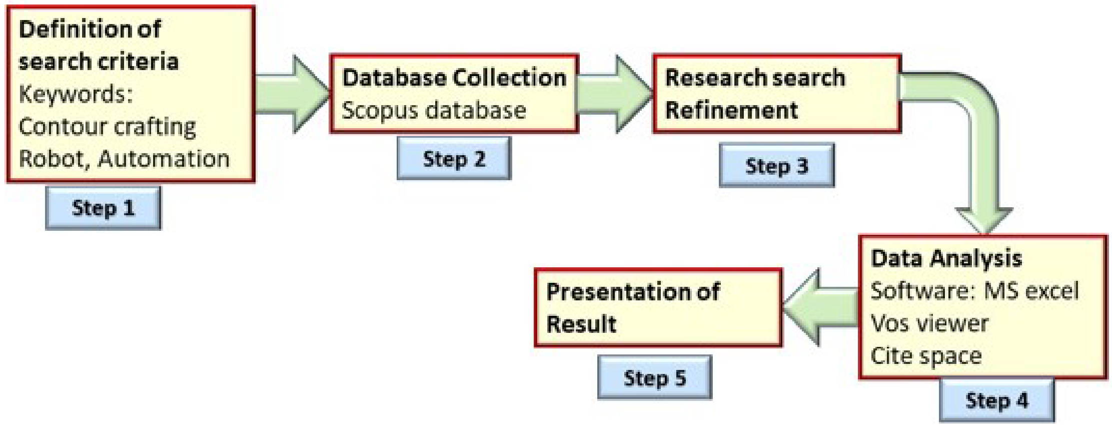

Figure 2. Stages of bibliometric analysis

After selecting the suitable keywords related to CC, the articles were retrieved from the Scopus database from 1950 to December, 31. 2022. While many articles related to architecture and robots are available, the articles related to CC are available only from 1996 in the Scopus database. Hence, the articles published from 1996 to 2022 were considered. To retrieve the articles accurately, the criteria were refined and the results further filtered. Finally, the results were exported in the .CSV format. The obtained results were further analyzed and bibliometric networks were constructed and visualized using the VOSviewer software. The networks were constructed and differentiated by using different colors. During the last step, the final results were presented for further analysis.

3. RESULTS AND DISCUSSION

The articles related to CC were retrieved from the Scopus database and analyzed using standard methods and tools. The obtained bibliometric analysis results are discussed in terms of performance analysis, countries/regions.

3.1 Annual indicators of publications and citations

Figure 3 and Figure 4 present the trends of annual publications and citations for CC, respectively. As illustrated in Figure 3, the number of articles related to CC has gradually increased, reaching a peak in 2021. This trend indicates that CC is a significant research area in modern architectural engineering.

Figure 4, reveal a notable upward trend in citations of CC articles over time. The first citation appeared in 1997, with citation counts gradually increasing from then until 2022. Initially, research output in the CC field was limited, resulting in relatively low citation counts until approximately 2017. However, as depicted in the figures, citation counts experienced a significant rise post-2018. This surge can be attributed to technological advancements that have facilitated the adoption of automated systems in architectural applications. Consequently, the increasing emphasis on automation within architecture has attracted more researchers to explore automated CC methodologies, thereby driving the observed increase in citations from 2018 onwards.

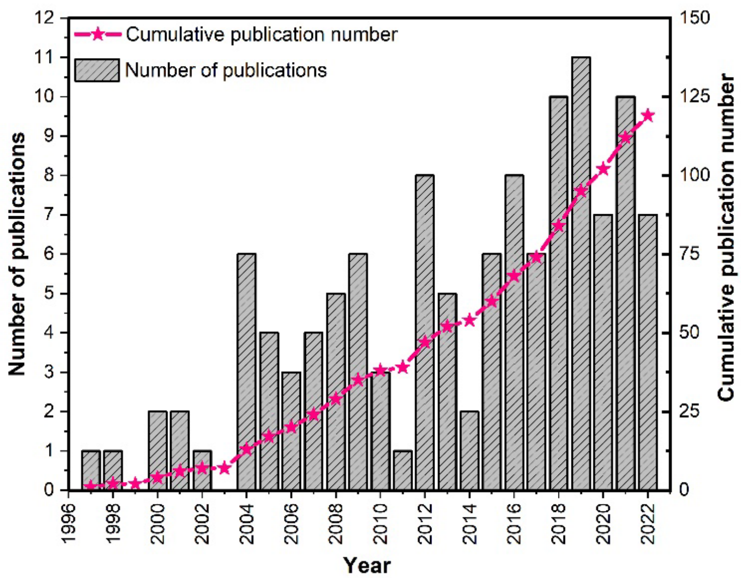

Figure 3. Details of annual CC publications

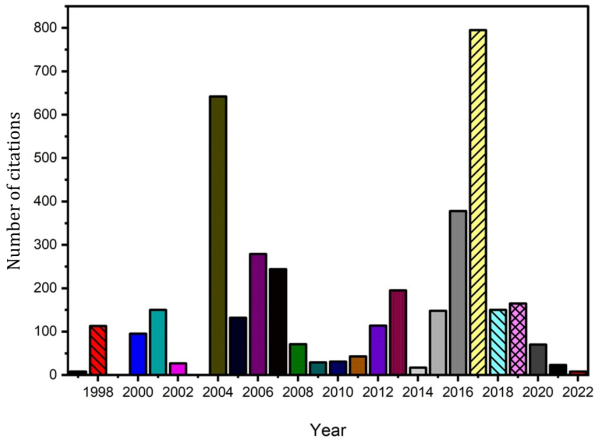

Figure 4. The details of CC article citations

3.2 Co-authorship analysis of authors

This paper employed the VOSviewer tool to analyze co-author relationships among authors in CC research, aiming to illuminate collaborative pathways and enhance understanding of knowledge exchange dynamics. Utilizing 'co-authorship' as the analysis type and 'authors' as the unit of analysis, the author cooperation network was generated to visually represent connections among 259 authors in the CC field. Authors who were not interconnected with others were filtered out, resulting in a map highlighting the 40 most collaborative authors organized into 9 clusters, each represented by a distinct color. Each author was exclusively assigned to one cluster, delineated by the resolution parameter, facilitating the identification of key collaborators within specific thematic areas (van Eck and Waltman, 2014). The network displays connections between authors through curved lines, known as links, indicating co-authorship relationships within clusters or across different clusters.

Figure 5a shows that author Khoshnevis et al. (2006) prominently features with a larger node size and font, reflecting a substantial total link strength (TLS) of 83 from 39 links, spanning 35 publications and affiliations with 9 clusters. This, in turn, underscores Khoshnevis's extensive collaboration within the CC research community, particularly highlighted by connections with authors clustered in green, indicating robust co-authorship relationships.

Figure 5b presents an overlay visualization of co-author networks generated using VOSviewer, showcasing the evolution of research collaborations and author structures over time. This visualization is similar to the network visualization but adds a temporal dimension, where the color of each node represents the average year of the authors' publications. The timeline of research activity is indicated by a color scale: dark blue for early years and red for recent years. Authors are plotted accordingly, with Author Bukkapatnam (violet) publishing around 2001, Khoshnevis (green) around 2011, Yuan (orange) between 2016 and 2018, and Xia B. and Davitalab (closer to red) around 2018, reflecting their respective average publication years.

Figure 5c offers a density view of the primary authors in CC research, illustrating collaboration density. In this visualization, colors range from red, indicating high collaboration density (hotspots), to yellow for moderate concentration, and blue/green for lower density. Khoshnevis and Yuan are identified as key hotspots: Khoshnevis is marked in red, highlighting his centrality and foundational contributions to the field, while Yuan is in yellow, indicating significant and ongoing contributions. Authors depicted in green or blue have comparatively lesser contributions. This overview helps to identify the most collaborative and influential authors within the CC research community, providing insights into the field's intellectual landscape.

The list of the top 10 authors was sorted based on the highest number of publications, including citation counts and TLS information, and is presented in Table 1. Yuan X. has the second-highest total link strength of 25, indicating his connections with other authors in CC research. It is also noteworthy that Bosscher P. and Williams II R. L. have the third-highest TLS of 17 in this CC research.

Table 1. Details of the top 10 researchers in CC

	Author	Documents	Citations	TLS
1	Khoshnevis B.	35	2,323	83
2	Yuan X.	8	493	25
3	Bosscher P.	7	223	17
4	Williams II R. L.	7	223	17
5	Zhang J.	6	205	13
6	Zahiri B.	4	76	13
7	Thangavelu M.	4	101	12
8	Kazemian A.	4	458	11
9	Xin M.	4	45	8
10	Zareiyan B.	4	335	4

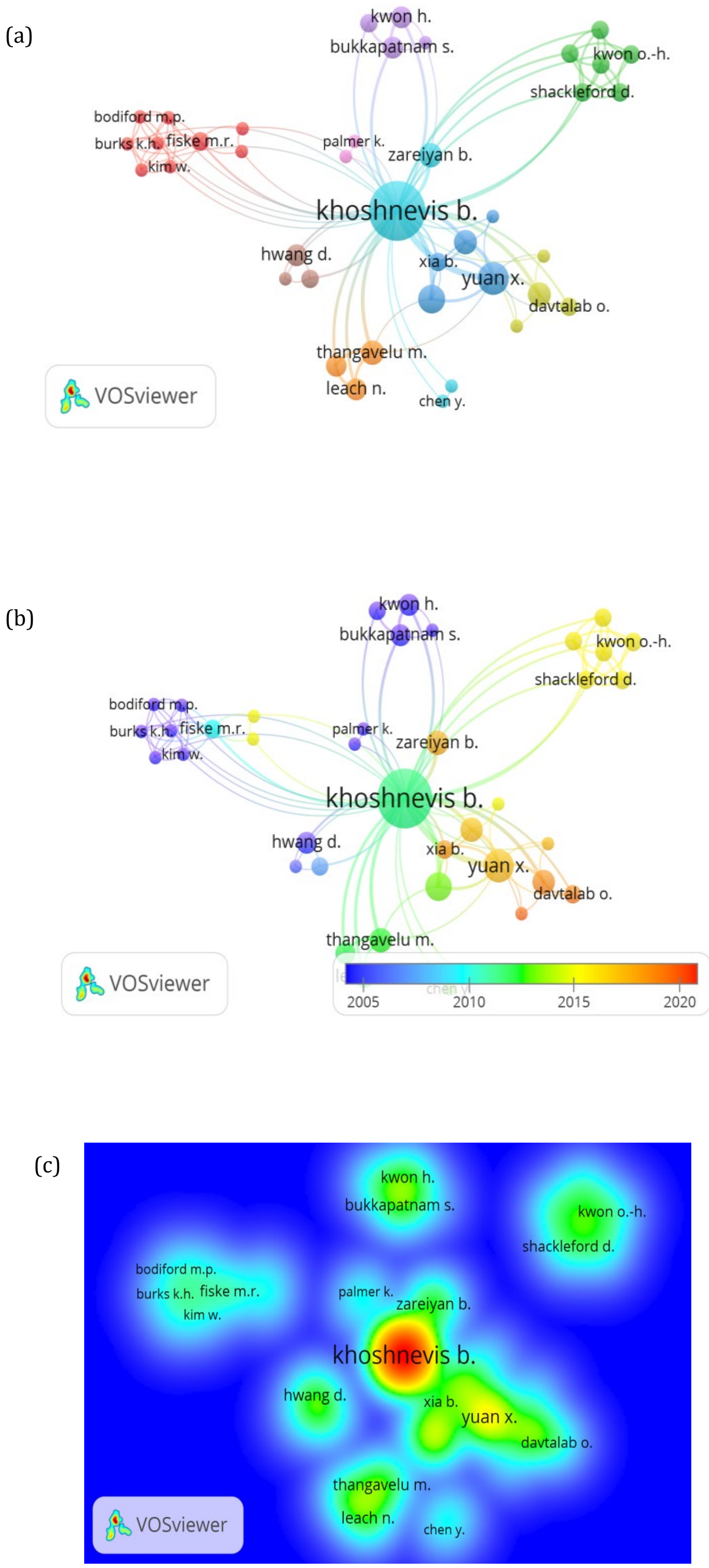

Figure 5. Visualization of co-authorship analysis: (a) network visualization, (b) overlay visualization, and (c) density visualization

3.3 Analysis of keywords

Keywords offer valuable insights into the content of a paper and help identify key subject areas within CC research. Figure 6 illustrates the percentage of keyword occurrences across various publications, with each keyword represented by differently colored boxes. Significant keywords are highlighted by larger box sizes. For example, "3D printers" appears in 28 publications (8%), "contour crafting" in 23 publications (6%), and "construction industry" in 17 publications (5%).

Word clouds provide scholars with insights into the most common words prevalent in a study or across multiple studies. In these visual representations, prominently published keywords appear in larger fonts, while less prominent keywords are shown in smaller fonts. Figure 7 displays the word cloud for CC research abstracts, highlighting the keywords that are most frequently mentioned. Terms such as 3D printing, construction, concrete, rapid prototyping, fabrication, additives, buildings, geometry, mixtures, and human are shown in large fonts, indicating their significance in the surveyed studies.

VOSviewer software was utilized to extract keywords from the collected Scopus data and identify the links between them. The keyword analysis is presented in Figures 8 showcasing the network visualization, overlay visualization, and density visualization, respectively. This analysis considered keywords from the titles, abstracts, or keyword lists of the studies, resulting in 988 keywords grouped into 27 clusters. Each node represents a keyword. The keyword "contour crafting" appeared in 42 journals, with a TLS of 573 and 375 links, depicted in the grey-colored cluster in Figure 8a. Other keywords in this cluster include 3D printer, automatic construction industrialization, production system design, lean construction, lean production, and waste in construction. The next most frequent keyword was "3D printers," with 28 occurrences and a TLS of 513, followed by "additive manufacturing" with 19 occurrences and a TLS of 294. The keyword "construction industry" had 17 occurrences and a TLS of 309. Keywords without interconnections were excluded from the analysis.

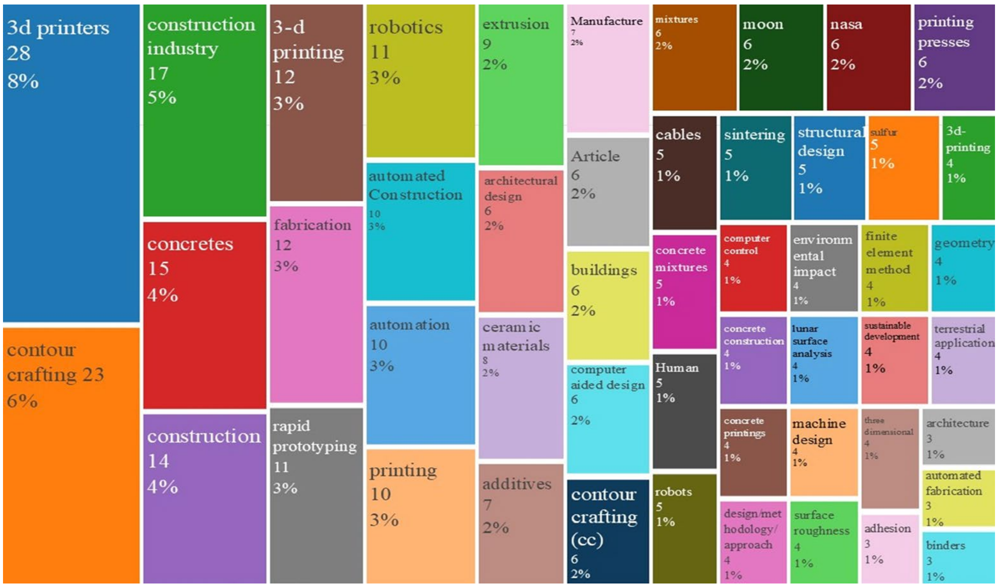

Figure 6. Keyword occurrence percentage

Figure 7. Word cloud of the keywords

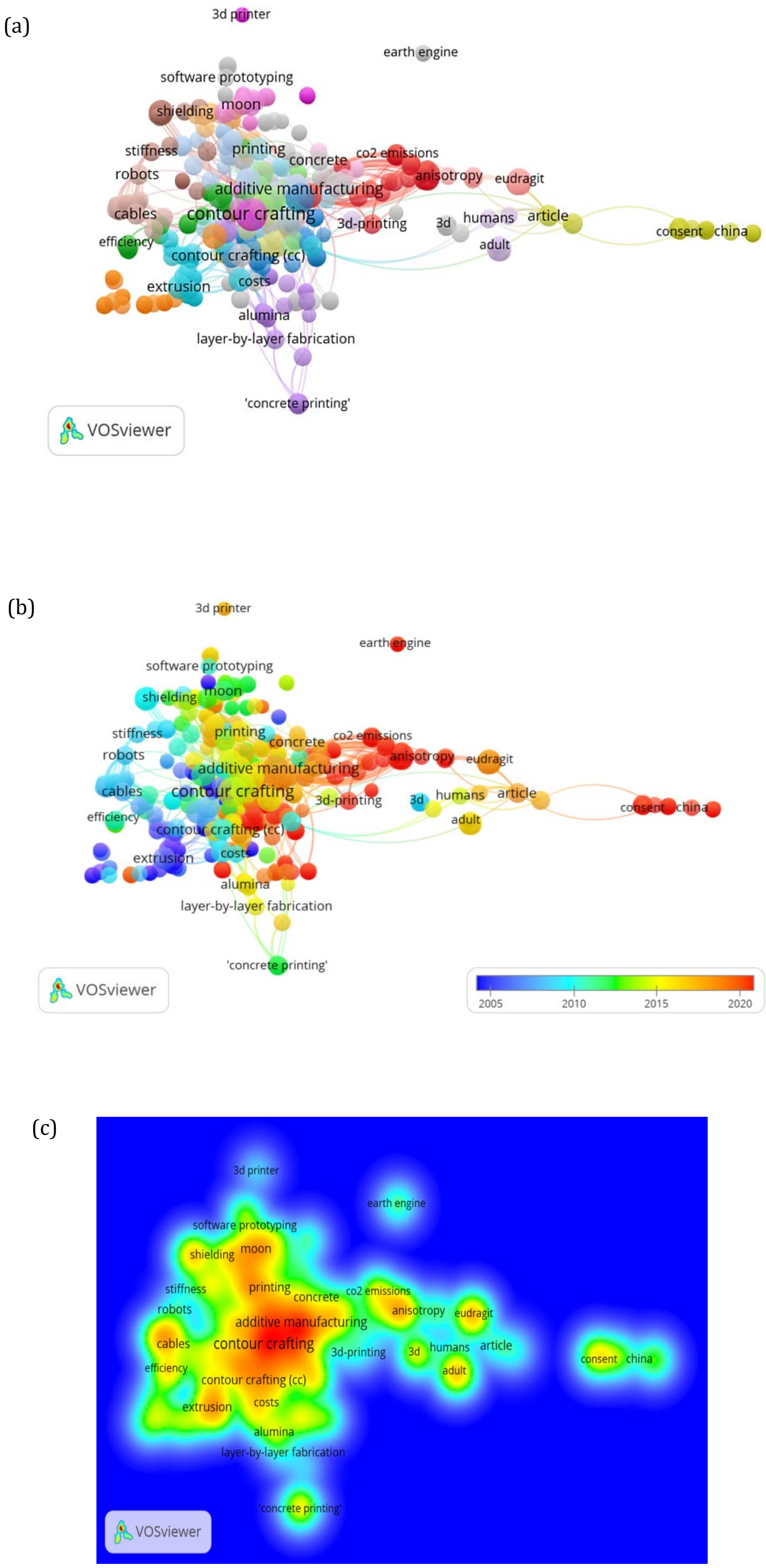

Figure 8. Visualization of keyword analysis: (a) network visualization, (b) overlay visualization, and (c) density visualization

VOSviewer can also analyze the year of occurrence of keywords, as shown in Figure 8b, facilitating the tracking of the CC field's evolution. The average publication year of a keyword is indicated by its color on the time scale. As a case in point, "extrusion" has an average publication year of 2006, "robots" around 2008, "contour crafting" in 2014, "additive manufacturing" in 2015, and "casting" and "contour crafting" in 2022. Each node represents a keyword, and the density of the node changes according to its value and surrounding keyword values (Figure 8c). The analysis highlights key focus areas such as contour crafting, additive manufacturing, costs, printing, concrete, the Moon, extrusion, cables, efficiency, anisotropy, and CO_2 emissions. The blue area on the periphery of the visualization indicates research frontiers, with emerging keywords including earth engine, layer-by-layer fabrication, robots, stiffness, and 3D printer. Additionally, the 15 most important keywords in CC research are listed in Table 2 sorted by the highest occurrences.

3.4 Bibliometric analysis of citations

3.4.1 Analysis of article citations

The citation analysis, performed using VOSviewer software, generated network and density visualizations presented in Figure 9a and Figure 9b, respectively. In Figure 9a, each node represents a document, with links indicating citation connections between them. Larger nodes signify articles with higher citation counts. Small clusters represent related articles on similar topics, enabling the identification of the most cited articles within specific clusters based on node size. The analysis identified 11 clusters consisting of 59 documents and 125 links; unlinked articles were excluded. Of the 118 documents analyzed, 98 had at least one citation.

Figure 9a highlights Khoshnevis's 2004 article, "Automated construction by contour crafting-related robotics and information technologies" (automation in construction), as the most influential, with 640 citations and 33 links, significantly impacting CC research. The second most cited article, "Cementitious materials for construction-scale 3D printing: laboratory testing of fresh printing mixture" by Kazemian et al. (2017), published in Construction and Building Materials, has 337 citations and 8 links. The third highest citation count was 263 for "Mega-scale fabrication by contour crafting" by Khoshnevis et al. (2006), with 13 links. These highly cited articles are pivotal references for researchers in CC.

Figure 9b shows the authors with the most citations over time, indicated by node color and density on a time scale. From blue to red, the timeline progresses, with Bukkapatnam's average publication year in 2001. Khoshnevis, represented in green, has an average publication year of 2011 and the highest citation count. Recent publications, marked in red, include Luhar's 2020 work with 8 citations and Akhnoukha's 2021 article, which cites the works of Khoshnevis and three other authors, demonstrating a connection to earlier research and further contributing to the field. Key authors frequently cited in this domain include Khoshnevis, Yuan, Zhang, Bosscher, Thangavelu, Zareiyan, Bukkapatnam, Fiskem, Saito, and Hwang, all noted for their significant contributions and numerous publications.

Table 3 highlights the top 9 most-cited documents, with corresponding reference numbers being listed in the table. These influential papers have made significant contributions to the field.

Table 2. Top 15 keyword occurrences

	Keywords	Occurrences	TLS
1	Contour crafting	42	573
2	3D printers	28	513
3	Additive manufacturing	19	294
4	Construction industry	17	309
5	3D printing	16	210
6	Concretes	15	234
7	Construction	14	237
8	3D-printing	13	311
9	Rapid prototyping	13	150
10	Automation	12	184
11	Fabrication	12	163
12	Robotics	12	200
13	Automated construction	10	150
14	Extrusion	10	132
15	Printing	9	181

Table 3. Details of the top 9 articles with more citations

	Document	Citations	Links	References
1	Khoshnevis	640	33	Khoshnevis (2004)
2	Kazemian	337	8	Kazemian et al. (2017)
3	Khoshnevis	263	13	Khoshnevis et al. (2006)
4	Hageri	247	8	Hager et al. (2016)
5	Bosscher	170	2	Bosscher et al. (2007)
6	Zareiyan	167	6	Zareiyan and Khoshnevis (2017a)
7	Zareiyan	133	8	Zareiyan and Khoshnevis (2017b)
8	Sakin	127	6	Sakin and Kiroglu (2017)
9	Perkinsi	125	6	Perkins and Skitmore (2015)

(a)

(b)

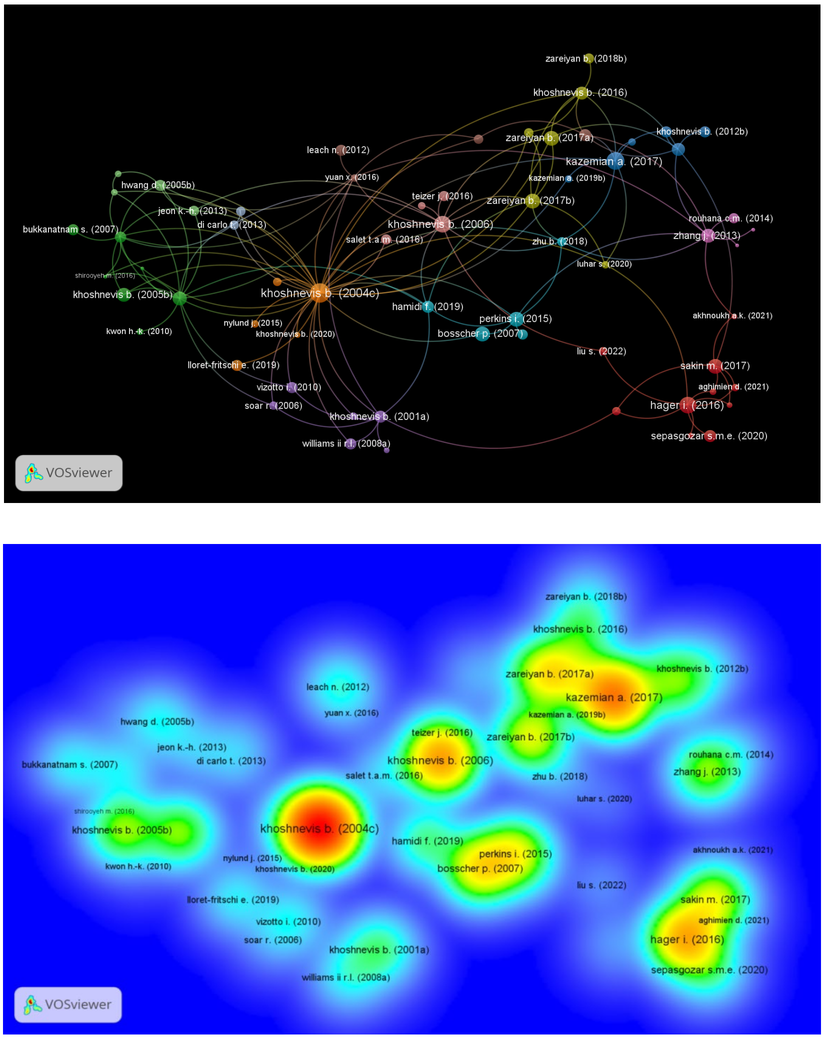

Figure 9. Visualization of document and citation analysis: (a) network visualization and (b) density visualization

3.4.2 Analysis of author citations

Figures 10(a) and 10(b) display the network and overlay visualizations of the author citation analysis, with each node symbolizing an author. The connections between nodes represent citation relationships among authors, and the size of the circles denotes the number of citations. Clusters illustrate groups of related articles, with closely related topics indicated by proximate clusters. Each connection has an associated strength value, and the TLS signifies the overall strength of citation links between authors.

The analysis identified thirty clusters, each represented in different colors, encompassing 138 authors with 585 citation links. Authors without citation links are excluded from the visualization. As shown in Figure 10(a), Khoshnevis in the orange cluster emerged as the most cited author with 2,323 citations, 119 links, and a TLS of 479, indicated by the larger font and circle size. Yuan, represented in violet, was the second most cited author with 493 citations, 28 links, and a TLS of 116. Kazemian ranked third with 458 citations, 23 links, and a TLS of 70. Bukkapatnam and Kwon had more citation links (44 each) and a TLS of 15 each, but they had fewer citations (177) and publications (3 each) compared to Kazemian This visualization effectively identifies the most influential authors and their citation connections in the field of CC research.

Table 4 provides details of the top 10 most cited authors, highlighting their citation counts and contributions to the field.

3.4.3 Analysis of organization citations

The analysis of organizational citations from the Scopus database offers valuable insights. Figures 11(a) and (b) illustrate the organizational citation details, with 175 organizations included in the analysis. After excluding unlinked organizations, 85 organizations were grouped into 34 clusters with 173 links. Organizations within the same cluster are related and are distinguished by color. Nodes represent institutions or departments, with larger nodes indicating highly cited articles. Linked nodes show citation connections, with thicker links indicating a greater number of citations. TLS represents the strength of citation links between organizations.

(a)

(b)

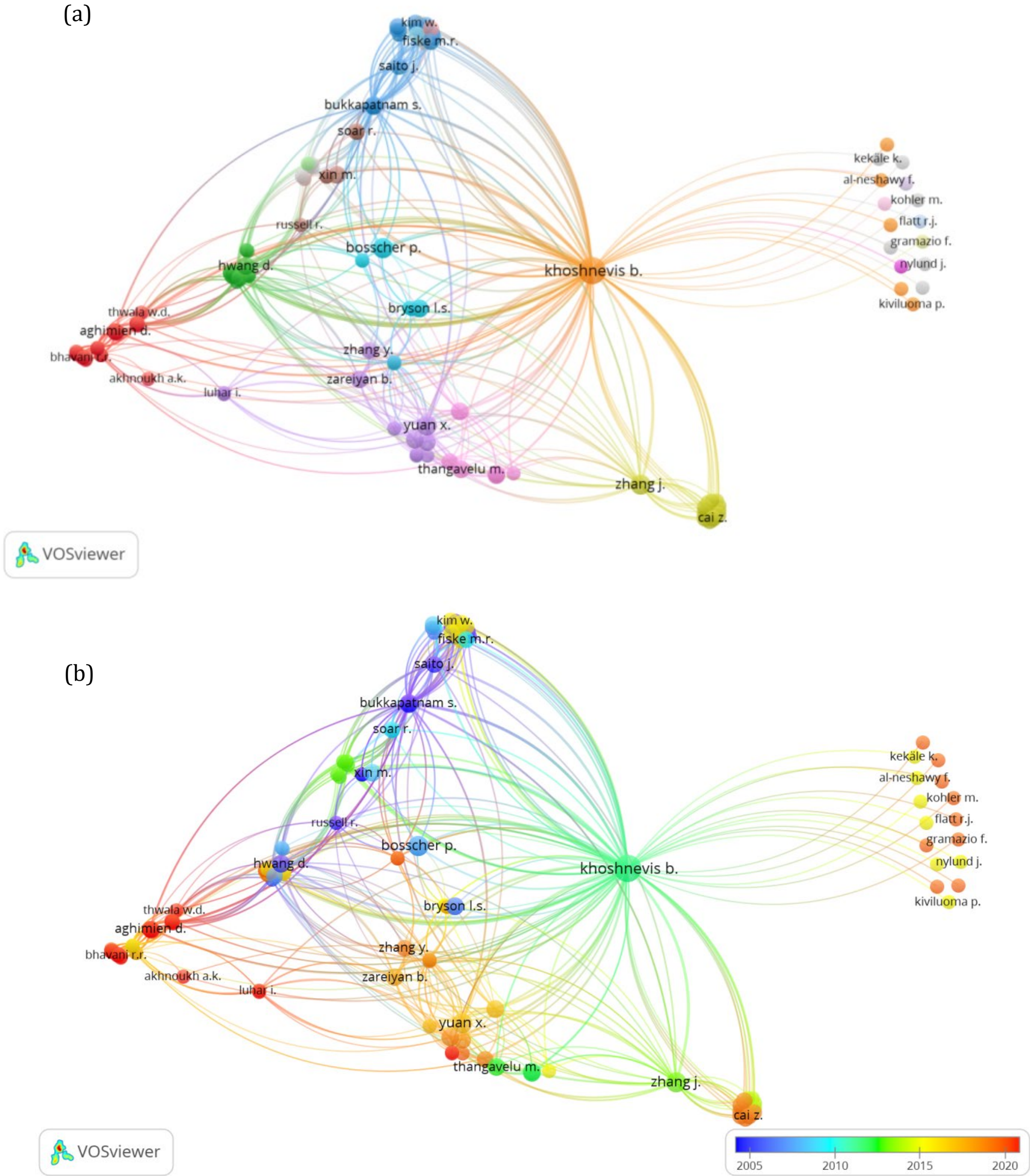

Figure 10. Visualization of author and citation analysis: (a) network visualization and (b) overlay visualization

Table 4. Details of the top 10 most cited authors

	Author	Documents	Citations	TLS
1	Khoshnevis	35	2,323	479
2	Yuan	8	493	116
3	Kazemian	4	458	70
4	Cochran	1	337	30
5	Zareiyan	4	335	51
6	Hwang	3	296	72
7	Yeh	2	273	46
8	Yao	1	263	42
9	Golonka	1	247	30
10	Hager	1	247	30

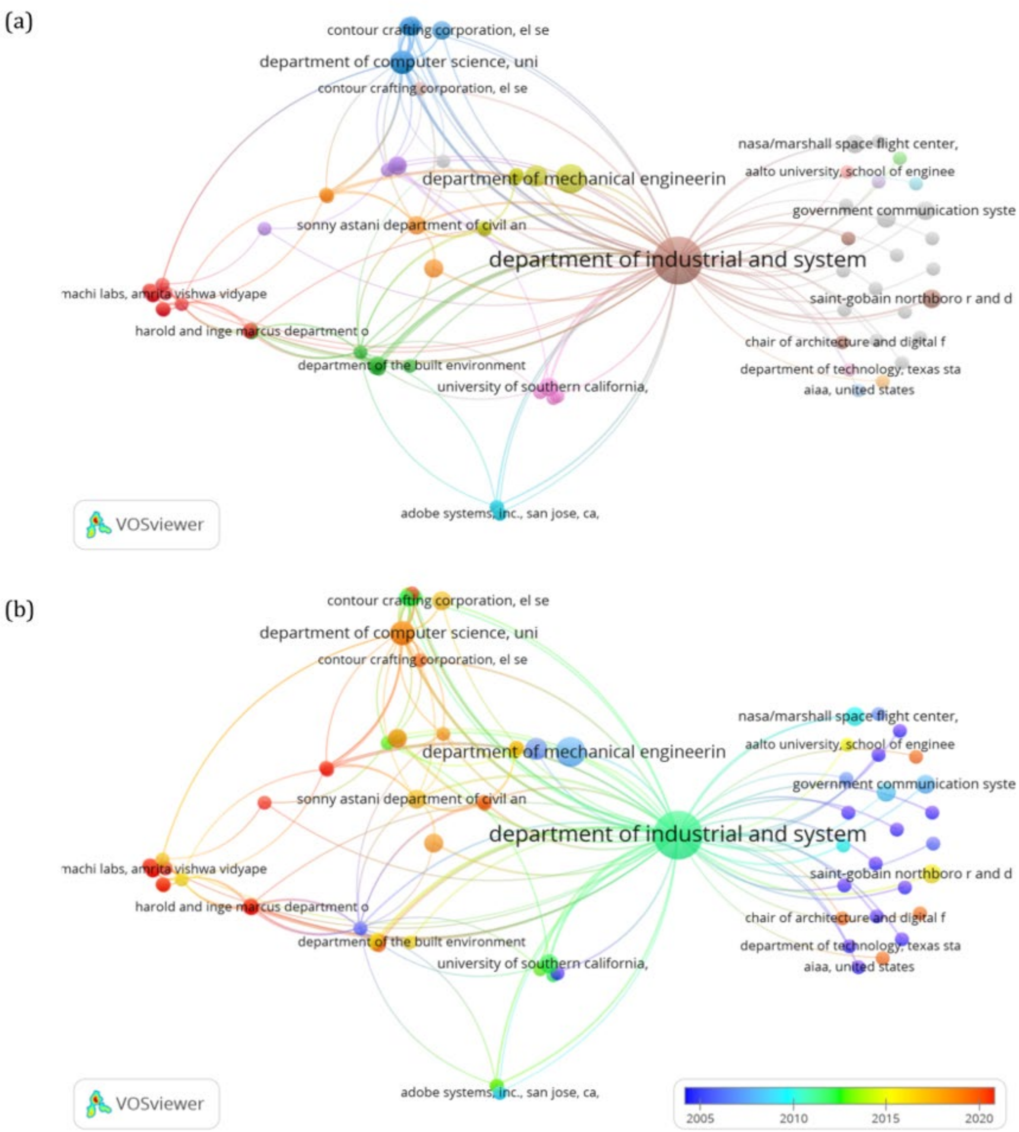

Figure 11. Visualization of organization and citation analysis: (a) network visualization and (b) overlay visualization

The Department of Industrial and Systems Engineering at the University of Southern California lead with the highest number of citations (2,194) and the highest TLS (210), establishing citation links with 71 departments or institutions. Following closely, the Sonny Astani Department of Civil and Environmental Engineering at the same university ranked second with 758 citations and a TLS of 62, while the Department of Computer Science, University of Southern California, followed with 458 citations and a TLS of 40. Additionally, Cracow University of Technology in Poland and the Department of Mechanical Engineering at Ohio University, United States, also demonstrated significant citation counts.

The analysis underscores the substantial contributions made by various departments at the University of Southern California to contour crafting research through extensive publications, collaborations, and citations. Globally, numerous academic institutions are actively collaborating in CC research publications, thereby fostering the advancement and expansion of the field.

Table 5 presents the top 10 institutions ranked by number of citations, alongside their corresponding publication quantity and link strength.

3.4.4 Analysis of country citations

Table 6 presents the top 10 productive countries, ranked by the number of publications and their related information. The United States, China, Australia, and India emerged as the top four countries with the highest productivity. The quantity of publications acts as an indicator of a country's productivity within a particular study. Notably, publications originating from the USA and Australia achieved the highest average number of citations per document, with 46 citations. France closely followed with an average of 15.7 citations, followed by the United Kingdom with 15 citations, Germany with 12.2, and Austria with 10.5. The United States notably leads in contributions to the CC field, accounting for 42.9% of the total 140 documents analyzed.

Table 5. Details of the top 10 most cited organizations

	Organization	Citations	Documents	TLS
1	Department of Industrial and Systems Engineering, University of Southern California, United States	2,194	26	210
2	The Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, United States	758	6	62
3	Department of Computer Science, University of Southern California, United States	458	4	40
4	Information Science Institute, University of Southern California, United States	263	1	25
5	Cracow University of Technology, Poland	247	1	17
6	Department of Mechanical Engineering, Ohio University, United States	223	7	7
7	Department of Civil Engineering, Ohio University, United States	178	3	3
8	Hasan Kalyoncu University, Turkey	127	1	13
9	School of Civil Engineering and Built Environment, Queensland University of Technology, Australia	125	1	10
10	NASA/Marshall Space Flight Center, Huntsville, United States	102	2	1

Table 6. Details of the top 10 most cited countries

Rank	Country	Documents	Citations	AC	%	TLS
1	United States	60	2,760	46	42.9	66
2	China	8	26	3.3	5.7	13
3	Australia	6	276	46.0	4.3	11
4	India	6	32	5.3	4.3	9
5	Germany	5	61	12.2	3.6	1
6	United Kingdom	5	75	15.0	3.6	4
7	Finland	3	29	9.7	2.1	1
8	France	3	47	15.7	2.1	0
9	South Africa	3	13	4.3	2.1	5
10	South Korea	3	20	6.7	2.1	6

Note: %: percentage of publications for all 140 documents; AC: the average number of citations per publication.

Figure 12a provides an overview of international collaboration in the contour crafting (CC) field, where the thickness of links between countries' frames indicates the level of collaboration based on shared citations. Each country is depicted by a frame, with the size of the frame and font proportional to the number of citations, larger indicating more citations. After filtering out unlinked countries, 25 nations were represented by distinct colors.

Figure 12b depicts the evolving landscape of collaboration among countries over time. Temporal distribution patterns in publications highlight peaks for the United States in 2011, Australia in 2016, China and Taiwan in 2020, and India in 2018, reflecting shifts in research focus and evolving global partnerships.

Figure 12c presents a density map of country-wise publications, emphasizing the most productive nations in this study. Leading in productivity was the United States with 60 publications and a diverse network of collaborative partners, followed by China (8 publications), Australia (6 publications), and India (6 publications). The varying shades of red on the density map correspond to publication volumes, with darker shades indicating higher publication counts.

4. CONCLUSION

This article explores essential bibliometric insights crucial for assessing and advancing CC research. The analysis aims to enhance citations, collaborations, and technological developments within the field. Using the Scopus database and VOSviewer tool, this study examines CC's evolution from 1996 to 2022, analyzing author and document networks, keyword frequencies, and citation patterns across countries, organizations, authors, and documents. The findings indicate a steady rise in both publications and citations in CC research, underscoring its global significance and growing interest. Notably, the past decade has witnessed a substantial increase in publications, with peak citation rates observed in 2021 and 2022, reflecting ongoing advancements in CC technology.

According to Scopus, the USA has been a significant contributor to CC research, with the University of California leading in publications. NASA has also provided substantial financial backing for CC projects. The search identified 154 patents related to CC, predominantly from the United States Patent & Trademark Office (99 patents) and the European Patent Office (27 patents). Additionally, the keyword 'contour crafting' appeared in 42 articles, highlighting increasing interest in automation within the construction industry.

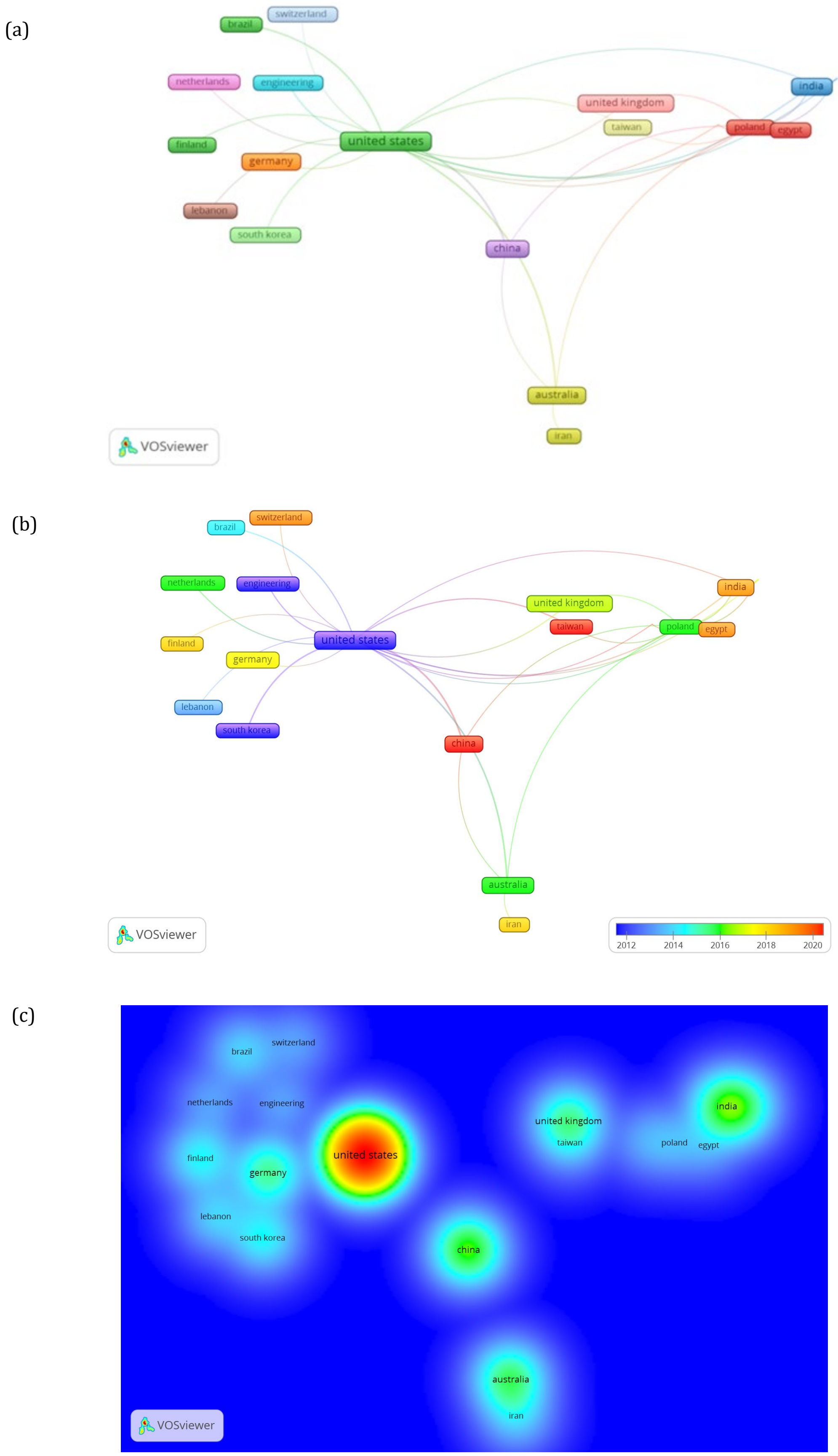

Figure 12. Visualization of country and citation analysis: (a) network visualization, (b) overlay visualization, and (c) density visualization

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