Supply Chain Management in Prefabricated Construction: An Overview of a Developed Conceptual Framework

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Abstract: Prefabricated construction (PC) have attracted increasing research attention worldwide due to their advantages such as high construction efficiency, short construction period, low labor cost and low energy consumption. Supply chain management is closely related to the application efficiency of PC, but only in the last three years has this interdisciplinary research received due attention. The global research network in the field of prefabricated construction supply chain management (PCSCM) have not been systematically reviewed so far. Especially in the recent three years, there has been an explosive growth of relevant literature. In this paper, the method of combining scientometrics analysis and thematic discussion was adopted to systematically review 152 important literatures from 2001 to 2018, aiming to provide a holistic understanding of the status in quo, trends and gaps of PCSCM research, and further analyze the prominent problems. The study constructed four kinds of visualized bibliographic information maps for the publication distribution across journals, co-occurrence of keywords, co-authorship analysis, and citation of articles. Then, the four themes summarized by clustering were discussed, mainly focusing on strategic research and project evaluation, PC supply chain process design and optimization, supply chain integration and management, and application of advanced technology. Finally, the research gaps and conceptual development framework to promote PCSCM were reported. This study contributes to grasping the research and development of PCSCM on the whole, and can also serve as an explorative manual to support PCSCM activities and innovative research.
Keywords: Prefabricated Construction; Supply Chain Management; Literature review; Bibliometric analysis; Thematic analysis; Conceptual Framework

1. Introduction

Prefabricated construction (PC), a sustainable construction method, has the advantages of low safety risks, high production efficiency, low cost and high energy saving compared with the on-site construction (Han & Wang, 2018). PC was widely developed in Europe after World War II during the construction industrialization boom (Wu and Feng, 2014). Subsequently, the United States, Canada, Australia and other countries began to research and implement PC (Goulding et al., 2014). In the last decade, Asian countries, such as China, South Korea and Singapore, have also put forward the PC development model and technology system suitable for their own needs (Sutrisna and Goulding, 2019; Ahmed, 2018). At present, the application density of prefabricated structures in the United States, the United Kingdom, South Korea and China was 40%, 50%, 35% and 30%, respectively (Khalili and Chua, 2014). PC has become a new direction and way for the construction industry to cope with the severe shortage of labor, environment and social resources.

PC technologies such as design, production and assembly have been relatively perfect (Wang et al., 2016). However, problems in the transportation and storage of component (Polat et al., 2010), schedule control (Shin et al., 2011; Ahmed et al. 2018) and information transmission (Wang & Hu, 2018) have exposed and become obstacles restricting project achievements. Management level, especially PC supply chain management (PCSCM), has become a critical factor restricting the popularization and development of PC (Zhai et al., 2018; Ahmed, 2019).

A great deal of research has made great contribution to the development of PC. They are mainly carried out from three aspects: performance and construction technology of prefabricated components, obstacles and drivers for prefabrication buildings and PC and management and performance of PC (Jaillon and Poon, 2014; Ahmed and Sobuz, 2019). From several important literature reviews in PC field, it can be found that technology is still an important topic in PC research, and PCSCM also plays an irreplaceable role in promoting the success of PC project (Chang et al., 2018). However, there is no independent complete literature systematically evaluate the nature, influence, contribution and existing problems of PCSCM. To bridge these gaps, the study tries to make a review of the current situation, trend, emphasis and gap of PCSCM by combining bibliometrics evaluation and system review. This paper aims to analyze three
problems existing in PCSCM research process: (i) Statistical characteristics of the literature; (ii) Key research topics of PCSCM; (iii) Research gaps and agendas; and (iv) Further obtain a research framework of promoting PCSCM. The findings contribute to obtain accurate and complete information about PCSCM research and provide insights into current academic fields, research frontiers and emerging trends.

2. A Brief Review of PC research

The whole process of PC, firstly defined by United Nations Department of Economic and Social Affairs in 1974, includes manufacturing and preassembling a certain number of building components, modules and components, and shipping them to the construction site for installation (Höök et al., 2008). The biggest difference between PC and traditional site construction is that the process and scope of construction management extend to the production source of components. The supply process which was not so important to the site construction becomes the key work of PC. A lot of research has promoted the implementation and promotion of PC. Several literature reviews summarize and analyze the development and research trend of PC, focusing on the construction and production technology, as listed in Table 1.

Table 1: Previous literature reviews

<table>
<thead>
<tr>
<th>Authors</th>
<th>Object of study</th>
<th>Article number</th>
<th>Topics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li et al. (2014)</td>
<td>PC Management</td>
<td>100</td>
<td>Industry prospect; environment for technology application; design, production, transportation and assembly strategies; performance evaluation</td>
</tr>
<tr>
<td>Mostafa et al. (2016)</td>
<td>Offsite construction</td>
<td>62</td>
<td>Offsite barriers and drivers; the integration of lean and agile principles; simulation</td>
</tr>
<tr>
<td>Boafo et al. (2016)</td>
<td>Modular prefab</td>
<td>146</td>
<td>The performance of modular prefab considering acoustic constrain, seismic resistance, thermal behavior, energy consumption; life cycle analysis</td>
</tr>
<tr>
<td>Kamali &amp; Hewage (2016)</td>
<td>Modular construction</td>
<td>104</td>
<td>Sustainability dimensions assessment (i.e., environmental, economic, and social)</td>
</tr>
</tbody>
</table>
From Table1, four main aspects of PC research can be summarized.

**Performance and construction technology of prefabricated components.**

Compared to site construction, PC has the advantages of lower safety hazard, higher production efficiency, lower cost and higher energy saving (Cavaco et al., 2018). The production and installation technology of prefabricated components is quite mature (Ji et al., 2018). Modular and standardized component design is basically realized (Huuhka et al., 2015). Bearing capacity, rigidity, ductility, waterproofness and construction technology of connection points of prefabricated components are the mainstream of research. (KIM et al., 2016). The seismic performance of connections still needs to be further studied (Vaghei et al., 2017).

**Prefabrication buildings and PC development obstacles and drivers.**

Generally speaking, PC has gained good market acceptance. Policies and regulations, technological innovation, industrial layout and other aspects all show the market potential and driving force of PC. However, the application of PC is still subject to local government policy preferences (Mao et al., 2015), high upfront investment (Zhan et al., 2014), a lack of highly skilled workers (Mostafa et al., 2016) and insufficient transportation supply capacity (Jaillon et al., 2014), leading some to argue that PC performance, while good, is not the best choice.

**The implementation management of PC.**

Many researches focus on the life cycle management of prefabricated buildings, and systematically study the prefabricated buildings from the aspects of organizational mode (Feng et al., 2017), contract management (Yang et al., 2018), and cooperative innovation (Ismail et al., 2017). Although the PC technology has been developed relatively mature, its actual performance does not have a significant advantage over the traditional building, which is largely related to its weak organizational coordination and management ability in the implementation (Schoenwitz et al., 2016).

**Transportation and Supply chain management.**

Supply chain management promotes strategic cooperation among participants by integrating product flow, information flow, capital flow and decision flow in the circulation process to realize value added (Zhang et al., 2013). Koskela et al. (1990) have long proposed the concept of supply chain management. Until the last three years, this interdisciplinary research has received its due attention in the
PC field. However, in practice, the transportation of PC components still adopts the extensive mode of traditional construction industry (Teng et al., 2017). The resulting delays, component damage and cost overruns have seriously affected PC performance and people's evaluation (Ergen et al., 2007).

Research on PCSCM can be divided into three levels: strategic analysis, supply chain optimization and specific link design, which will be discussed in detail later. However, in general, the research on PCSCM cannot meet the demand of market implementation. No article has summarized the research status quo to analyze the gap between theory and practice. Therefore, with the use of scientometrics technology, this study attempts to systematically review the state, trends and gaps of PCSCM research, and to build a framework to promote PCSCM.

3. Method

The method of combining bibliometric evaluation with systematic review is an effective way to identify, examine and evaluate all relevant literature on a particular research topic at an early stage (Cerchione & Esposito, 2016). Bibliometric evaluation is a quantitative strategy to evaluate, cluster and map the quality and relevance of articles through mathematical models and algorithms, thus enhancing the visual and logical perception of the results of systematic reviews (Mingers & Leydesdorff, 2015). Systematic review is a basic and critical method for condensing topics, discovering research gaps, and building knowledge frameworks (van den Berg et al., 2009). The combination of the two can effectively avoid the common subjectivity and unreliability in literature review.

Fig.1 shows the three steps of the method. Literature review starts always with literature collection. After a statistical analysis of the selected literature review portfolio, five branches of bibliometric analysis experiments were conducted, including 1) Publication Distribution across Journals, 2) Co-occurrence of Keywords, 3) Co-authorship Analysis, and 4) Citation of Articles. They are the core of bibliometric analysis and can summarize the overall situation of the research field (Jin et al., 2018). For example, keyword analysis can help identify the research focuses, and co-author analysis can find the most influential contributors.
VOSViewer, a text-mining tool, was selected as the bibliometric evaluation tool. Compared to other text-mining tools, VOSViewer is better suited for visualization of large networks (Van Eck et al., 2010). The data can be imported directly into VOSViewer to generate the network of the articles (Van Eck et al., 2009) and create a network map, with the distance between nodes indicating how close they are (Zhao, 2017).

Based on the clustering results of bibliometric evaluation, four topics in the current research field of PCSCM were summarized, including 1) Strategic research and overall design, 2) PC supply chain process design and optimization, 3) Supply chain integration and management, and 4) Application of advanced technology. Then, combined with the systematic review, a framework to promote the implementation of PCSCM was further proposed and discussed.

4. Data collection

The data collection process consists of three steps, which follows the Meho (2008), as shown in Fig. 2.

Step1: Select the database. Scopus, Elsevier, Web of Science (WoS) core, Engineering (EI) Village, and EBSCO Host were selected as the main retrieval databases.
Step 2: Data retrieval. Using the retrieval syntax in Fig. 2, a total of 516 initial records were obtained. The search scope was restricted to the “Title/Abstract/Keywords” field. There was no limit to the publication, and the date range was set to “all years to the present”. The earliest record retrieved was published in 2001.

Step 3: Literature screening and supplement. Some inclusion/exclusion criteria still need to be set to ensure the accuracy of the retrieval results. First, the initial retrieved records were imported into EndNote X8 software to filter duplicates. Next, the following two types of articles were deleted, a) articles that were obviously unrelated to PCSCM (e.g., biology, agriculture, pharmacology, medicine); b) articles in a wide range of categories as "editorial", "book review", "discussion and conclusion", "letters" and "newspaper articles". Then, a backward search (cross-referencing) was performed in the references to avoid missing important references. Eventually, 152 qualified titles were included in our literature review portfolio.

Additionally, the papers on supply chain management/prefabrication/construction in broad sense were not directly adopted because the focus of this work is on PCSCM rather than the broad field it covers. Nevertheless, views from these areas might be used to strengthen the analysis, although the papers might not be included in the literature review portfolio.

Fig. 2. Literature retrieval and screening process

Fig. 3 shows the annual number of publications from 2001 to 2018. Through the simple statistical analysis, it can be found that the research on PCSCM has been growing rapidly in recent years, reaching a considerable number of 37
papers in 2018.

Fig. 3. Yearly publications from 2001 to 2018

5. Results of Bibliometric Experiments

5.1. The cross-journal publication distribution experiment

The results of the cross-journal publication distribution experiment can reflect the contributions of each journal to the PCSCM field to some extent. Under the selection criteria of the minimum publication quantity and citations of 3 and 10 articles respectively, the top 10 of 38 journals included in our literature review portfolio are shown in Fig. 4. Node size and journal name font size are proportional to the number of publications published in the journal. The larger the fonts and nodes represent the more publications. The node color represents the average year of publication. The lighter the color, the more recent articles. The thickness of the link between nodes indicates the frequency of references between two journals.

Table 2 details the total link strength, number of articles, total citations, average publication years, average citations and average normalized citations. The total link strength, number of articles and total citation are usually highly correlated with each other, and are used as quantitative indicators to measure the productivity of journals. Average citations and average normalized citations are taken as qualitative indicators to measure the impact of the journal. In terms of the publications number, Automation in Construction, Journal of Construction Engineering and Management, Journal of Cleaner Production and Sustainability are the top three Journals. Expert Systems with Applications, Automation in
Construction, Journal of Construction Engineering and Management have the highest average number of citations, indicating their high field influence. It can be found that Automation in Construction is the most influential journal in this field due to its high average normalized citations.

Table 2: Analysis of sources publishing PCSCM research.

<table>
<thead>
<tr>
<th>Source</th>
<th>Total link strength</th>
<th>Number of articles</th>
<th>Total citations</th>
<th>Avg. pub. year</th>
<th>Avg. citations</th>
<th>Avg. norm. citations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automat. Constr.</td>
<td>70</td>
<td>26</td>
<td>462</td>
<td>2014</td>
<td>18</td>
<td>1.28</td>
</tr>
<tr>
<td>J. Constr. Eng. M. ASCE</td>
<td>37</td>
<td>8</td>
<td>141</td>
<td>2011</td>
<td>18</td>
<td>0.72</td>
</tr>
<tr>
<td>J. Cleaner Prod.</td>
<td>31</td>
<td>10</td>
<td>78</td>
<td>2017</td>
<td>8</td>
<td>2.22</td>
</tr>
<tr>
<td>Sustainability</td>
<td>25</td>
<td>6</td>
<td>10</td>
<td>2017</td>
<td>1</td>
<td>0.72</td>
</tr>
<tr>
<td>Can. J. Civ. Eng.</td>
<td>24</td>
<td>6</td>
<td>33</td>
<td>2013</td>
<td>7</td>
<td>0.44</td>
</tr>
<tr>
<td>Expert Syst. Appl.</td>
<td>19</td>
<td>4</td>
<td>39</td>
<td>2011</td>
<td>20</td>
<td>1.01</td>
</tr>
<tr>
<td>Int. J. Prod. Res.</td>
<td>13</td>
<td>3</td>
<td>11</td>
<td>2016</td>
<td>4</td>
<td>0.59</td>
</tr>
</tbody>
</table>
5.2. Co-authorship analysis experiment

Co-authorship analysis experiment can identify the important scholars in PCSCM and their cooperative relationships (Hosseini et al., 2018). Under the selection criteria of the minimum publications and citations of 3 and 15 respectively, the top 14 of 225 authors included in our literature review portfolio are shown in Fig. 5. The experiment formed a main cluster represented by Hu, Xue and Shen, as well as Arashpour, Ergen and other independent researchers. The main cluster focuses on supply chain integration and management (Li et al., 2018).

![Co-authorship analysis](image)

Fig. 5. Co-authorship analysis.

Table 3: List of active researchers in PCSCM.

<table>
<thead>
<tr>
<th>label</th>
<th>Number of publications</th>
<th>Total Citations</th>
<th>Avg. pub. year</th>
<th>Avg. citations</th>
<th>Avg. norm. citations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hu</td>
<td>8</td>
<td>81</td>
<td>2014</td>
<td>10</td>
<td>1.09</td>
</tr>
<tr>
<td>Shen</td>
<td>7</td>
<td>53</td>
<td>2017</td>
<td>8</td>
<td>2.74</td>
</tr>
</tbody>
</table>
Table 3 shows the five quantitative indicators of the top 11 published authors. Hu published the most papers, with eight, followed by Shen, Arashpour, Xue and Wang, all with six. However, Ergen and Akinci have published only four papers, but are the most cited on average. This, of course, has to do with the earlier age of publication. In addition, although the total citation rate is not high, the average normalized citation rate of Li, Hong and Shen is relatively high. This indicates a significant increase in the impact of their research.

5.3. Citation of articles

According to the citation statistics of SCOPUS database, the top ten papers are shown in Table 4 with citation number ranges from 36 to 103. Specifically, the top three of citations are Ergen and Akinci (2007), Yin et al. (2009) and Chen et al. (2010), which are cited 103, 58 and 54 times respectively. Ergen and Akinci (2007) innovatively integrated RFID into PCSCM, effectively avoiding construction delay and labor cost increase caused by repeated processing, parts dislocation and incorrect installation. Yin et al. (2009) combined Personal Digital Assistant (PDA) and RFID to build a precasting production management system, which solved the difficulties of data storage and record audit, avoided repeated data entry and facilitated immediate feedback. Chen et al. (2010) proposed a transparent construction method selection model (CMSM) to assist scientific prefabrication decision.

Table 4: List of publications with highest impact in PCSCM.

<table>
<thead>
<tr>
<th>Author</th>
<th>Title</th>
<th>Year</th>
<th>Citations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arashpour</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xue</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wang</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Akinci</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zhong</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ergen</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wakefield</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hong</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

53
<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Title</th>
<th>Year</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ergen &amp; Akinci</td>
<td>Tracking and locating components in a precast storage yard utilizing radio frequency identification technology and gps</td>
<td>2007</td>
<td>103</td>
</tr>
<tr>
<td>Yin et al.</td>
<td>Developing a precast production management system using RFID technology</td>
<td>2009</td>
<td>58</td>
</tr>
<tr>
<td>Chen et al.</td>
<td>Decision support for construction method selection in concrete buildings: prefabrication adoption and optimization</td>
<td>2010</td>
<td>54</td>
</tr>
<tr>
<td>Bankvall et al.</td>
<td>Interdependence in supply chains and projects in construction</td>
<td>2010</td>
<td>50</td>
</tr>
<tr>
<td>Ergen et al.</td>
<td>Life-cycle data management of engineered-to-order components using radio frequency identification</td>
<td>2007</td>
<td>49</td>
</tr>
<tr>
<td>Pan et al.</td>
<td>Strategies for Integrating the Use of Off-Site Production Technologies in House Building</td>
<td>2012</td>
<td>44</td>
</tr>
<tr>
<td>Jaillon &amp; Poon</td>
<td>Life cycle design and prefabrication in buildings: a review and case studies in Hong Kong</td>
<td>2014</td>
<td>43</td>
</tr>
<tr>
<td>Pheng et al.</td>
<td>Just-in-time management of precast concrete components</td>
<td>2001</td>
<td>42</td>
</tr>
<tr>
<td>Chan et al.</td>
<td>Constraint programming approach to precast production scheduling</td>
<td>2002</td>
<td>40</td>
</tr>
<tr>
<td>Leu et al.</td>
<td>GA-based resource-constrained flow-shop scheduling model for mixed precast production</td>
<td>2002</td>
<td>36</td>
</tr>
</tbody>
</table>

5.4 **Keywords co-occurrence experiment**

Keywords co-occurrence experiment describes the research topics and interrelationships in a given domain. Take the frequency of co-occurrence of two keywords as the link strength between them (Šubelj et al., 2016). Among the 536 keywords in all literatures, 61 met the setting condition of the minimum link strength of 3. Then, combine the synonyms, such as “BIM” and “Building Information Modeling”, and omit general terms such as “prefabrication”, “supply chain” and “management”. Finally, PCSCM research topic relational network is
generated as shown in Fig. 5, which contains 24 nodes and 132 links.

Based on the frequency and co-occurrence probability of keywords, the 24 keywords shown were further divided into clusters with different node colors. For example, as shown in Fig. 6, yellow node cluster includes RFID, BIM and technology, etc. By extracting the commonness of the keywords in each cluster, the clusters were named as:

Strategic research and overall design (red nodes): focus on the integrated management and sustainability performance evaluation of the whole process of PC management. Much of the research is based on the China case.

PC supply chain process design and optimization (green nodes): focus on the modeling and simulation (Li et al., 2017) of the four main parts of PCSCM: ordering (Dallasega et al., 2018), manufacturing (Ma et al., 2018), transportation and installation (Kong et al., 2017). Genetic algorithm is the most commonly used algorithm.

Supply chain integration and management (blue nodes): focus on the internal integration and external integration. The former aims to improve the interests of all stakeholders, while the latter focuses on the cooperation and communication (Liu et al., 2017). Much of the research is based on the Hong Kong case.

Application of advanced technology (yellow nodes): focus on adopting advanced technologies, including BIM, RFID and lean, etc., to solve highly decentralized PCSCM problems (Arashpour et al., 2014) and optimize the efficiency of supply chain (Azman et al., 2014).
Table 5: Summaries of most frequently studied keywords in PCSCM

<table>
<thead>
<tr>
<th>Category</th>
<th>Key-word</th>
<th>Link strength</th>
<th>Occurrences</th>
<th>Avg. pub. year</th>
<th>Avg. citations</th>
<th>Avg. norm. citations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategic management</td>
<td>Construction Management</td>
<td>43</td>
<td>21</td>
<td>2014</td>
<td>19</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>Barriers</td>
<td>9</td>
<td>3</td>
<td>2017</td>
<td>8</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>Integration</td>
<td>19</td>
<td>8</td>
<td>2015</td>
<td>10</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>Sustainability</td>
<td>11</td>
<td>3</td>
<td>2018</td>
<td>1</td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td>China</td>
<td>28</td>
<td>10</td>
<td>2017</td>
<td>11</td>
<td>1.19</td>
</tr>
<tr>
<td></td>
<td>Innovation</td>
<td>17</td>
<td>7</td>
<td>2015</td>
<td>14</td>
<td>1.02</td>
</tr>
<tr>
<td>Route design and optimization in PCSCM</td>
<td>Model</td>
<td>32</td>
<td>19</td>
<td>2016</td>
<td>10</td>
<td>1.39</td>
</tr>
<tr>
<td></td>
<td>Simulation</td>
<td>27</td>
<td>12</td>
<td>2014</td>
<td>9</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>Optimization</td>
<td>43</td>
<td>18</td>
<td>2016</td>
<td>6</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Genetic algorithm</td>
<td>29</td>
<td>16</td>
<td>2013</td>
<td>11</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>Scheduling</td>
<td>12</td>
<td>4</td>
<td>2010</td>
<td>16</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Productivity</td>
<td>12</td>
<td>4</td>
<td>2011</td>
<td>15</td>
<td>0.69</td>
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<tr>
<td>Supply chain integration and management</td>
<td>Project Management</td>
<td>7</td>
<td>4</td>
<td>2016</td>
<td>9</td>
<td>0.89</td>
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<tr>
<td></td>
<td>Design</td>
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<td>2015</td>
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<td>Inventory</td>
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<td>2018</td>
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<td>0.69</td>
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<td></td>
<td>Hong Kong</td>
<td>40</td>
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<td>2017</td>
<td>10</td>
<td>1.25</td>
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<tr>
<td></td>
<td>Performance</td>
<td>37</td>
<td>12</td>
<td>2016</td>
<td>7</td>
<td>0.73</td>
</tr>
<tr>
<td>Application of advanced technology</td>
<td>Lean construction</td>
<td>14</td>
<td>5</td>
<td>2017</td>
<td>3</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>RFID</td>
<td>20</td>
<td>11</td>
<td>2013</td>
<td>24</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td>Technology</td>
<td>19</td>
<td>6</td>
<td>2017</td>
<td>3</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td>BIM</td>
<td>18</td>
<td>7</td>
<td>2017</td>
<td>8</td>
<td>1.46</td>
</tr>
<tr>
<td></td>
<td>Internet</td>
<td>12</td>
<td>3</td>
<td>2018</td>
<td>2</td>
<td>0.79</td>
</tr>
</tbody>
</table>
Table 5 further summarizes the quantitative measurement of keywords. Link strength represents the correlation between a given keyword and other keywords. Construction management, optimization and performance have the highest link strength, reflecting the overall focus of the study. The number of keyword occurrence is similar to the ranking of link strength. According to the average publication year, BIM, internet, information and sustainability seem to be emerging keywords, which shows the importance and necessity of the application of advanced technology and sustainability. In contrast, although there are many researches on the design and optimization of PCSCM route based on genetic algorithm, the popularity of it has decreased significantly. Tracking, BIM and RFID show prominent performance in the average normalized citations index, which further shows the degree of attention of advanced technology applications in PCSCM. The detailed thematic discussion is given in section 6.

6. Thematic discussion

Based on the results of scientometrics analysis, we further divided the four important directions of current research (Table 5) into the management and technical levels shown in Fig. 7 for discussion. Obviously, the management level includes 1) Strategic research and overall design, and 2) Supply chain integration and management, while the technical level includes 3) Supply chain process design and optimization, and 4) Application of advanced technology. Then, according to the convention, this study proposed the research gap and the future research direction. Finally, an innovative and reasonable framework was constructed to promote the development of PCSCM.
6.1. Strategic research and project evaluation

In general, the development of PC is still a long way from large-scale application (Jaillon et al., 2008). Regional industrial layout and enterprise level strategic research still cannot meet the needs of market development (Moon et al., 2018). Although enterprises or projects as the main body of the project management are aware of the importance of supply chain management, most of the innovative management modes developed were still centered on the construction and installation management on the site, have not substantially extended to the whole supply chain (Kim and Nguyen, 2017). Market awareness and acceptance of PC is still insufficient (Lee et al., 2014). The market almost passively accepts the government's policy regulation and has not been able to actively participate in the strategic planning of PCSCM development (Lee et al., 2013). The research level also focuses on three core issues in the process of promoting the development of PCSCM and market cognition: obstacles and drivers, sustainable performance evaluation and risk evaluation.

**Obstacles and Drivers.** Compared with conventional techniques, cost is the main obstacle to the adoption of PC, which is reflected in every link of the supply chain, including the cost increase caused by the long decision-making time of the supply chain (Mao et al., 2015). In addition, lack of understanding of PCSCM (Mao et al., 2017) and complicated implementation process (Almusallam et al., 2018) are also important factors hindering the advancement of PC (Blismas et al., 2009). Of course, PCSCM is driven by many obvious factors, such as sustainable competitive advantage (Eshtehardian et al., 2013) and favorable policy environment (Tam et al., 2015), technological innovation (Chang et al., 2018) and diversified market demand (Hong et al., 2018).

**Sustainable performance evaluation.** It mainly includes environmental performance, economic performance, and social performance (Arashpou et al., 2017). In terms of economic performance, the implementation of effective supply chain management on prefabricated projects can increase enterprise profits by nearly 40% (Wong et al., 2010). For environmental performance, PC itself have better life cycle performance in energy performance (Albuquerque et al., 2012). Effective integration of PCSCM has more significant social effects, such as reducing labor consumption and improving the social image of the construction industry. In a word, the considerable sustainable performance of PCSCM is the main reason why it is favored by the government and the market.

**Risk evaluation.** Risks in the whole PCSCM are diverse, dynamic, uncertain and interactive (Sacks et al., 2004). Due to the complexity of the supply process,
schedule risk is recognized as the most important and should be strictly controlled (Polat, 2008), and emphasizes the importance of information interoperability between resource planning systems of different supply chain bodies (Luu et al., 2009). One of the most common risk factors is delayed delivery due to inconsistent logistics information caused by human error (Li et al., 2017).

6.2. Supply chain integration and management
External integration of supply chain management ensures real-time information exchange among all participants by looking for effective cross-organization cooperation mode, and realizes the sharing of market demand, inventory status, production plan, demand forecast and delivery plan. The advantages of external integration of supply chains have been widely proven in the manufacturing and logistics industries. For PCSCM, no matter in research or practice, enterprises are still trying to improve their own interests through internal integration (Yang et al., 2016), but ignore the overall interests of the supply chain.

![Fig. 8. Research framework of supply chain integration](image)

**Internal integration.** Supply chain participants improve their benefits through self-integration within the enterprise (Zhong et al., 2017). Production plan, purchasing decision and supplier selection are the core issues of internal integration. It is necessary for the supplier to develop an appropriate inventory management plan for the delivery requirements of multiple contractors (Ko & guo, 2015). In contrast, contractor procurement decisions include multi-component coordination and supplier relationship management (Voordijk et al., 2006). The selection of supplier affects the performance of PCSCM, and its evaluation criteria include procurement process, operational efficiency, relationship coordination and strategic adjustment, and corporate social responsibility (Liu et al., 2018). Using the operational research method to deal
with the complexity of internal integrated management decisions is the main means of research, such as production variability (Arashpour et al., 2016), procurement preference and supplier reliability (Gosling et al., 2013).

**External integration** focuses on supply chain cooperation mode and information communication. The research of cooperation mode is mainly to design reasonable models of cost sharing (Xu et al., 2018), risk (Goh et al., 2016) and benefit distribution (Zarbakhshnia et al., 2018). Using game theory to dynamically analyze the cooperation and competition behavior of supply chain participants is an effective method (Feng et al., 2017). Such as, London et al. (2017) explored the factors influencing the formation and disintegration of cooperative network. Information communication is mainly about how to use advanced information technology to realize real-time communication to reduce the delay and waste and create maximum common interests (Teng et al., 2017).

**6.3. Supply chain process design and optimization**

There is a big difference between the PC supply chain and traditional supply chain. PC supply chain is customization, and the total number of components matches the needs of construction site, so there is no need to keep safety inventory (Ma et al., 2018). The PC supply chain process design consists of four stages: ordering, manufacturing, transportation and assembly. Simulation is mostly used in the process design to evaluate its effectiveness. Supply chain process optimization targeted at time limit or cost is developing towards multi-objective optimization (Wang & Gong, 2018).

![PC Supply chain process design and optimization](image)

**PC supply chain process design based on simulation.** Dynamic simulation of PCSC process could help participants to predict the profit level under different behavioral decisions, so as to make rational decisions (Han et al., 2017). Wang et al. (2018) proposed an overall disturbance evaluation simulation model to evaluate the uncertainty of the PCSCM, which can prevent various disturbances in time and improve profits. In addition, simulation can effectively improve the professional quality of practitioners and their understanding of PCSC concepts and knowledge (Arashpour et al., 2018).
**PC supply chain process optimization.** Among optimization goals, schedule is considered to be primary. Timely delivery of prefabricated components is the major bottleneck that constrain the project productivity. Delays may result in prolonged construction cycles and higher labour costs. But early delivery can also lead to additional storage costs and wasted space (Arashpour et al., 2018). Genetic algorithm (Chan et al., 2002) and mixed integer linear programming (Khalili et al., 2002) are commonly used method systems. Based on the cost target, resource constraints such as molds (Li et al., 2018), workers, inventory (Wang et al., 2017) and workspace (Hong et al., 2014) were integrated into the model to develop the production scheduling scheme with the lowest production cost. In recent years, multi-objective optimization besides cost is concerned, and the concept of Just-In-Time (JIT) has been incorporated into production scheduling and delivery decisions (Kong et al., 2017).

**6.4. Application of advanced technology**
The application of advanced technology runs through the whole process of PCSC, including information technology and management technology. Management technology could reduce waste and improve efficiency to achieve optimal allocation of resources (Arashpour et al., 2015). Information technology enables real-time tracking and positioning of precast components and real-time communication between participants (Xu et al., 2018).

![Research framework of advanced technology](image)

Fig. 10. Research framework of advanced technology

**Management technology** mainly include lean construction and agile construction. Wet construction in the traditional construction industry limits the
promotion of lean construction (Purvis et al., 2014). However, lean construction is valued and promoted in PC because of the standardized design, factory-based parts and integrated information. The advantage of lean construction is that its strict production planning and process can effectively reduce waste and constantly improve the PC supply chain (Höök et al., 2008). Agile principles are an important complement to lean concepts in PCSCM. The Lean Principle applies to stable conditions (stable requirements of quantity), while the PC is characterized by uncertainty (e.g. changes in demand) (Mostafa et al., 2016). Therefore, it is necessary to supplement agile principles to reduce these uncertainties (Sertyesilisik et al., 2014).

**Information technology** applied in PCSCM can be divided into the following four categories: mobile terminal devices (PDA, mobile phones, wearable equipment), mobile terminal enabling technology (RFID, GPS), access network (WLAN, Zigbee) and application service (AR/VR, cloud computing) (Shi et al., 2016). The purpose of applying information technology is to promote the real-time acquisition and sharing of information among different stakeholders of PCSCM and reduce human error (Chen et al., 2017). One kind of research focuses on the real-time tracking of prefabricated components or materials in the whole supply chain. For example, BIM and RFID-based prefabricated component management system can actively and accurately facilitate the collection and transmission of information related to material storage and use, so as to timely adjust production objectives and plans (Ergen et al., 2007). RANSAC model, an RFID-based optimal management system, can quickly and automatically screen a large amount of RFID data to obtain effective information (Altaf et al., 2018), and provide the data to mobile terminal equipment (e.g., PDA) or mobile terminal enabling technology (e.g., GPS), so as to strengthen quality control and improve supply chain efficiency (Yin et al., 2009). Another type of research focuses on rapid communication in supply chains. Such as, VR based 3D dynamic interaction models that can be presented on mobile client can promote information communication in the whole supply chain (Li et al., 2018). Cloud computing and BIM provide solutions for data sharing among the Architecture, Engineering and Construction (AEC), which further helps reduces supply chain costs (Li et al., 2017) and time (Wang et al., 2017).

**6.5. Research Gap and Future Research Direction**

**Collaborative PCSCM with advanced technology**

Many advanced technology have been applied in PCSCM, but they are still low-level applications (Bilal et al., 2015). Fast and accurate processing of massive data in PCSCM, especially rich tacit knowledge and knowledge sharing of supply
chain, to achieve multi-technology integration and collaboration with the whole process of PCSCM, could effectively promote the decision-making optimization of supply chain. Big data and cloud computing, which has been widely used in manufacturing supply chain management, may provide more efficient support for PCSCM's timely interaction and tracking of prefabricated components.

**Cooperative mode of PCSCM**

The cooperation mode of supply chain and the contract system are the core problems of PCSCM. They reflect the complexity of supply chain marketing and construction contracts. Theoretical research and application are limited to the analysis of risk sharing model and other local relations (Li et al., 2016). Distributable benefits in the supply chain are not just profits. Benefit sharing model or contract terms should also adapt to the complex supply chain environment and cooperation model, rather than adopt a certain paradigm. Therefore, an important research direction is to develop innovative PCSCM cooperation mode to optimize the costs, risks and benefits of each participant.

**Introducing third-party logistics into PCSC**

Third-party logistics (TPL) means that contractor employ logistics professionals to manage all logistics activities (transportation, material procurement and storage). The employment of TPL helps to centralize the control and management of prefabricated components from multiple suppliers and avoid the unsynergies caused by the producer's separate responsibility for the transportation of their own products. But this will bring about a redistribution of responsibility and new coordination management problems. Integrating TPL into PCSCM can optimize delivery time and production cost. This creates a logistics management platform that allows suppliers and contractors to share information, thereby avoiding uncertainty and reducing operating and total supply costs. The application of TPL may be a new trend in the outsourcing of the prefabricated construction, which is conducive to the improvement of efficiency and sustainability from the perspective of PCSCM.

**Multi-level strategy research based on market characteristics**

The development of technology cannot be separated from the market characteristics and industrial level of the region. Most of the current studies take China and Hong Kong as the empirical background. It is obvious that more extensive research in more regions will contribute to the promotion and theoretical development of PCSCM. Supply chain optimization and industrial integration depend on the interaction of governments, contractors, suppliers and carriers. Internal integration and optimization of each independent level is the premise. In addition, compared with supply chain management of manufacturing
industry, PCSCM has unique construction technology and market environment. Based on this, the conceptual development framework of PCSCM is presented in Fig. 12.

### 6.6. A Conceptual Development Framework for PCSCM

The conceptual development framework to facilitate PCSCM implementation consists of three parts: technology base, market circumstances and decisions of main participants. Strengthening the practical application of technology and standardization of market environment is the basis to promote the implementation of PCSCM. The decision optimization of participants based on the integration of
industrial chain can further optimize the PCSC efficiency.

**Technology base.** Technology, including management technology, information technology and construction technology, is the basis to promote PCSCM. At present, the joint waterproof, joint joint and other construction technologies have developed more perfect. Combining lean and agile management methods to create a flexible supply chain at minimal cost and to adapt to the diversity of contractor needs is the focus of further research. BIM, RFID and other information technologies have been widely used in PCSCM, but how to process a large amount of data quickly and accurately is one of the current problems.

**Market circumstances.** Favorable market circumstances can further promote the implementation of PCSCM. The first is the standardized operation of the market, including clarifying the standard system of the key links of PCSC and realizing PC standardization and modularization. It is necessary to establish the codes and standards for the design, production, construction and acceptance of prefabricated buildings. In addition, the implementation of general, standardized, modular has become a consensus, standardization is the symbol of the level of industrialization, a high degree of standardization can achieve mass production, and mass production is also the main means of prefabricated construction cost reduction. The second is a change in management philosophy. PCSCM is transformed from being dominated by the contractor to having different core enterprises in different stages. The traditional construction supply chain is a satellite enterprise group with contractors as the core. However, for prefabricated buildings, the schedule and cost are largely limited by the production and transportation stages, which forms a group of enterprises with relatively balanced rights.

**Decisions of main participants.** PCSC involves many participants, such as contractors, suppliers, developers, governments, etc. Different participants must have different goals and conflicts of interest. After integrating the responsibilities of all parties, two aspects are obtained: optimization of production process design and optimization of contract system. In terms of production process design, suppliers need to integrate lean and agile concepts, optimize production planning, inventory management, and coordinate production lead time hedging (PLTH). The contractor needs to consider factors such as delivery time and volume of prefabricated components to develop a reasonable production layout plan. A whole-process resource scheduling scheme combining cost and time objectives needs to be developed. And BIM and other information technologies needs to be combined to realize the real-time communication, information collection,
performance monitoring and positioning functions. For the optimization of contract system, the optimal cost sharing, profit distribution and risk management measures under different contract modes are the further research direction. In addition, due to the strong positive externalities of PC, the government plays an indispensable role in the early stage. Government needs to formulate incentives such as subsidies and penalties, so as to guide enterprises to enter the PC market reasonably and form a good market operation mechanism.

Only through the coordinated development of technology, market circumstances and decision-making level of participants, can the PCSC form an integrated whole, so as to optimize the efficiency of supply chain and improve the level of supply chain.

7. Conclusions

PC has become a new direction for the construction industry to cope with the severe shortage of labor, environment and social resources. At present, PCSCM has become a critical factor restricting the popularization and development of PC. This paper systematically reviewed the status in quo, trends and gaps of PCSCM research and deeply analyzed the prominent topics. Of 516 records retrieved from five popular online databases, a total of 152 eligible documents were screened. Then, based on the scientometrics experiment, this paper made a statistical analysis of the publication year profile and journal allocation of the included literature, and constructed four kinds of visualized bibliographic information maps for the publication distribution across journals, co-occurrence of keywords, co-authorship analysis, and citation of articles. The main findings are as follows:

1) Influential journals that publish articles on supply chain management of fabricated construction include automation in construction and Journal of construction engineering and management.

2) The co-authors analyze the article numbers and influence of scholars in PCSCM. Among them, Hu published the most papers and Ergen got the highest Cited frequency.

3) The most frequently cited articles in this field are identified and the main research topics of these influential articles are discussed.

4) Keywords such as “Construction Management”, “Model”, “Optimization”, “Performance”, “Design”, “Genetic algorithm”, and “RFID” are frequently tracked, which is consistent with the main research topics obtained by cluster analysis.

5) Using data mining to cluster index keywords, 24 categories were further
summarized into four themes, including strategic research and project evaluation, PC supply chain process design and optimization, supply chain integration and management, and application of advanced technology.

Afterwards, a series of topics, including collaborative PCSCM with advanced technology, cooperative mode of PCSCM, introducing third-party logistics into PCSC and multi-level strategy research based on market characteristics, were proposed to explore the knowledge structure of PCSCM. Finally, a framework was constructed to promote PCSCM implementation for supply chain participants. The research findings provide an intuitionistic demonstration for the bibliographic information of PCSCM literature, and put forward new ideas and requirements for the development of PCSCM. It will contribute to the evaluation of the current situation of PCSCM and the grasp of the future direction by academics and practitioners.

Inevitably, this work has limitations in specimen integrity. First, while we believe that the right keywords have been selected to achieve our goals, they may be improved in the future to search articles more comprehensively. Second, the shortlisted samples were all in English, while books, reports and manuscripts in other languages were excluded. These limitations may affect the statistical results of the study, but have little impact on the concentration of the research trends and the discussion of topics.

References


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