Understanding Sustainability in Off-Site Construction Management: State of the Art and Future Directions

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Abstract: Many countries and regions consider off-site construction a modern construction method that facilitates sustainability in the construction industry. Sustainability research in off-site construction (SROSC) is crucial for its development and is a nonnegligible part of its management. However, an in-depth understanding and critical analysis of SROSC to summarize recent research and inform future research directions are lacking. In this study, we address this issue by offering a mixed-review method integrating scientometric analysis and systematic review to explore state-of-the-art SROSC. We aim to uncover sustainability themes and topics, distinguish research trends, and identify gaps in knowledge that can be addressed in future research. Scientometric analysis was used to perform statistical analysis and visual map research on the knowledge landscape formed by 272 related studies of SROSC. The systematic review was used to identify and analyze six major knowledge themes (e.g., environmental, economic, social, decision-making, optimization, and industry management) and 21 knowledge topics for SROSC. We proposed possible future research directions based on the resulting structured body of knowledge. This research contributes to the body of knowledge by visualizing and analyzing the state-of-the-art of SROSC, as well as identifying the future research directions in this area to improve architectural, engineering, and construction practices. **DOI: 10.1061/(ASCE)CO.1943-7862.0002396.**

Author keywords: Off-site construction; Sustainability; Scientometric analysis; Systematic review; Body of knowledge.

Introduction

The construction industry produces approximately 33% of global carbon emissions and consumes approximately 40% of the world's raw materials, 16% of available water, and 40% of energy; thus, it is important to promote modern sustainable construction methods (Pan et al. 2012a). The global architecture, engineering, and construction (AEC) industry widely regards off-site construction (OSC) as a modern construction method that facilitates sustainability in terms of environmental protection, energy saving, emission reduction, efficiency improvement, and labor-friendliness (Ahn et al. 2020; Ji et al. 2020; Monahan and Powell 2011; Shahpari et al. 2020; Teng et al. 2018). OSC management is garnering attention in academic research and industrial applications because it is critical to achieving sustainable development in both industry and the built environment (Hosseini et al. 2018; Li et al. 2014b). Sustainability research in OSC (SROSC) management refers to content exploration that can contribute to sustainability performance (e.g., environmental, social, and economic) during the OSC process. SROSC has attracted considerable attention from researchers with a sequential increase in related publications (Hussein et al. 2021). Despite the desirability of such attention, the accumulation of publications in this field presents particular challenges (Shahpari et al. 2020). Thus, a frontier review of the body of knowledge is justified.

Previous review studies have provided us with significant knowledge and quantitative analysis methods, including holistic reviews (López-Guerrero et al. 2022; Wuni et al. 2020) and critical issues focused on OSC. Table 1 lists existing reviews concerning the holistic study and critical issues focused on OSC, such as carbon emissions (Teng et al. 2018), BIM (Yin et al. 2019; Zhang et al. 2021), supply chain (Hussein et al. 2021), environmental performance (Hu and Chong 2021; Jin et al. 2020), life cycle performance (Boafo et al. 2016; Kamali and Hewage 2016), stakeholders (Hu et al. 2019a), and policy (Luo et al. 2021b). Previous sustainability-related OSC reviews have focused on only one dimension (e.g., environmental sustainability), or they have only analyzed the most relevant indicators; however, they have not provided a structured body of knowledge. There is a lack of comprehensive review of the triple bottom line of the environmental, economic, and social dimensions of OSC sustainability. Specifically, the available literature does not summarize the exact nature, impact, and contribution of OSC in a way that combines visualization with in-depth analysis and most importantly lacks the analysis of critical and underexplored areas of SROSC (Luo et al. 2021a). To build a more structured and clearer SROSC body of knowledge to assist scientific research and industry practice, a frontier review is urgently required. This study addresses this gap

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Table 1. Summary of literature review in OSC

References	Methods	Research content	Research theme	
			Holistic review	Critical issues
Jaillon and Poon (2014)	Case study	Life cycle design in OSC	—	X
Kamali and Hewage (2016)	Systematic review	Life cycle performance of modular buildings	—	X
Jin et al. (2018)	Holistic review	Off-site construction	X	—
Teng et al. (2018)	Systematic review	Carbon emissions in OSC	—	X
Hosseini et al. (2018)	Scientometric analysis	Off-site construction	X	—
Hu et al. (2019a)	Content analysis	Stakeholders in OSC	—	X
Yin et al. (2019)	Mixed review	BIM in OSC	—	X
Innella et al. (2019)	Systematic review	Lean construction in OSC	—	X
Jin et al. (2020)	Critical review	Environmental sustainability in OSC	—	X
Wuni et al. (2020)	Scientometric analysis	Sustainability of OSC	X	—
Hu and Chong (2021)	Content analysis	Environmental sustainability in OSC	—	X
Qi et al. (2021)	Systematic review	Emerging technologies in OSC	—	X
Luo et al. (2021b)	Mixed review	Policies in OSC	—	X
Hussein et al. (2021)	Mixed review	Supply chain management in OSC	—	X
Zhang et al. (2021)	Scientometric analysis	BIM in OSC	—	X
López-Guerrero et al. (2022)	Case study	Sustainability indicators of OSC	X	—
The current study	Mixed review method	Sustainability of OSC	X	—

through a structured mixed-review method based on scientometric analysis and systematic review to visualize and generate a comprehensive objective portrait of the existing state of the SROSC, as well as to propose future research directions.

This mixed review can eliminate biased conclusions and subjective interpretations of domain knowledge and research trends while providing a deeper insight into research gaps and needs. Consequently, this research theoretically contributes to the body of knowledge in three folds: (1) the global research panoramic of SROSC is portrayed by updating the knowledge networks of publication, distribution of journals, article citations, and popular research topics; (2) research themes and topics regarding SROSC are identified; and (3) research gaps and future research directions are revealed via an in-depth analysis method.

The remainder of this paper is organized as follows. The Background Section reviews the research background and provides basic information. The Methodology Section presents a mixed-review method that integrates scientometric and systematic reviews. Subsequently, the scientometric analysis and systematic review sections provide a detailed analysis of the obtained results. The Discussion and Future Directions Section discusses the significant findings and proposes future research directions. The final section concludes the paper by highlighting the research contributions of this study.

Background

OSC is defined as the process of manufacturing building components in a controlled factory and transporting them to the construction site where the building is to be assembled (Taylor 2010). Various interchangeable terms express the concept of OSC in the global AEC industry (Hu et al. 2019a). Considering that the affix can reflect a profound contextual meaning, the previous study classified those terms into various categories according to the affix off-site (e.g., off-site construction/fabrication/manufacturing), modular (e.g., modular construction/building), pre- (e.g., prefabrication, preassembly, precast, and prework), and industrialized (e.g., industrialized construction/building) (Pan et al. 2012b). The affix "off-site" means that numerous construction activities in the spatial dimension occur outside the construction site. The affix "pre" indicates that several preworks in the time dimension are completed before on-site construction. The affix "modular" emphasizes the full integration of materials into modules outside the site in the product dimension in order to be directly installed on site. The affix "industrialized" promotes the formation of a complete industrial chain from stakeholders, technological innovation, and business processes in the industrial dimension, thus changing the fragmentation of the traditional industrial production process. Owing to these characteristics, OSC naturally exhibits sustainability properties.

The concept of sustainability has gained widespread recognition since the World Commission released the well-known Brundtland Report on Environment and Development (WCED) in 1987 (Lozano 2008). This concept is described as "the capacity to maintain something in a continuous state" (Lozano 2008) and has been applied by various other studies. Applying the concept of sustainability to OSC is an inevitable sustainable development trend for industrial upgrading (Hu and Chong 2021; Li et al. 2020a). Theoretically, the OSC can address all three sustainability principles of the triple bottom line (TBL) in the AEC industry (Li et al. 2020a): (1) for economic sustainability: standardization, production lines, lean process, and coordinated scheduling between off-site manufacturing and on-site construction can significantly improve efficiency and reduce costs (Arashpour et al. 2017; Dan et al. 2021; Li et al. 2018d). (2) For environmental sustainability, controllable production and scale effects can maximize energy efficiency, reduce greenhouse gas emissions, and eliminate wet-trade pollution and waste, thereby contributing to the sustainability of the construction process and the built environment (Hong et al. 2016b; Tam and Hao 2014; Teng et al. 2018). (3) For social sustainability, the OSC can actively respond to labor shortages and benefit occupational health and community disturbance; this people-oriented approach benefits social sustainability (Ahn et al. 2020; Hyun et al. 2021; Kordi et al. 2021).

However, although proponents of industrialized construction have focused on sustainability in OSC, the obstacles to industry-wide promotion have not yet been resolved (Yuan et al. 2021; Zhang et al. 2014a). Generally, the higher the off-site level, the better the environmental benefits and social sustainability. However, economic benefits have struggled to meet these expectations (Mao et al. 2015, 2016). Previous research has proven that the high cost overrun, time delay, and scheduling complexity of the use of prefabricated components limit economic sustainability (Hong

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et al. 2018). In addition, simultaneously improving environmental, social, and economic sustainability performance is a significant challenge for academic research and industry practice (Kamali and Hewage 2017). A systematic understanding of the existing research themes, topics, hotspots, and knowledge systems that constitute SROSC could help address this challenge. Therefore, the mission and motivation of this study is to fill this gap.

Methodology

The objective of this research is to synthesize domain knowledge and identify the research gaps and future research directions within the field of SROSC. Toward this objective, a mixed-review method was employed in this study. Generally, this method consists of a quantitative review (i.e., scientometric approach) and a qualitative review (i.e., systematic approach) for eliminating biased conclusions and subjective interpretation while providing an in-depth understanding of domain knowledge and future research directions (Harden and Thomas 2015).

Mixed-Review Method

In the mixed-review method, typically, reviews are conducted using integrated quantitative and qualitative methodologies within single research. The goal of the mixed method is to utilize the strengths and minimize the weaknesses of both the qualitative and quantitative methods (He et al. 2017). Yin et al. (2019) used a mixed-review method of scientometric analysis and a systematic approach to review the literature on OSC, BIM, and the application of BIM in OSC. Araújo et al. (2020) used a mixed-review method of scientometric and content analysis to review relevant literature in the field of sustainable construction management. In this study, we exploit the mixed method to gain an in-depth understanding of the reviewed themes and topics while offsetting the weaknesses inherent in using either the quantitative or the qualitative method in isolation. We specifically used scientometric and social network analysis as a quantitative approach and systematic review as a qualitative approach. The scientometric method is a statistical analysis method that aims to visualize the structural and dynamic aspects of scientific research, which is prevalent in many fields, such as information science, computer science, social science, management, and environmental sciences (van Eck and Waltman 2010). Bibliometric mapping is an important technique in the field of scientometry that visualizes the knowledge domain and relationships among articles, journals, and keywords (Cobo et al. 2013; van Eck and Waltman 2010). Previous studies have extensively used bibliometric mapping-supported scientometric methods to conduct OSC review studies and achieved good results (Hussein et al. 2021; Wuni et al. 2020; Zhang et al. 2021). This study employed bibliometric mapping tools to calculate, map, and visualize a particular large-scale scholarly dataset in a knowledge domain, such as VOSviewer, Gephi, Histcite, and Ucinet, with their functions tabulated in Appendix I. A systematic review can extract, integrate, and compare themes, topics, methods, and theories to identify, evaluate, interpret, and summarize all available research related to a specified domain (Kitchenham 2004). Therefore, a systematic review was conducted to provide a comprehensive view of existing research to identify gaps in the body of knowledge and anticipate future research. On this basis, we employed social network analysis to calculate the visual knowledge network and deepen the knowledge structure analysis output by the systematic review. Consequently, a mixed-review method integrating bibliometric and systematic review was developed to construct a complete picture of the reviewed topics while ensuring an in-depth investigation.

In this study, we designed a four-stage mixed-review research framework, as shown in Fig. 1. First, we followed preferred reporting items for systematic reviews and metaanalyzes (PRISMA) data collection procedure to ensure comprehensive and accurate research literature. Second, we used scientometric analysis to generate multiple knowledge graphs in the SROSC field, such as article distribution, regional cooperation, influential units as well as their interactions, citation analysis toward significant articles, and cooccurrence keyword clustering. Third, a systematic literature review was employed to analyze themes and topics based on the clusters produced by the scientometric analysis and to build the body of knowledge in the SROSC field. Fourth, we further discussed the knowledge structure and proposed future research directions in the field of SROSC based on the results of the mixed review.

Data Collection

Comprehensive and accurate literature data collection forms the basis of a mixed review. To identify the relevant literature in SROSC, we followed the literature search process provided by the PRISMA method. As shown in Fig. 2, data collection consists of four stages: identification, screening, eligibility, and included (Moher et al. 2009).

Identification

We first searched the literature in the OSC management field using keywords. Considering the affix interchangeability of OSC (Hosseini et al. 2018; Hu et al. 2019a; Li et al. 2014b), we constructed a comprehensive search algorithm to cover all sustainability-related literature in OSC through the Scopus database. According to the title, abstract, and keyword (T/A/K) search, the relevant literature was summarized as the initial research result. The main algorithm is illustrated in Fig. 2. The first round of data collection identified 23,896 OSC research items.

Screening

In the second round, we employed the following criteria for literature data screening in the Scopus database: (1) The time slice is from January 1, 2001, to December 31, 2021; (2) the targeted papers are all published in peer-reviewed scientific journals in English; and (3) only research articles and review papers are retained. Preliminary screening excluded literature that did not meet the presented criteria, and 1,157 pieces of literature were retained.

Eligibility

In the third round, we read the T/A/K section to confirm that the literature is in the field of OSC management. There are two steps to the manual qualification procedure: (1) eligible literature is relevant to the AEC industry, not unrelated disciplines, such as medicine, biology, and geography; and (2) the literature should be related to the management field; research on the structure and materials is not within the scope of this study. Therefore, the T/A/K eligibility assessment ensured that the remaining 507 items were relevant to OSC management.

Included

In this study, we read the full text in the fourth round to further limit the literature to the SROSC field. We determined the final database according to the following two criteria: (1) items are directly related to sustainability and sustainable development, and (2) expanded research topics are subordinate to sustainability, such as research on carbon, resources, and the environment. Finally, 272 articles were included in the SROSC review research database.

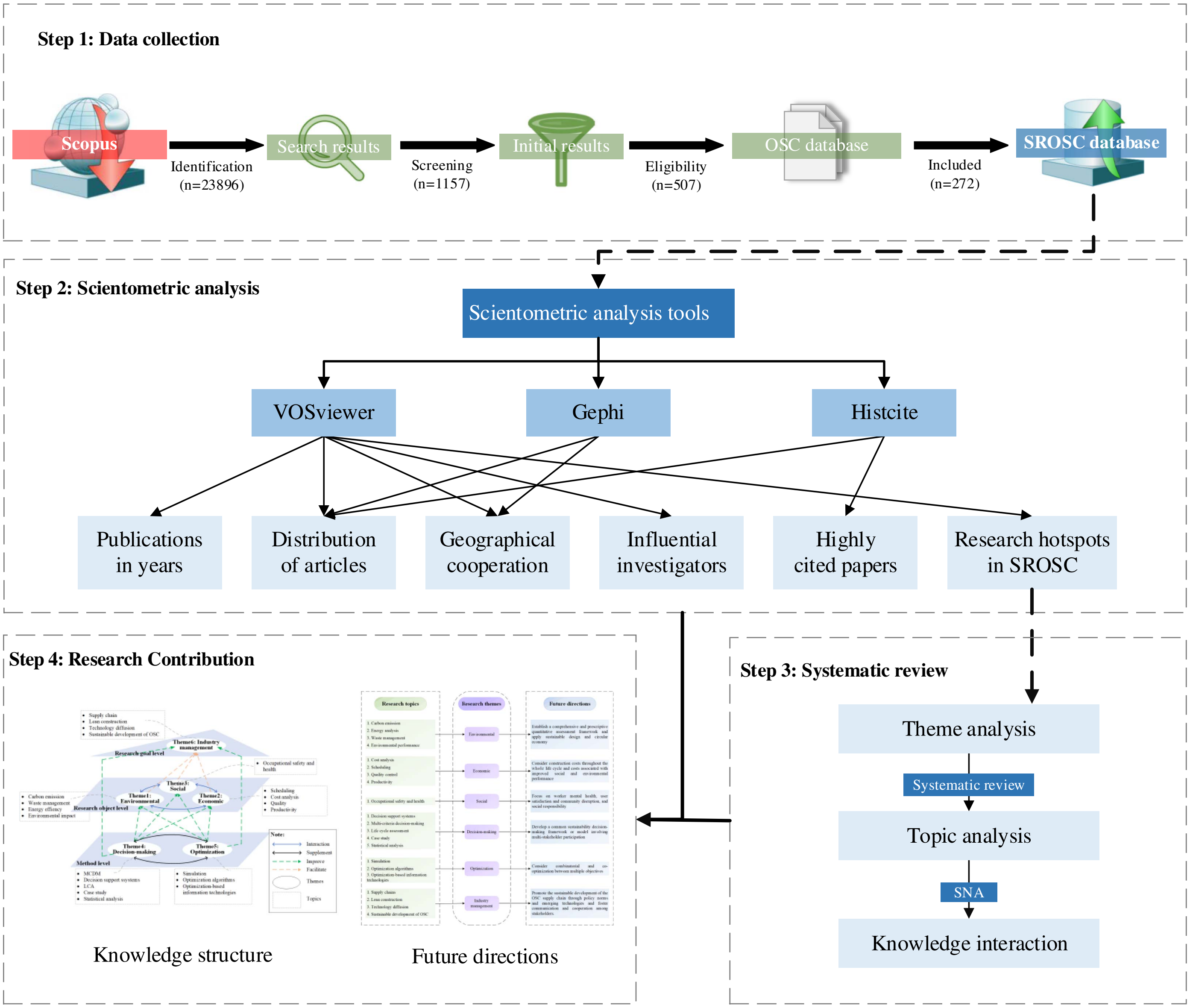

Fig. 1. Adopted research methodology.

Scientometric Analysis

Publications in Years

As shown in Fig. 3, sustainability-related studies are continuously growing; this is also indicated by the number of articles published in years that have shown a tendency to increase during the two-decade study period. The number of articles reached a peak in 2021, and we believe that this growing trend will continue owing to the Paris Agreement and carbon neutrality strategy. In particular, the increase after 2017 was remarkably steady, indicating that sustainability research is a prevalent topic in OSC management (Hosseini et al. 2018). In recent years, the requirements of the AEC industry for sustainable development have become more prominent, prompting sustainability research to become more widely concerned with OSC management (Luo et al. 2021a).

Distribution of Articles

According to the criteria contributing three or more papers, Table 2 lists the 22 leading journals included in the SROSC field and calculates the TLCS (total local citation scores) and TGCS (total global citation scores) metrics of the papers published in these journals. TLCS and TGCS represent the frequency of a specific journal cited in the database identified in this study and the global database, respectively (Wang et al. 2019). Journals with a higher TLCS and TGCS were considered more cited. The top six journals in terms of the number of publications cover 60% of the literature in the field of SROSC, including conventional construction engineering management (CEM) journals, such as *ASCEJCEM*, *AutoCon*, and *ECAM*, as well as environmental science journals, such as *JCLP*, *EB*, *Sustainability*. Although *Sustainability* has a high publication ranking, the TLCS is zero, that is, the journal has included many publications without being cited. However, *EB* published 12 papers and was cited 901 times. Additionally, *HI* has a high citation frequency, but the number of publications is small. Furthermore, Fig. 4 shows the journal collaboration network, illustrating citation relationships between journals. VOSviewer created the journal network and submitted it to Gephi for further analysis. The arrow link indicates the citation relationship; it points to the party applying the citation, and the thick detail of the arrow link represents citation strength.

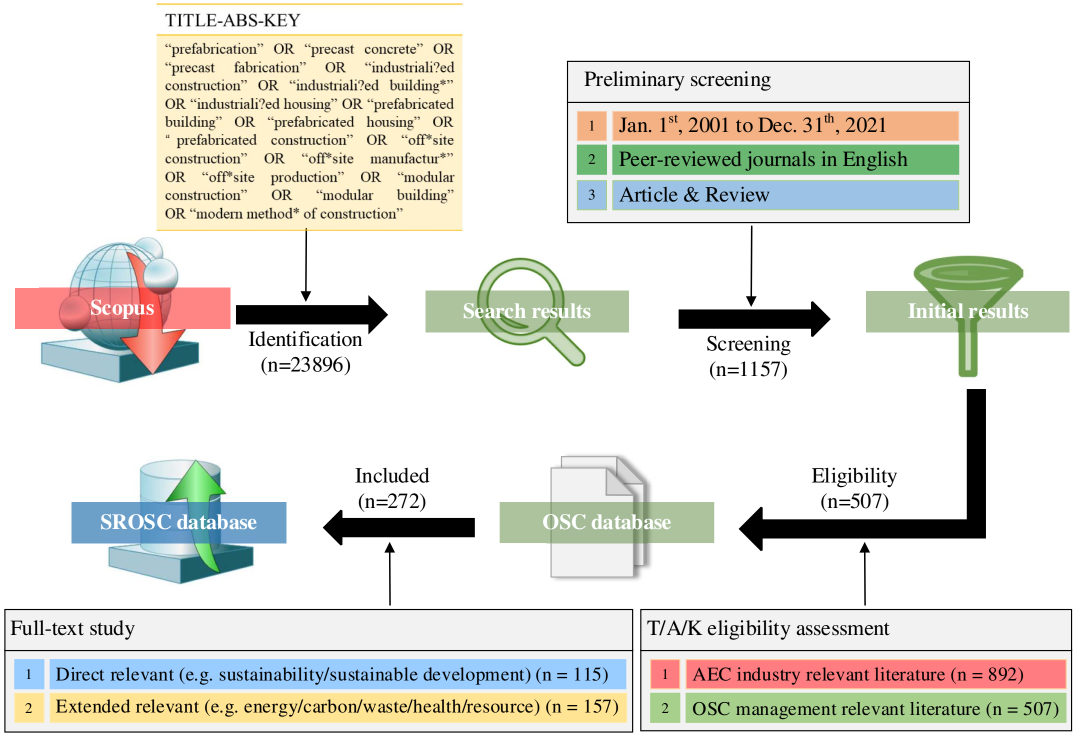

Fig. 2. PRISMA flowchart of study selection.

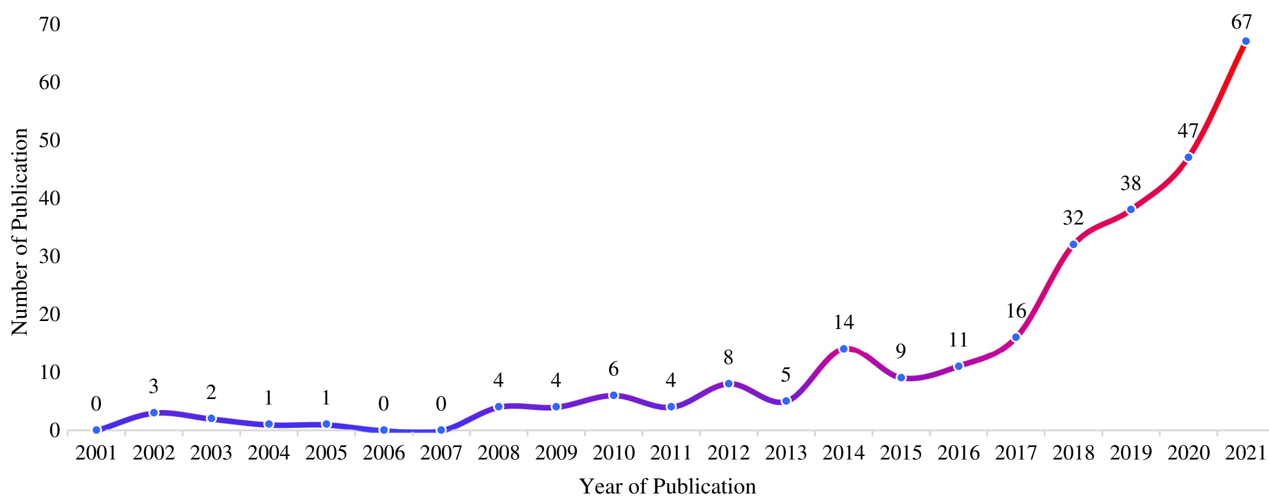

Fig. 3. Annual publication distribution in SROSC (January 1, 2001, to December 31, 2021).

AutoCon and *EB* are two significant sources of citation in the literature. *JCLP* played a critical role as a bridge. Thus, *EB* and *JCLP* from environmental science journals, and *AutoCon*, *ASCEJCEM*, and *ECAM* from CEM journals are critical journals in SROSC. Overall, Table 2 and Fig. 4 provide readers with a reference for journal reading. Table 2 shows the importance of each journal, whereas Fig. 4 shows the associations between the journals.

Geographical Cooperation

Research on SROSC in various countries and regions varies based on factors, such as local industrialization development, product types, and user needs. Fig. 5 provides a visual panoramic map that reviews the geographic distribution of global research on SROSC to help readers identify the critical contribution regions of publications and their interactions (Yan et al. 2020). The blue block indicates the publication amount, and the darker the color, the greater the number. The red link indicates the interaction between the research in each region, and the link thickness indicates the connection strength. The interaction among various areas is intensive; thus, SROSC is an open and dynamic global field. China, Australia, Hong Kong SAR, the United States, the United Kingdom, and Canada are the central contributing regions in SROSC, and there is a close relationship between these areas. Among these, the connection between China and the Hong Kong SAR is the closest, which can be understood as their product types are similar: high-rise concrete residential buildings (Jaillon and Poon 2008, 2014). The close connection between China and Australia is attributed to

Table 2. Journal distribution in SROSC

No.	Acronym	Journal	Papers	TLCS	TGCS
1	*JCLP*	Journal of Cleaner Production	42	214	1,548
2	*Sustainability*	Sustainability (Switzerland)	34	0	324
3	*AutoCon*	Automation in Construction	31	174	1,478
4	*ECAM*	Engineering, Construction and Architectural Management	21	24	156
5	*ASCEJCEM*	Journal of Construction Engineering and Management	20	34	435
6	*EB*	Energy and Buildings	12	108	901
7	*CME*	Construction Management and Economics	11	30	559
8	*RCR*	Resources, Conservation and Recycling	10	33	383
9	*JCCE*	Journal of Computing in Civil Engineering	8	7	95
10	*JBE*	Journal of Building Engineering	7	7	100
11	*BE*	Building and Environment	6	18	212
12	*CI*	Construction Innovation	6	8	50
13	*IJCM*	International Journal of Construction Management	6	5	96
14	*ACE*	Advances in Civil Engineering	5	0	36
15	*HI*	Habitat International	5	119	510
16	*JCiEM*	Journal of Civil Engineering and Management	5	12	57
17	*ASCEJME*	Journal of Management in Engineering	5	5	92
18	*KSCEJ*	KSCE Journal of Civil Engineering	5	17	44
19	*RSER*	Renewable and Sustainable Energy Review	5	63	325
20	*SCS*	Sustainable Cities and Social	4	9	82
21	*AS*	Applied Science (Switzerland)	3	0	16
22	*CJCE*	Canadian Journal of Civil Engineering	3	8	48

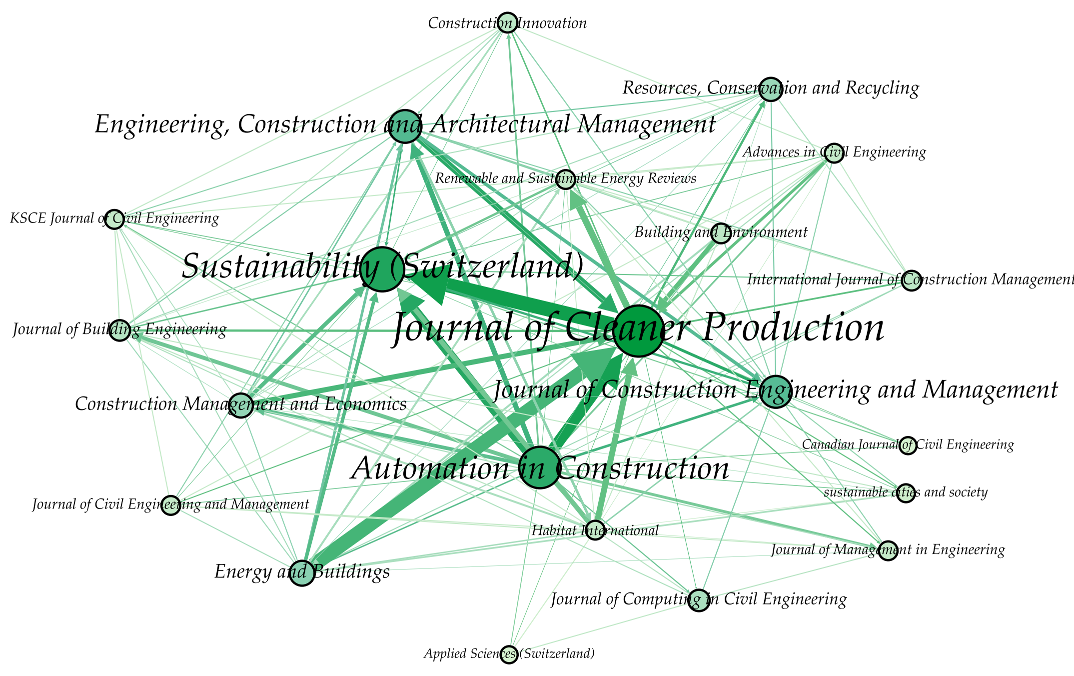

Fig. 4. Mapping of journal collaboration network in SROSC.

the many Chinese authors engaged in related research work in the Australian agency. From the perspective of evolution over time in significant regions, the United Kingdom and Hong Kong focused on the SROSC earlier than other areas (Alwan et al. 2017; Pan et al. 2008). However, after 2015, the volume of publications in China sharply increased. This phenomenon is in line with China's recent large-scale urbanization, which pursues sustainable and high-quality development (Jiang et al. 2018).

Influential Investigators

This section identifies influential investigators in SROSC. According to the two criteria that they published as the first author or corresponding author, and the document number threshold was three or more, 20 researchers met the aforementioned criteria. Fig. 6 depicts influential authors in the field through two dimensions: the number of publications and cumulative citations. The author's institution is indicated by a colored circle. The data were updated on December 31, 2021.

Highly Cited Papers

This section uses the metrics of local citation scores (LCS), which indicates the number of citations in the SROSC database, to perform a historiographic analysis of highly cited papers (Wang et al. 2019). The papers with the top 20 LCS values and their citation

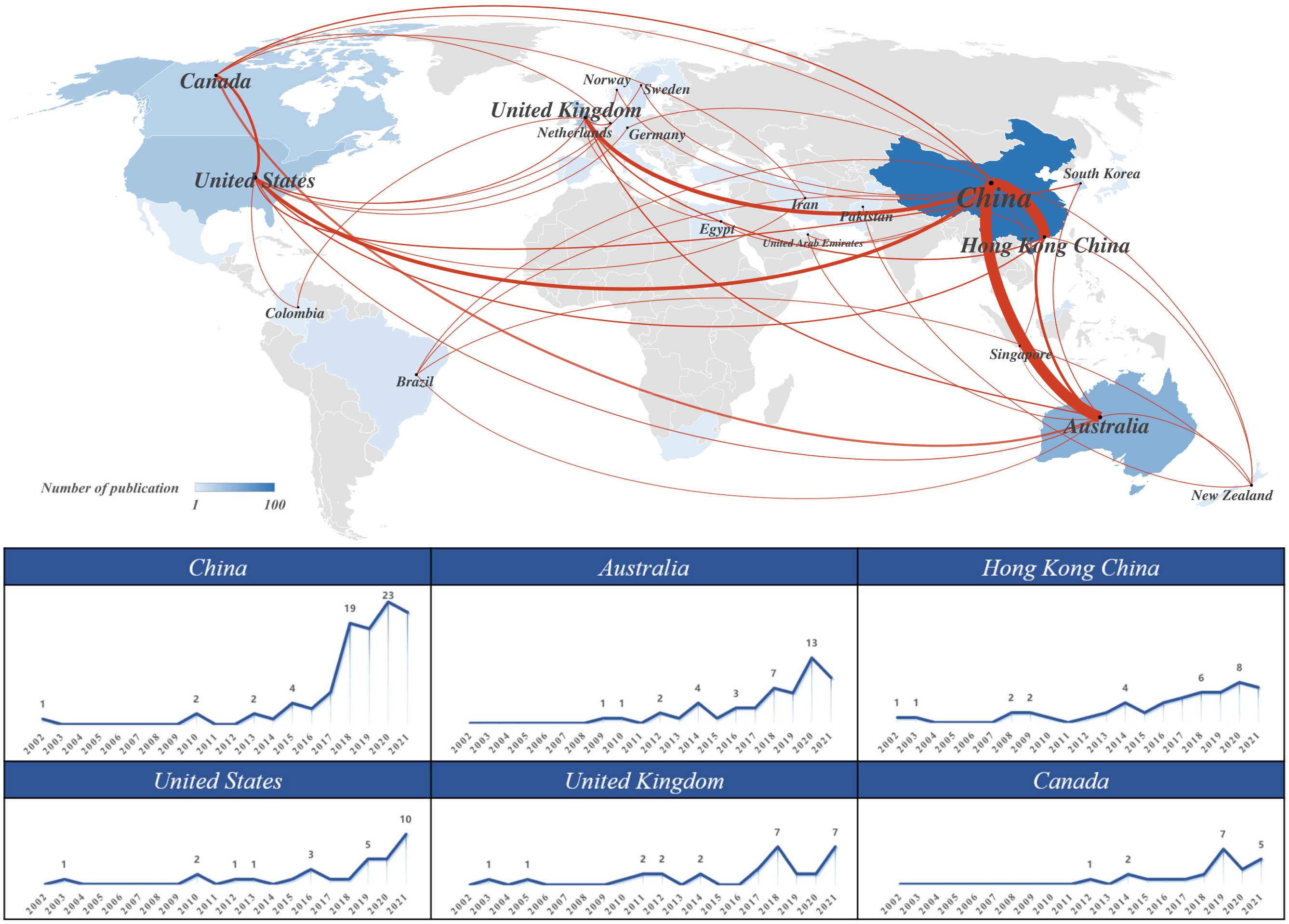

Fig. 5. Geographical cooperation in SROSC.

relationships were calculated using the Histcite tool, as illustrated in Fig. 7. Each circle in this figure represents a highly cited paper. The radius indicates the citation frequency of publications in SROSC, as indicated by the number in the circle. The red arrows indicate the citation relations between publications. This reveals that Aye et al. (2012) published the most highly cited paper, with an LCS value of 40, followed by Jaillon et al. (2009) (LCS = 35), Hong et al. (2018) (LCS = 35), Mao et al. (2013) (LCS = 34), and Cao et al. (2015a) (LCS = 32). These highly cited papers focused on greenhouse gas emissions, energy efficiency, waste reduction, and environmental performance research using life cycle analysis and case study (Aye et al. 2012; Chen et al. 2010a; Lu and Yuan 2013; Monahan and Powell 2011; Pan et al. 2012a), all of which are environmental sustainability dimension. Therefore, the research on environmental performance is well recognized in SROSC. Table 3 summarizes the details of the top-ranking papers, including the topics, research methods, and LCS. Carbon, energy, waste reduction, greenhouse gas emissions, and sustainable development are the most investigated topics. Meanwhile, case study, life cycle assessment (LCA), reviews, and multicriteria decision-making models (MCDM) are the commonly used methods.

Research Hotspots in SROSC

Keywords represent the core content of published studies and depict a range of research areas (Su and Lee 2010). The cooccurrence of keywords can reflect research hotspots in a specific field and provide an accurate picture of the scientific framework regarding topic patterns, relationships, and intellectual structure (Oraee et al. 2017). In this study, we used VOSviewer to conduct cooccurrence analysis and then built a network to understand the leading research stream and themes in this field (Jin et al. 2019). A minimum of five occurrences was set as the threshold to form a network of 55 keywords, as shown in Fig. 8. The links between keywords represent the cooccurrence between the two keywords. The weight of the link was calculated based on the number of publications in which both keywords occurred together (Oraee et al. 2017). The network density reached 2.76, and it indicated that SROSC has formed a stable research area. This study further conducted quantitative measurements of cooccurrence in SROSC, and the hotspots are summarized in Table 4. The total link strength represents the degree of node cooccurrence with other nodes. The metric of average citations is the average number of citations of the document in which the keyword is located. Because older articles have more time to be cited than recent ones, papers that have only made contributions to the field in recent years may be underrepresented; average normalized citations are used to eliminate the effect of time on article citations (Zhang et al. 2021).

Combined with Fig. 8 and Table 4, the hotspots and their associations were analyzed. *Sustainable development*, *Sustainability*, and *Sustainable Construction* are the goals that SROSC aims to achieve. The methods adopted in the implementation of SROSC include *Prefabrication construction*, *Modular construction*, and *OSC*, which are also the main objects of research; therefore, they

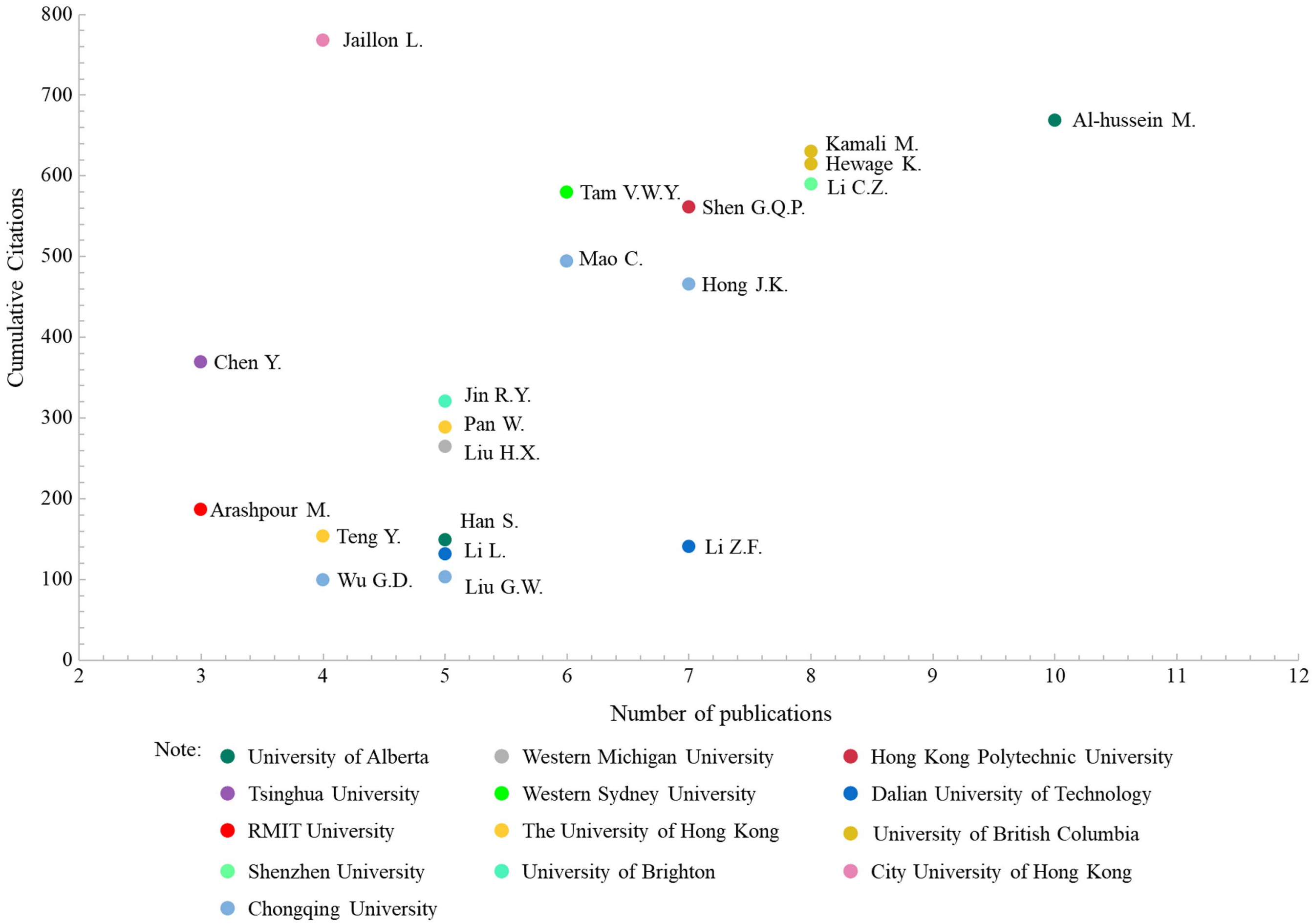

Fig. 6. Influential investigators in SROSC (retrieved on December 31, 2021).

have a high number of occurrences. *Architectural design*, *Decision-making*, *Precast production*, *Construction management*, and *Construction activities* are the process stages involved in improving the sustainability performance of OSC. *Environmental impact*, *Energy efficiency*, *Carbon emission*, *Waste management*, *Cost-benefit*, *Scheduling*, and *Occupational health* are critical issues that investigators focus on in the field of SROSC. To this end, researchers have adopted research methods, such as *LCA*, *Genetic algorithms*, *Simulations*, *Decision support systems*, *Numerical models*, and emerging technologies, such as *BIM*, *Internet of things (IoT)*, *radio frequency identification devices (RFID)*, and *Robotics* to solve the aforementioned issues.

Systematic Review

Themes Analysis

The results of scientometric analysis, especially hotspot analysis, show that research in SROSC is pervasive, and it is necessary to perform cluster analysis on these keywords to identify core themes. In Fig. 8, the keywords were categorized into intuitive clusters, indicating the mainstream field under sustainability research in OSC, with a total of six clusters formed and distinguished by different colors. However, it is challenging to define and explain clusters without a deep understanding of the literature. Therefore, we conducted an in-depth analysis according to a systematic review of these papers and defined six themes: environmental, economic, social, decision-making, optimization, and industry management.

Environmental

According to the descriptive analysis section, environmental sustainability is a cluster of concerns in SROSC. Environmental impact, energy efficiency, greenhouse gas emissions reduction, and waste disposal are critical environmental sustainability issues. Activities during the construction, operation, and demolition stages of buildings have a direct impact on the built and natural environment (López-Guerrero et al. 2022), including the consumption of a large amount of energy and resources, generation of greenhouse gases, production of a large amount of construction waste, and pollution, such as dust and noise (Alwan et al. 2017; Yu et al. 2021). Outstanding environmental impact is one of the most critical reasons for the adoption of OSC by the AEC industry.

Economic

The economic theme is the top concern for most stakeholders and the foundation of the TBL (Hong et al. 2018). The focus of economic sustainability research lies in the gap between the theoretical advantages of OSC and the difficulty of practice promotion. Specifically, they include cost overruns, schedule delays, quality defects, and productivity (Hong et al. 2018; Luo et al. 2020; Yu et al. 2019). Improving the economic sustainability of OSC and removing obstacles in the promotion process are problems that researchers have committed to solving.

Social

Regarding TBL content, research on social sustainability is often marginalized, possibly owing to a lack of awareness (Sierra et al. 2017). The OSC uses multiple construction equipment, which

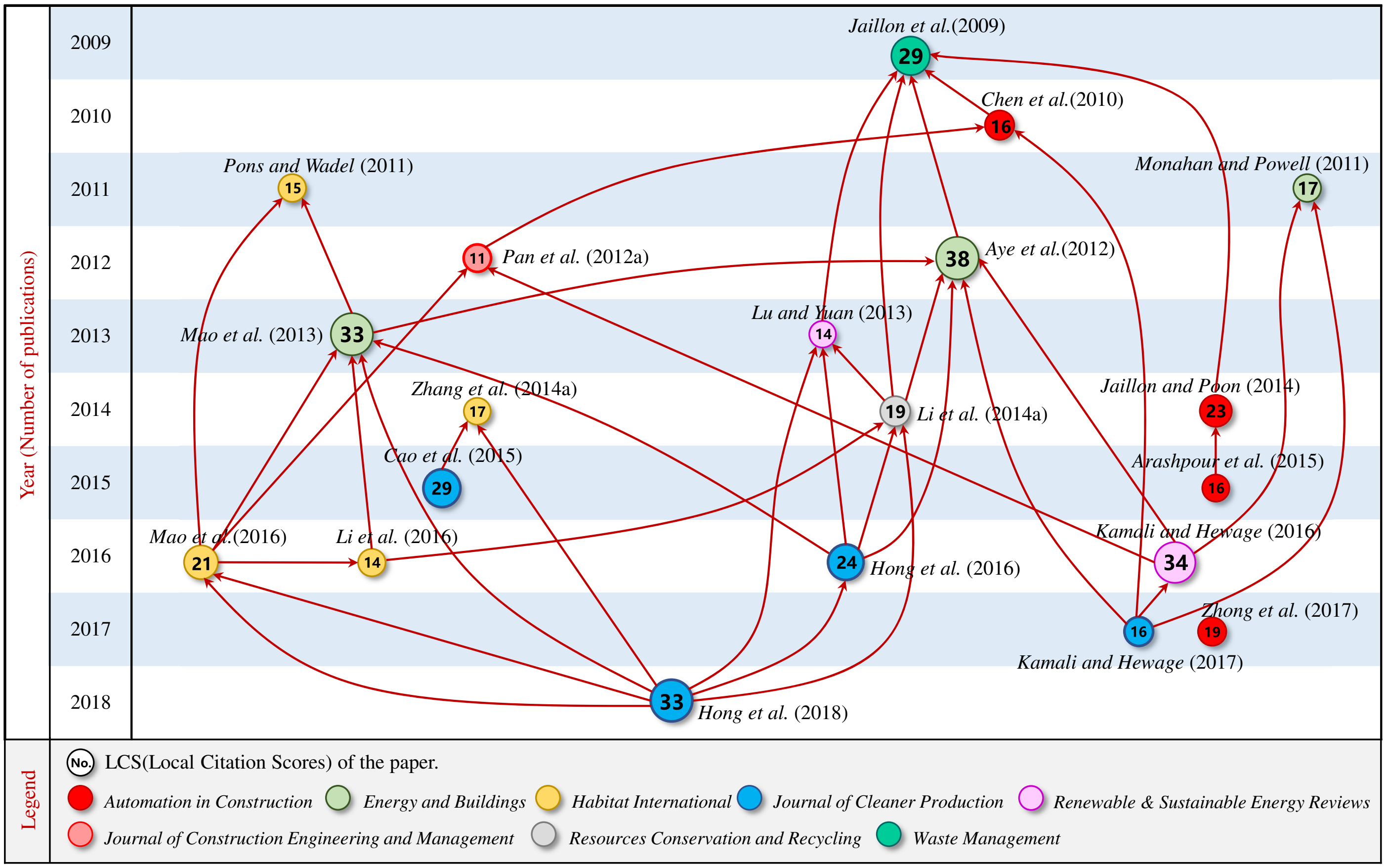

Fig. 7. Historiography analysis and influential articles in SROSC.

Table 3. Top 20 papers with the highest impact in SROSC

No.	Reference	Topics	Methods	LCS
1	Jaillon et al. (2009)	Waste management	Case study	35
2	Chen et al. (2010b)	Sustainable development	MCDM	18
3	Monahan and Powell (2011)	Energy analysis	Case study	17
4	Pons and Wadel (2011)	Environmental performance	Case study	18
5	Aye et al. (2012)	Carbon emission/energy analysis	Case study	40
6	Pan et al. (2012a)	Sustainable development	Case study	13
7	Mao et al. (2013)	Carbon emission	LCA	34
8	Lu and Yuan (2013)	Waste management	LCA/case study	18
9	Zhang et al. (2014a)	Sustainable development	Factor analysis	19
10	Jaillon and Poon (2014)	Sustainable development	Review/case study	24
11	Li et al. (2014a)	Waste management	System dynamics model	22
12	Arashpour et al. (2015)	Productivity	Algorithm	16
13	Cao et al. (2015a)	Environmental performance	LCA/case study	32
14	Hong et al. (2016b)	Energy analysis	LCA	27
15	Kamali and Hewage (2016)	Sustainable development	Review	35
16	Li et al. (2016)	Technology diffusion	Review	16
17	Mao et al. (2016)	Cost analysis	Case study	22
18	Kamali and Hewage (2017)	Sustainable development	MCDM	17
19	Zhong et al. (2017)	Technology diffusion	Case study	22
20	Hong et al. (2018)	Cost analysis	Case study	35

significantly improves the automation of the construction process (Li et al. 2020a; MacAskill et al. 2021), and creates a safer and healthier working environment for construction workers while increasing the demand for construction worker skills and training (Kordi et al. 2021). In addition, this study has significant implications for users and communities. Overall, research on this theme is minimal.

Decision-Making

Decision-making relevant keywords were automatically clustered, which is consistent with the fact that they have a significant impact on SROSC (Boonstra et al. 2021; Guerra and Leite 2021). Investigators aim to improve the sustainability of OSC through scientific decision-making. Decision-making typically involves many uncertainties (Darko and Chan 2016; Zhang et al. 2014b). To reduce

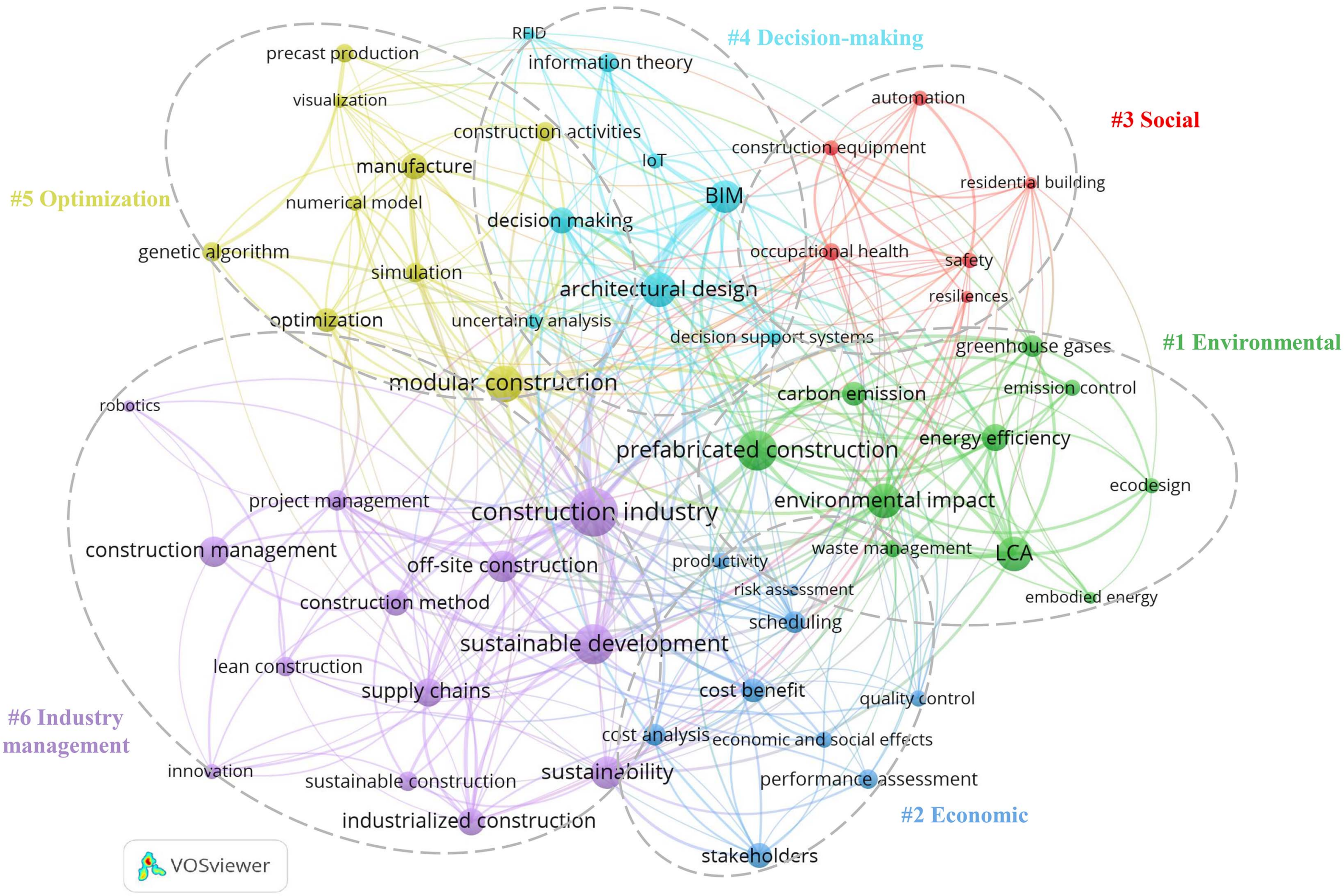

Fig. 8. Network visualization of cooccurrence of keywords in SROSC.

uncertainty in decision-making, information theory and emerging technologies, such as BIM, RFID, and the IoT are gradually being applied to assist the decision-making process (Li et al. 2018b, 2019b). Decision-making research focuses on achieving reasonable decisions on construction and design plans, energy strategies, carbon trading, and policies to generate an excellent program that can achieve energy efficiency, emissions, waste reduction, scheduling optimization, and labor-friendly organization.

Optimization

Optimization is an indispensable theme in SROSC. Considering the fragmentation of the design, production, transportation, and assembly processes, optimization research has aimed at optimizing the scheduling of production and construction processes under uncertainties, including design optimization, production and scheduling of prefabricated components, and scheduling of construction activities (Arashpour et al. 2016; Boonstra et al. 2021; Hammad et al. 2020). Simulation, visualization technology, metaheuristic optimization algorithms, numerical models, and other intelligent methods have been applied in this field, significantly improving the efficiency and effect of the optimization process (Wang et al. 2019).

Industry Management

Researchers aim to achieve sustainable development in the construction industry to promote SROSC. Industry management analyzes the driving factors, obstacles, challenges, and status quo of OSC sustainable development from a holistic perspective based on environmental, social, and economic dimensions (Chen et al. 2010b; Hammad et al. 2019). Alternatively, we can study its resilience from the perspective of an OSC supply chain to achieve just-in-time delivery in the supply chain (Ekanayake et al. 2021a). Research has also been conducted to explore how to realize the industrialization and sustainable development of buildings using the concepts of lean construction and sustainable construction (Goh and Goh 2019). In addition, the diffusion of OSC technologies and emerging information technologies among construction companies and various stakeholders has accelerated its application in industry, effectively promoting sustainability (Dou et al. 2019, 2020).

Topic Analysis

To understand the research status and development level of various knowledge themes in SROSC, we used a systematic review method to extract and classify the research content and methods of related literature in SROSC and identify popular research topics under each theme. A total of 21 hot topics under six themes were identified, as shown in Table 5. There are gaps in the time of appearance and quantity of literature on these topics in the SROSC field. An in-depth analysis of their time, quantity, and content is helpful for researchers to discover future research directions.

Theme 1: Environmental

Topic 1: Carbon Emission. Most studies have indicated that OSC produces fewer greenhouse gases than conventional construction, although their reduction levels vary significantly (Pervez et al. 2021; Teng and Pan 2019). However, there are also some opposing

Table 4. Quantitative measurements of cooccurrence keywords in SROSC

Keywords	Occurrences	Total link strength	Average citations	Average normalized citations
Construction industry	76	352	35.36	1.07
Prefabricated construction	52	170	31.60	1.22
Sustainable development	51	214	40.20	1.39
Modular construction	44	172	22.25	0.87
Architectural design	40	176	27.98	1.35
Environmental impact	40	168	43.38	1.26
LCA	39	169	47.31	1.42
BIM	34	148	30.65	1.32
Sustainability	34	128	27.65	1.23
Off-site construction	32	120	33.38	1.35
Construction management	30	42	69.50	1.00
Supply chains	25	95	17.16	1.15
Industrialized construction	24	84	14.38	0.77
Energy efficiency	23	110	45.83	1.25
Construction method	22	94	65.68	0.91
Decision-making	22	102	35.18	0.91
Manufacture	22	99	29.05	0.84
Stakeholders	21	45	27.45	0.94
Cost benefit	19	71	32.42	1.02
Carbon emission	18	77	23.17	1.10
Optimization	18	66	22.22	0.64
Cost analysis	16	47	54.45	1.15
Scheduling	16	60	24.06	0.65
Greenhouse gases	15	74	38.00	1.25
Project management	14	116	45.23	0.98
Information theory	13	50	65.90	1.98
Lean construction	13	46	30.85	1.04
Construction activities	13	29	7.80	0.56
Sustainable construction	12	51	52.42	1.51
Simulation	12	39	39.00	0.74
Genetic algorithm	12	28	19.50	0.71
Performance assessment	12	30	17.29	0.47
Precast production	11	11	41.00	0.58
Occupational health	10	35	32.80	0.73
Waste management	10	25	71.90	1.47
Economic and social effects	9	43	26.33	1.25
Emission control	9	34	45.11	1.75
Quality control	9	30	41.56	1.55
Productivity	9	29	15.00	0.97
Decision support systems	8	52	60.00	1.12
Uncertainty analysis	8	27	37.20	0.90
IoT	8	35	32.00	2.03
Safety	8	22	21.33	0.68
Ecodesign	7	44	17.29	0.88
Innovation	7	26	31.43	0.37
Numerical model	7	33	14.43	0.44
Construction equipment	7	16	48.40	1.36
Automation	7	25	11.67	0.57
Visualization	6	31	13.67	0.62
Embodied energy	5	25	126.40	1.66
Residential building	5	26	101.80	1.56
Resiliences	5	12	1.80	0.23
RFID	5	27	80.20	1.54
Risk assessment	5	15	13.00	0.35
Robotics	5	11	11.00	0.72

conclusions suggesting that prefabricated buildings produce more life-cycle greenhouse gases (Pons and Wadel 2011). The inconsistent results can be understood as various factors impacting the emissions calculation, and these studies adopted different calculation criteria and methods (Teng et al. 2018). The building material is a crucial factor affecting the performance of life-cycle carbon emissions (Teng et al. 2018). Among the prevalent OSC types, timber (Bergström and Stehn 2005) and steel structures (Eckelman et al. 2018) are suitable for industrial prefabrication. Previous studies have shown that prefabricated steel structures produce more carbon than timber and concrete systems, which is reasonable because the manufacturing and transportation of steel structures consume more energy than other types of structures (Pan and Teng 2021). The carbon emission from concrete structures is related to the degree of prefabrication in specific projects.

Topic 2: Waste Management. Numerous studies have shown that the use of prefabricated building elements is one of the most effective techniques to reduce construction waste (Lu and Yuan 2013;

Table 5. Hot topics in SROSC

Theme	Label	Topics	Average publication year	Documents	Reference
Environmental	En1	Carbon emission	2018	21	Pervez et al. (2021), Teng and Pan (2019), Mao et al. (2013), Liu et al. (2019b), Jiang et al. (2019), and Aye et al. (2012)
	En2	Waste management	2016	17	Jaillon et al. (2009), Tam and Hao (2014), Tam et al. (2005, 2006), (Lu et al. 2021), and Rausch et al. (2021)
	En3	Energy efficiency	2018	18	Eckelman et al. (2018), Zhu et al. (2018), Hong et al. (2016b), Aye et al. (2012), and Monahan and Powell (2011)
	En4	Environmental impact	2017	17	Kamali et al. (2019), Wang et al. (2018b), Cao et al. (2015a), Shen et al. (2019), Yao et al. (2020), and Ji et al. (2020)
Economic	Ec1	Scheduling	2016	26	Dan et al. (2021), Ma et al. (2021), Hyun et al. (2021), Ma et al. (2018), Taghaddos et al. (2010), and Lee and Hyun (2019)
	Ec2	Cost analysis	2016	24	Mao et al. (2016), Pan and Sidwell (2011), Shen et al. (2019), and Ji et al. (2019)
	Ec3	Quality	2018	6	Yu et al. (2019), Valinejadshoubi et al. (2019), and Kim et al. (2015)
	Ec4	Productivity	2015	9	Arashpour et al. (2016), Khalili and Chua (2014), and Yin et al. (2009)
Social	So1	Occupational safety and health	2019	12	Dias Barkokebas and Li (2021), Chu et al. (2020), Li et al. (2019b), Ahn et al. (2020), and Hammad et al. (2019)
Decision-making	De1	MCDM	2018	7	Sánchez-Garrido et al. (2021), Kamali et al. (2018), and Chen et al. (2010a)
	De2	Decision support systems	2017	8	Hwang et al. (2018), and Sobotka and Sagan (2021)
	De3	LCA	2016	29	Hong et al. (2016b), Mao et al. (2013), Zhu et al. (2018), Yao et al. (2020), and Kamali et al. (2019)
	De4	Case study	2015	27	Xing et al. (2021), Liu et al. (2019b), Ji et al. (2019), Mao et al. (2016), and Teng and Pan (2019)
	De5	Statistical analysis	2017	45	Guerra and Leite (2021), Wu et al. (2021c), Chen et al. (2010b), Dou et al. (2019), and Mostafa et al. (2020)
Optimization	Op1	Simulation	2017	24	Li et al. (2018a), Li et al. (2018c), Wang et al. (2021), and Goh and Goh (2019)
	Op2	Optimization algorithms	2016	22	Lee and Hyun (2019), Hyun et al. (2021), Ma et al. (2018), Liu et al. (2019a), Rausch et al. (2021), and Ma et al. (2021)
	Op3	Optimization-based information technologies	2017	25	Ji et al. (2019), Valinejadshoubi et al. (2019), Li et al. (2016, 2017), and Dias Barkokebas and Li (2021)
Industry management	In1	Supply chains	2019	13	Liu et al. (2020), Hussein et al. (2021), Wang et al. (2019), and Ekanayake et al. (2021a, b)
	In2	Lean construction	2016	19	Innella et al. (2019), Xing et al. (2021), Goh and Goh (2019), Li et al. (2019a), and Nahmens and Ikuma (2012)
	In3	Technology diffusion	2019	14	Wu et al. (2021c), Mostafa et al. (2020), Dou et al. (2019), Cao et al. (2015b), and Dou et al. (2020)
	In4	Sustainable development of OSC	2017	38	Kamali and Hewage (2016), Luo et al. (2021a), Kamali and Hewage (2017), Hu et al. (2019b), Hammad et al. (2019), and Kamali et al. (2018)

Tam and Hao 2014). Jaillon et al. (2009) indicated that OSC can reduce construction waste by 52% compared with the conventional construction method. Furthermore, prior studies revealed the waste reduction levels of different OSC activities, such as plastering, timber formwork, concreting and reinforcement, rebar fixing, and tiling (Tam et al. 2005, 2006; Tam and Hao 2014). Several factors result in waste reduction in OSC, such as reduction of material waste (Lu and Yuan 2013), reduction of material loss or misplacement (Tam et al. 2005), and optimized processes (Rausch et al. 2021). In addition, the amount of construction waste in the demolition stage can be reduced by increasing the ratio of recycling to reuse, such as demountable and layered design (Guerra and Leite 2021) and normative design standards (Ajayi and Oyedele 2018).

Topic 3: Energy Efficiency. The improved energy and resource performance of OSC at the industry level and the entire life cycle of the building are recognized owing to the adoption of sustainable design methods, environmentally friendly materials and facilities, and greening and reusability strategies throughout the life cycle (Aye et al. 2012; Satola et al. 2020; Wan Omar 2018; Wang et al. 2021). A previous study indicated that the use of prefabrication demonstrated a certain degree of advantages, including a 35.82% reduction in timber and water resource depletion, and a 20.49% reduction in total energy (Cao et al. 2015a). The recycling process could achieve a 16%–24% energy reduction in the life cycle of prefabricated buildings (Hong et al. 2016b). However, some studies have indicated that the energy reduction potential of OSC adoption is not apparent, and there is even an increase in energy consumption (Aye et al. 2012; Jaillon et al. 2009). This may be because the calculation calibrations in various studies are inconsistent (Quale et al. 2012). In addition, incremental energy use is nearly linearly associated with the prefabrication rate, although the situation may vary in a specific project (Hong et al. 2016a).

Topic 4: Environmental Impact. The environmental impact of OSC includes resource utilization, consumption of materials such as steel and concrete, air pollution, water pollution, noise, dust, photochemical pollution, and thermal performance (Eckelman et al. 2018; Hu and Chong 2021; Yu et al. 2021). Some studies have found that prefabricated buildings have environmental benefits;

however, they are not significant (Shen et al. 2019). Quantifying the environmental impact of OSC has been a problem that researchers have extensively investigated. In addition, emerging information technologies, such as sensors and IoT, are widely used to study the environmental pollution impact of OSC, not only in the data collection process of greenhouse gas emissions but also in the control of dust, noise, and water pollution (Jin et al. 2020).

Theme 2: Economic

Topic 1: Scheduling. The fragmentation of design, manufacturing, storage, transportation, and on-site assembly in OSC has caused widespread project schedule delays (Li et al. 2017, 2018a). In addition, a poor sequence of construction activities, unskilled and inexperienced workforce, and inadequate coordination are critical factors affecting the construction schedule (Abdul Nabi and El-adaway 2021). Optimizing the scheduling of the construction process, including production scheduling (Dan et al. 2021; Hyun et al. 2021), assembly scheduling (Moghadam et al. 2012; Taghaddos et al. 2010), and collaborative scheduling optimization, is an effective method of alleviating delays (He et al. 2021; Lee and Hyun 2019).

Topic 2: Cost Analysis. Theoretically, standardization strategies and scale effect contribute significant cost benefits to OSC. However, the opposite is true in practice. Scholars have always debated whether OSC has a cost advantage. Many studies have criticized OSC's cost disadvantages and obstacles to sustainable development (Mao et al. 2016; Hong et al. 2018); however, there have been many efforts to overcome cost obstacles in transaction cost theory, stakeholder management, optimization models, and digital manufacturing (Arashpour et al. 2018; García de Soto et al. 2018; Wu et al. 2021a, b). Delayed scheduling caused by the fragmentation of the OSC process is an essential reason for harming economic sustainability (Cho et al. 2021; Hu et al. 2019a). Scholars usually focus on achieving process integration using advanced technologies (Altaf et al. 2018; Li et al. 2020b).

Topic 3: Quality. Structural integrity during production, vibration during transportation, and misalignment during installation can have a significant impact on the quality of prefabricated components, thus affecting the quality of the entire building (Valinejadshoubi et al. 2019; Yu et al. 2019). Emerging information technologies can help industry practitioners effectively control the quality of prefabricated components. For example, monitoring the vibration, strain, and deformation of components through BIM and sensors can help uncover hidden damages and defects (Valinejadshoubi et al. 2019). Quality defects on the surface of the prefabricated components were measured using BIM and 3D laser scanning (Kim et al. 2015).

Topic 4: Productivity. Improving productivity depends on optimizing the scheduling of the construction process and the quality of components (Shahpari et al. 2020). Process improvements can be achieved by optimizing the production processes, eliminating production bottlenecks, shortening waiting times, and optimizing resource allocation (Arashpour et al. 2016; Khalili and Chua 2014; Li et al. 2016). Generally, provided scheduling and quality control problems are solved, productivity problems can be greatly improved.

Theme 3: Social

Topic 1: Occupational safety and health. Social sustainability research is a new theme in SROSC. Many studies have suggested that OSC has a lower level of worker safety risk compared to the traditional method, owing to the significantly fewer work-at-height tasks included in OSC schemes, which in turn reduces accident incidence (Ahn et al. 2020). Thus, OSC can provide workers with safer and cleaner work environments. In two case studies by Hammad et al. (2019), the injury risks of modular construction were reduced by 25% and 40%. The use of prefabricated components can control dust and noise pollution on-site while protecting the environment, improving employees' occupational health, and better avoiding occupational diseases (Usefi et al. 2021; Wang et al. 2018b). Factors, such as worker behavior, posture, and attitude also affect safety and health. Therefore, ergonomic research is a research hotspot for improving worker safety and health (Chu et al. 2020; Dias Barkokebas and Li 2021; Li et al. 2019b).

Theme 4: Decision-Making

Topic 1: MCDM. MCDM can effectively solve complex decision-making problems that involve multiple attributes and objectives. For example, Sánchez-Garrido et al. (2021) used 49 indicators to select the optimal sustainable structural scheme from the provided three schemes according to the analytic hierarchy process (AHP) and VIKOR (VIseKriterijumska Optimizacija I Kompromisno Resenje, in Serbian) methods. Chen et al. (2010a) selected the optimal prefabricated construction method from the provided 15 schemes using 33 sustainability indicators according to the simple multiattribute rating technique and multiattribute utility theory. However, MCDM relies on the subjective experience of decision makers in making decisions, which may cause conflicting decision-making results (Chen et al. 2010a).

Topic 2: Decision Support Systems. Based on MCDM, decision support systems can support the decision-making process more objectively and systematically. For instance, Hwang et al. (2018) developed a knowledge-based prefabricated prefinished volumetric construction (PPVC) decision support system composed of a knowledge base, decision support system, and user interface. This system can calculate and evaluate the construction method based on the input information to help decide whether to choose the PPVC construction method, which significantly improves the efficiency of decision-making.

Topic 3: LCA. LCA is a state-of-the-art technique for quantifying environmental sustainability (Marjaba and Chidiac 2016) and includes three quantitative methods: process-based analysis, input-output analysis, and hybrid analysis (Aye et al. 2012; Hong et al. 2016a; Zhu et al. 2018). It has been used to quantify the carbon emission and energy consumption of buildings (Aye et al. 2012; Hong et al. 2016a; Mao et al. 2013). Although many investigators have used the LCA approach, the life cycle stages of their studies are inconsistent. Common life cycle stages include cradle-to-gate (Kamali et al. 2019), cradle-to-site (Jiang et al. 2019), cradle-to-grave (Teng and Pan 2019), and cradle-to-cradle stages (Pan et al. 2018).

Topic 4: Case Study. Case studies can be used for data collection and preliminary analysis or as validation for decision-making problems. For case studies, research is conducted by collecting objective data, which helps to understand how OSC is developing in practice. Therefore, it is mostly used for the environmental, economic dimensions, and sustainable development measurement of OSC in the industry management dimension. For instance, it is employed in the analysis of energy performance (Iddon and Firth 2013), carbon reduction potential (Liu et al. 2019b), cost (Mao et al. 2016), sustainability performance (Jaillon and Poon 2008), and the impact of prefabrication on construction waste reduction (Lu et al. 2021; Tam and Hao 2014).

Topic 5: Statistical Analysis. Statistical analysis is performed in the early stages of decision-making and provides a basis for decision-making. It has been used to collect the attitudes and opinions of stakeholders on OSC issues through questionnaires and interviews, which are often used in the industry management dimension as well as in cost analysis. For example, investigating barriers to BIM implementation for industrialized construction (Wu et al. 2021c) and factors affecting the resilience of industrialized construction supply chains (Ekanayake et al. 2021a), understanding the sustainability perceptions of OSC stakeholders (Hu et al. 2019b), and identifying the main risks affecting the cost and schedule of modular construction (Abdul Nabi and El-adaway 2021).

Theme 5: Optimization

Topic 1: Simulation. In this current study, simulation refers to the modeling and calculation of the design, manufacturing, and construction for OSC with the help of various simulation tools, which aim to improve sustainability by simulating the actual procedure. In SROSC, simulation is used for energy efficiency, lean construction, scheduling, and so on. For example, Wang et al. (2021) used the Design Simulation Toolkit (DeST) to dynamically simulate the energy consumption of a designed prefabricated zero-energy building structure for calculating its annual energy consumption, thereby proving the reliability of the design of the zero-energy building. Li et al. (2018c) applied the JaamSim platform for discrete event simulations of a designed lean precast production system to calculate the optimal quantity of work-in-process, effectively shortening the cycle time and improving productivity. Li et al. (2018a) employed AnyLogic to conduct hybrid system dynamics and discrete event simulation of the construction schedule for prefabricated housing production to calculate the construction duration.

Topic 2: Optimization Algorithms. Optimization algorithms determine the best solution by building a numerical model and solving heuristic algorithms, which are often used for scheduling and cost analysis. Heuristic algorithms currently used in SROSC include genetic algorithms (Dan et al. 2021; Hyun et al. 2021), particle swarm optimization (Liu et al. 2019a), algorithm solvers (Ma et al. 2018), and novel algorithms developed by researchers (Ma et al. 2021; Rausch et al. 2021).

Topic 3: Optimization-Based Information Technologies. Optimization-based information technologies refer to the use of emerging information technologies to solve problems, which is applied to all current topics. BIM (Ji et al. 2019; Valinejadshoubi et al. 2019), IoT (Li et al. 2016), and RFID (Li et al. 2018d) are the commonly used emerging information technologies in SROSC, followed by virtual reality (VR) and augmented reality (AR) (Ahn et al. 2019; Dias Barkokebas and Li 2021) and laser scanning (Kim et al. 2015). The comprehensive use of multiple technologies is a popular trend for adopting technical optimization. For example, Li et al. (2017) developed an RFID-enabled BIM platform that enables different end-users to monitor the construction status and progress in real-time to reduce risks and improve performance.

Theme 6: Industry Management

Topic 1: Supply Chain. Off-site construction supply chain (OSC-SC) management is a critical challenge for successful OSC project delivery (Hussein et al. 2021; Wang et al. 2019). Liu et al. (2020) found that improving the integrity of OSC-SC can promote the optimization of the efficiency and sustainability of the construction industry. However, the decentralized and fragmented nature of OSC makes OSC-SC complex and fragile and is highly susceptible to disruption (Luo et al. 2020). Therefore, it is important to enhance the ability of OSC-SC to resist vulnerability and enhance resilience. Some studies have found that production-based supply chain fragility is the most significant factor in supply chain disruption (Ekanayake et al. 2021a). Critical capabilities for improving supply chain resilience include resources, flexibility, capacity, adaptability, efficiency, and financial strength (Ekanayake et al. 2021b).

Topic 2: Lean Construction. Lean construction (LC) aims to reduce waste, eliminate nonvalue-added activities, and maximize value to improve the construction process (Li et al. 2019a), which is in line with the idea of sustainable development. For instance, Nahmens and Ikuma (2012) found that LC of modular construction reduced waste by 64% (environmental impact), production time by 31% (economic impact), and improved safety (social impact). Additionally, multiple studies applying lean principles and methods (e.g., the last planar system, Kanban system, and just-in-time) to practical cases have concluded that LC helps improve the construction process, productivity, and quality (Goh and Goh 2019; Xing et al. 2021).

Topic 3: Technology Diffusion. The technologies mentioned in this current study include emerging construction and information technologies, and their application can greatly contribute to sustainability. However, the construction industry is conservative and sluggish in adopting change and innovation (Gholizadeh et al. 2018), resulting in the limited application of emerging technologies in the construction industry. Therefore, it is necessary to increase the rate of diffusion of emerging technologies to accelerate sustainable progress in the construction industry. Researchers have analyzed barriers to implementing BIM and robotics in construction industrialization (Mostafa et al. 2020; Pradhananga et al. 2021; Wu et al. 2021c) and factors affecting the diffusion and promotion of prefabricated technology (Cao et al. 2015b; Dou et al. 2019). Moreover, the adopters of emerging technologies are enterprises, and the diffusion of emerging technologies among enterprises should be facilitated (Dou et al. 2020).

Topic 4: Sustainable Development of OSC. In this study, we explore the overall sustainable development of OSC. Researchers have focused on sustainable performance, factors, and assessments of OSC (Yuan et al. 2022). Considering the series of studies conducted by Kamali and Hewage as an example, the researchers first reviewed the life cycle performance of modular buildings from three aspects: environmental, economic, and social (Kamali and Hewage 2016). Subsequently, sustainability indicators of modular buildings involving environmental, economic, and social dimensions were identified (Kamali and Hewage 2017). On this basis, a life-cycle sustainable performance assessment framework for modular residential buildings was proposed to help researchers choose sustainable construction methods (Kamali et al. 2018).

Knowledge Interaction

SROSC topics can be divided into two types: problem-type topics, such as environmental, social, economic, and industry management, and method-type topics, such as decision-making and optimization. Interactions existed between the two types of topics. This scientific path structure, based on problem-method correspondence, describes a popular research paradigm. To demonstrate the interaction relationship, we adopted a two-mode social network and core-peripheral structure analysis to visualize the interactions and identify the core problems and methods in SROSC. The results are shown in Figs. 9 and 10, and Table 6, respectively.

In Fig. 9, circles represent problem-type topics, and squares represent method-type topics. Colors were used to distinguish different knowledge topics, and the size was measured by the number of articles. Optimization-based information technologies, case studies, and statistical analysis are the core of the entire network, indicating that they can solve most problems. In addition, the arrangement of nodes can be found regularly. Optimization algorithms usually resolve scheduling problems, LCA solves environmental issues, and simulation is mainly used to solve lean construction and productivity problems.

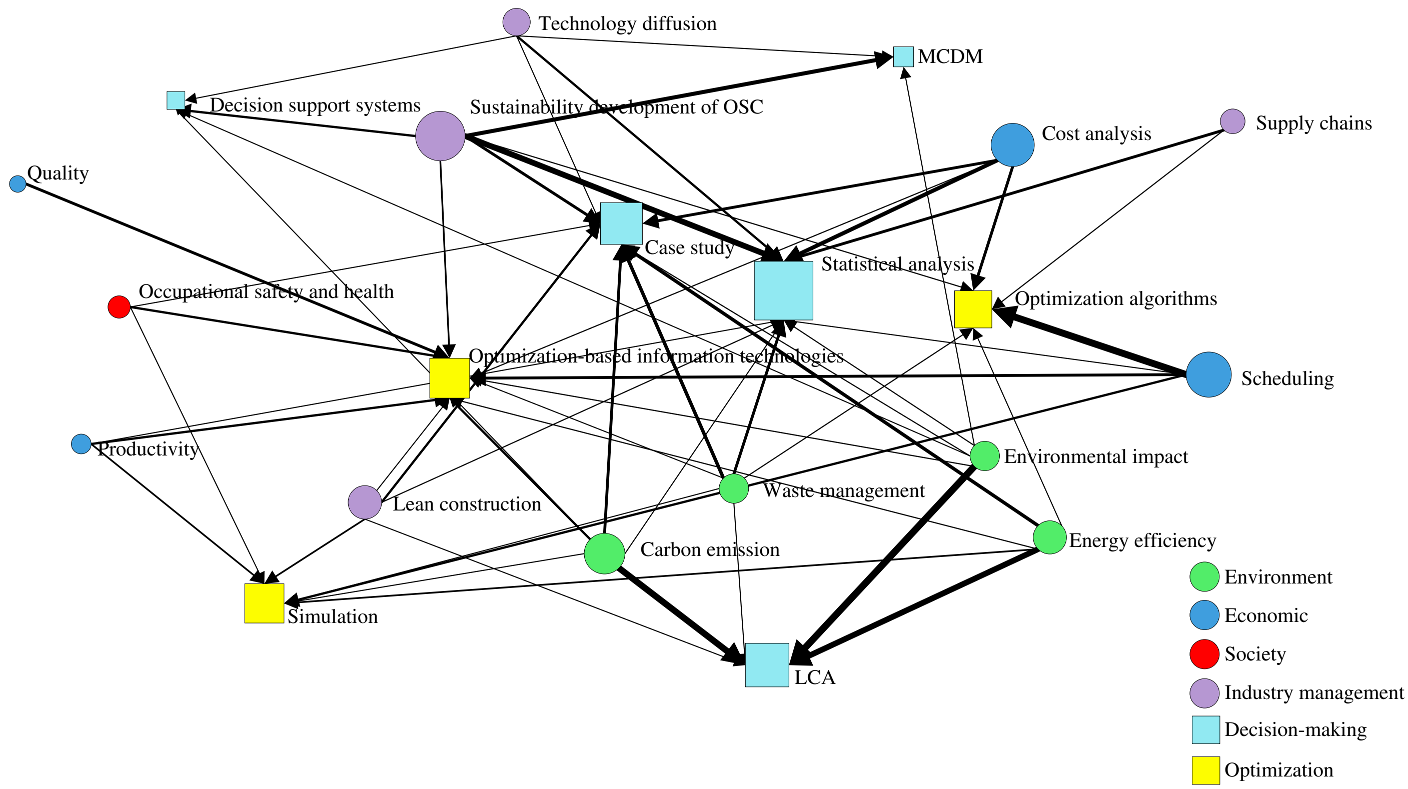

Fig. 9. Two-mode social network of hot topics.

In Table 6, the density between the core problems and core methods is 0.885, indicating a close relationship between them. The interaction density between core problems and peripheral methods and between peripheral problems and core methods are 0.338 and 0.24, respectively, reporting that they are loosely connected. The final fitness of 0.786 demonstrates that the structure of the problem-method network is near to the ideal core–periphery structure. These favorable data results reflect the reliability of the problem-method network structure summarized in this study. Furthermore, Fig. 10 shows the core–periphery structure of topics, where "1" indicates that the problem in the corresponding row can be solved using the method in the corresponding column. The upper-left corner of Fig. 10 contains nine core issues and three core methods. Specifically, the core methods include optimization-based information technologies, case studies, and statistical analysis, which can solve 13, 9, and 10 problems, respectively, corresponding to the core positions in Fig. 9. Topics in the environmental dimension are all core issues. Scheduling and cost analysis issues in the economic dimension are often the focus of stakeholders and, therefore, they are also core issues. In the social dimension, occupational health and safety is the most marginal core issue, and the core level should be urgently strengthened.

	Op3	De4	De5	De3	Op2	De2	Op1	De1
En1	1	1	1	1		1	1	
En2	1	1	1	1	1		1	
En3	1	1		1	1		1	
En4	1	1	1	1		1		1
Ec1	1		1		1		1	
Ec2	1	1	1		1			
In4	1	1	1		1	1		1
In2	1	1	1	1			1	
So1	1	1					1	
In1	1		1		1			
Ec4	1		1				1	
In3	1	1	1			1		1
Ec3	1							

Fig. 10. Core–periphery structure model of hot topics.

Discussion and Future Directions

Knowledge Structure Discussion

The descriptive analysis of the knowledge structure explains the information that SROSC has devoted to exploring in the past. Therefore, Fig. 11 summarizes the SROSC knowledge structure composed of six themes and 21 topics, as well as the relationship between them.

First, the six themes were grouped into three levels. Optimization and decision-making are part of the method level, which can effectively solve and improve problems existing in other themes, playing a pillar role. Environmental, social, and economic

Table 6. Density matrix

Problems	Methods	
	Core	Periphery
Core	0.885	0.338
Periphery	0.24	0.028
Final fitness	0.786	

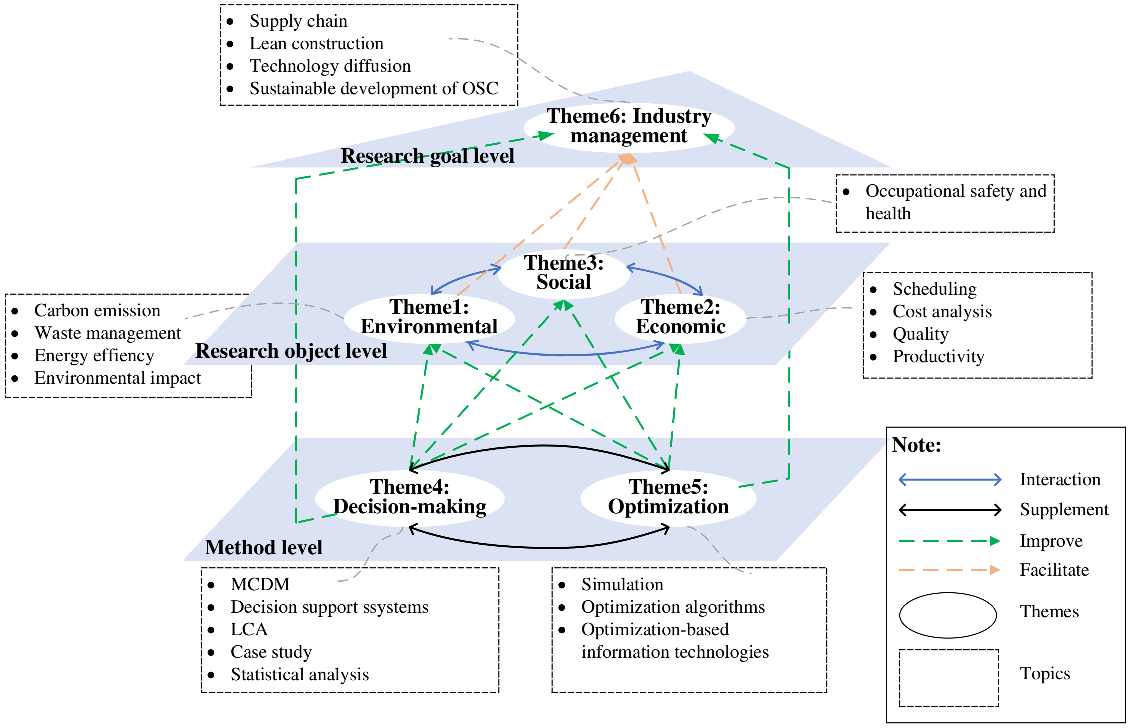

Fig. 11. Knowledge structure in SROSC.

sustainability issues are the research objects of researchers and industry practitioners in SROSC. The improvement of sustainability in these three dimensions can significantly promote the sustainability of industry management, which is the ultimate goal of SROSC. The positive effect between the three levels is the premise for improving the sustainability of OSC.

Within the same level, there were interactions among various themes. For example, the three dimensions of the research object level interact with one another. Improvements in environmental sustainability help OSC fulfill its social responsibilities but may cause increased environmental costs. Therefore, improving the sustainability of OSC requires a synergistic consideration of the three dimensions. Decision-making and optimization at the method level can complement each other and enrich the way problems are solved. BIM technology can integrate and share the information of various stakeholders, which is helpful for the construction of expert databases in decision support systems. Therefore, the integrated use of methods can provide better solutions.

Future Directions in SROSC

In recent years, the increasing literature on SROSC has promoted vigorous development in academic research, while promoting progress in practice. Therefore, it is necessary to predict future research directions based on existing research. Fig. 12 provides suggestions for future research directions in SROSC summarized from six theme aspects.

First, note that emerging information technologies can provide smarter and more efficient solutions. Future research should focus on integrating these six knowledge themes with emerging information technologies to improve the sustainable performance of OSC projects.

Environmental: Topics in the environmental dimension are all dominant and quantifiable; therefore, existing studies focus on the quantification of carbon emission, energy consumption, construction waste, and environmental impacts. However, researchers have used different criteria to quantify the aforementioned issues, resulting in inconsistent quantification results. Therefore, it is necessary to establish a comprehensive and standard quantitative evaluation framework to address inconsistent results (Pan et al. 2018). Furthermore, unlike previous research that focused on the construction phase, the concept of environmental sustainability assessment in the whole life cycle is important, such as sustainable design (i.e., zero-energy design, demountable, and deconstructed design), recycling, and circular economy (Jaillon and Poon 2014; Jin et al. 2019; Naji et al. 2021), which should receive the attention of researchers in SROSC.

Economic: Previous research on economic sustainability was concerned with the cost-benefit analysis of OSC. It is believed that economic sustainability is a critical barrier to achieving TBL and that economic efficiency is a prerequisite for the other two dimensions (Kamali and Hewage 2017). Environmental and social sustainability will be pursued by benefit-oriented construction industry participants after their economic aspirations are met (Yuan et al. 2021). In future research, the economic dimension should consider the entire life cycle stages, meaning not only reducing the direct cost associated with constructing buildings as well as considering the indirect cost of improving the social and environmental sustainability of OSC (Xue et al. 2022).

Social: Social dimension research in OSC management focuses on occupational safety and health, and these people-oriented studies deserve recognition. However, previous studies have focused more on the physical safety and health of construction workers and have not systematically explored workers' mental health from a larger spatiotemporal dimension, which also affects workers' efficiency and safety. In particular, after buildings are completed, both user satisfaction and disturbance to the surrounding community can affect social sustainability; thus, these should be considered in the early planning, design, and decision-making stages (Kordi et al. 2021; Wang et al. 2018a). Moreover, how OSC affects sustainability by fulfilling its social responsibilities should be the focus of future research (Det Udomsap and Hallinger 2020).

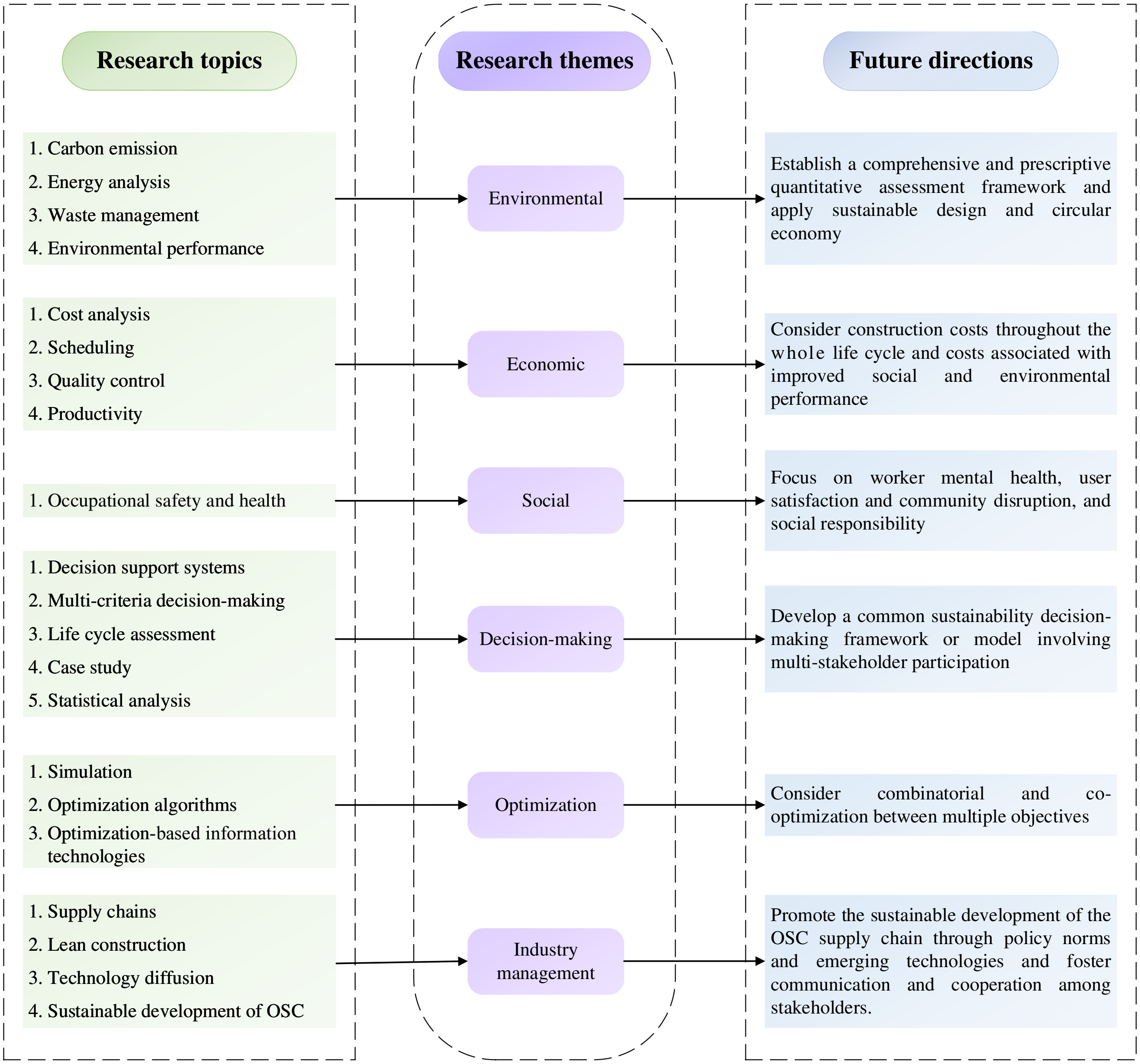

Fig. 12. Future research directions in SROSC.

Decision-making: Decision-making research will always be a critical topic in SROSC. In the OSC practice process, OSC design, production, construction, and even demolition plans are jointly decided by multidisciplinary decision makers. Integrating multidisciplinary decision makers, joint decision-making can effectively promote sustainability and avoid rework (Chen et al. 2010a; Yu et al. 2019). However, decision makers often make decisions based on their subjective experiences and preferences, which may result in unsatisfactory decision-making results (Chen et al. 2010a). Therefore, it is necessary to develop a common sustainability decision-making framework or model to improve the objectivity and efficiency of decision-making processes.

Optimization: The three dimensions of TBL indicate that sustainable optimization cannot be limited to one objective; in future research, multiple objectives and their relationships should be considered to achieve the combination and synergistic optimization of multiple objectives (Ning et al. 2011). In addition, emerging technologies and smart methods should provide the necessary support and improvements.

Industry management: Off-site construction methods are accepted by researchers and industry practitioners; however, the development of OSC is still relatively sluggish (Gan et al. 2018; Li et al. 2021). This is closely related to the imperfections in the OSC supply chain. Consequently, it is necessary to promulgate effective policies and norms and adopt emerging information and construction technologies to promote the sustainable development of OSC supply chains (Luo et al. 2021b). Furthermore, the promotion of communication, cooperation, and knowledge integration among the multidisciplinary stakeholders involved in the supply chain contributes to the formulation of efficient sustainable development strategies (Zhang et al. 2021).

Practical Implications

The results of this study provide some practical implications for stakeholders in the construction industry. First, as industry regulators, governments should consider that the sustainability of OSC can only be achieved if the mutual benefits of multiple stakeholders are aligned. Formulating policies that benefit multiple stakeholders to integrate industry chains is crucial to driving sustainability. Second, improving the sustainability of OSC does not mean realizing the optimal condition for all sustainability criteria (such as economic, environmental, and social) as the performance of these criteria tend to be dynamically balanced. For profit-oriented construction industry participants, environmental and social performance goals are typically pursued after economic pursuits. Professional practitioners should make reasonable decisions based on the priority of each criterion in the business management process. Third, professional participants should be fully aware that the sustainability of OSC does not always exhibit excellent performance in all scenarios. Therefore, professional participants should design and optimize an OSC scheme according to specific engineering scenarios. For example, a previous case study indicated that a maximized prefab rate does not support economic sustainability in high-rise concrete residential building construction. Precast concrete components are more suitable for nonload-bearing horizontal elements. The precast method and cast-in-situ method used in load-bearing parts are not in conflict with one another and can be used collaboratively in appropriate schemes. It is challenging to develop a one-size-fits-all practical OSC scheme. Therefore, the best method is the one that is most suitable for all participants. Meanwhile, professional practitioners and managers need to keep an open mind to emerging information technologies for their vast potential to improve workflow, collaborative behaviors, and business models, which is critical for achieving sustainability in OSC. Finally, managers should be fully aware of the importance of industrial workers in realizing the sustainability of OSC since their role is vital to the success of project implementation. Continuous improvement of the skills and well-being of industrial workers could significantly enhance the social sustainability of OSC, which is the mission of corporate social responsibility of managers.

Conclusion

OSC is gaining popularity in the construction industry because of its contribution to sustainable performance. To understand the performance of OSC in terms of sustainability, we conducted an in-depth literature review on sustainability research in OSC management in pursuit of a better understanding of this concept and acquiring the future directions of research. The reviewed literature covers 272 peer-reviewed authoritative journal articles published over the past two decades. Using scientometric analysis, we conducted a statistical analysis of the knowledge landscape in the SROSC domain, including journals and geographic distribution, authors, institutions, highly cited articles, and hotspot networks. Using a systematic review method, we conducted a descriptive analysis of the multihierarchy knowledge structure composed of themes and topics, employed social network analysis to assist in the visualization of the knowledge structure, and further proposed future research directions for SROSC.

The contributions of this study can be categorized into three aspects: (1) expanding and updating the overall knowledge landscape in SROSC to facilitate researchers' literature search in SROSC; (2) summarizing the multihierarchy knowledge structure system composed of research themes and topics in SROSC, and providing a meaningful reference for relevant researchers and industry practitioners; and (3) discussing the frontiers in SROSC from the perspectives of environmental, social, economic, decision-making, optimization, and industry development, as well as providing suggestions for the future research directions of SROSC. This is important to both academic research and practical implementation of the AEC industry.

This study provides many meaningful conclusions regarding SROSC. First, the growing trend in annual publications indicates that SROSC will remain a research focus in the AEC field in the future, requiring continued attention from researchers. The geographic distribution covers the most representative regions in the sustainable development of the global AEC industry, and the specific research content of each region will vary significantly with the development of their respective industries.

Twenty-two mainstream journals in the SROSC field were identified; however, the most influential journals were inconsistent due to different measurement criteria. Second, the six knowledge themes covered three levels: method, research object, and research goal. The logical relationship between themes showed that SROSC has formed a relatively complete research system, and the sustainable development of OSC can achieve preliminary results. Finally, the environment is currently the most concerned dimension; economic is the least effective dimension, which poses a formidable challenge for researchers. Social is an equally important but is the most neglected dimension. Technical optimization, case study, and statistical analysis of the topics of decision-making and optimization are commonly used solutions in SROSC. The topics in these two themes also reflect the diversity of solutions in the current SROSC field. However, the limitation of this study is that only the English literature in Scopus was analyzed. Information from actual sources, such as industry reports or interviews, should be included in future research.

Appendix I. Detailed Description of the Techniques Used in This Study

Knowledge map type	Related figure/table	Tool	Description
Co-author relationship analysis of documents	Fig. 5	VOSviewer, Gephi	VOSviewer was used to count and calculate the countries and regions of the authors of the literature, which extracted 19 countries and regions from the database. The data is then submitted to Gephi to generate a national and regional distribution network map with geographic coordinates.
	Fig. 6	Vosviewer	The authors of the articles in the database were manually screened, and only the first and corresponding authors were retained. Then, VOSviewer was used to count and count the authors of the literature, which extracted 246 authors from the database. In this study, the top 20 authors with outstanding contributions were analyzed by the cumulative contributions of the authors in Fig. 6.

Appendix I. (*Continued.*)

Knowledge map type	Related figure/table	Tool	Description
Documents citation analysis	Fig. 4 Table 2	VOSviewer Gephi Histcite	VOSviewer was used to count and calculate the journals in which the literature belongs, and 31 journals are extracted from the database. The data were then submitted to Gephi, and with a threshold of 3, network relationships between 22 major journals were generated, as shown in Fig. 4. In addition, Histcite was used to calculate the TGCS and TLCS metrics of each journal, as shown in Table 2.
	Fig. 7 Table 3	Histcite	Histcite was used to count and calculate the number of citations of documents. Based on the LCS metric, the top 20 highly cited papers are displayed and analyzed in Fig. 7 and Table 3.
Cooccurrence analysis	Fig. 8 Table 4	VOSviewer	VOSviewer was used to count and calculate the keywords of the literature, which extracted 1893 keywords from the database. Then, with 5 as the threshold, the keyword cooccurrence network (Fig. 8) was constructed for the top 55 keywords with more prominent contributions. In addition, keywords were measured using indicators calculated by VOSviewer, as shown in Table 4.
Topic interaction	Fig. 9 Fig. 10 Table 6	Ucinet	Ucinet was used to count and calculate the interaction between 13 question-type topics and eight method-type topics in systematic reviews and obtain a two-mode social network of problem-method. Then, the influence of each topic in the network is analyzed, and the core-peripheral structure of the topic and the network density table are obtained.

Data Availability Statement

All data generated or analyzed during the study are available from the corresponding author by request.

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