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Crane Operations and Planning in Modular Integrated Construction: Mixed Review of Literature

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ABSTRACT: Cranes are the centrepiece of construction equipment during the on-site installation stage of Modular integrated construction (MiC). Any disruption which occurs during this stage can wipe away the efforts made in the production and transportation stages, and hence the privilege of adopting MiC is missed. Therefore, crane operations and planning (COP) research in MiC has witnessed tremendous growth over the past years. This research aims at monitoring and classifying of COP research in MiC to identify its trends and gaps, and hence highlight future research areas. To achieve this objective, this study utilizes a mixed review method of scientometric and systematic reviews. The scientometric review clarifies the most prolific journals, institutions, researchers, keywords correlations and geospatial connection network between research countries in COP. On the other hand, the systematic review analysis shows that there are five main research topics in COP of MiC. Further analysis shows that these topics are approached by six different solution methodologies. Four potential research areas identified in COP are COP in dynamic MiC sites, COP in multi-cranes high-rise MiC sites, risk management of COP and autonomous COP.

Keywords: Crane operations; Crane planning; Modular integrated construction; Modeling; Research gaps; Mixed review.

1. INTRODUCTION

Modular integrated construction (MiC) is a revolutionary construction method, where a whole building is divided into modules. These modules are produced in an off-site facility and then transported by special trailers to the construction site for direct assembly [1]. MiC has many advantages over the traditional cast-in-situ construction method. These advantages are related to construction duration, quality, safety and sustainability [2]. Cranes are considered to be the centrepiece of construction equipment in MiC sites. They play a pivotal role in the horizontal and vertical transportation of MiC modules to their final destinations. Cranes are high-cost components in the management of MiC projects representing about 36% of the total project procurement cost [3]. To reap their benefits, construction engineers need to spend time and effort to make planning decisions on cranes in MiC projects. Such planning includes the number, types, and location of cranes; position of supply areas; scheduling of lifted modules; motion planning of lifted modules and design of crane supporting systems. In addition, these decisions are affected by many factors, such as site layout, crane characteristics, weather conditions, surrounding environment and governing regulations [4]. Therefore, these factors contribute to the complexity of crane operations and planning (COP) in MiC. However, ignoring some of these decisions in the planning stage can result in fatal accidents, schedule delays and cost overruns. Hence, the merits of using MiC can be easily wiped out.

Consequently, COP in MiC has garnered much attention from researchers working to provide construction engineers and crane operators with automated decision-making models. Several optimization techniques have been proposed to address the challenges associated with crane location on MiC sites [5]; [6]; [7]; and [8]. The main focus of current researchers has been to provide an integrated system to combine the cumulative advantages of various solution techniques [9]; [10]; [11]; and [12]. Indisputably, researchers and MiC industry experts will find these academic publications useful. However, a conscious effort to integrate and classify existing literature on COP in MiC is currently needed. This will foster a better understanding of the subject area and create a comprehensive reference platform for future researchers. A preliminary search has been conducted to find review papers on COP in MiC, and hence ensure the novelty of the research idea [13]. The results of this search indicate that [14] has reviewed studies on crane safety in general construction sites without considering COP in MiC. Also, [15] and [16] have published reviews on mechanical control systems of cranes. From the operations research perspective, [17] have reviewed quantitative methods used in the construction research field. They discussed a variety of problem settings and applied operations research techniques used to solve different problems related to construction site layout planning, scheduling of construction projects and COP. Despite the contributions of these review papers, the literature still lacks systematic and scientometric reviews devoted to COP in MiC. To bridge this gap, this study exploits a mixed review method to provide a holistic science mapping and a classification of COP in MiC. This approach is chosen to combine the benefits of both the scientometric review and the systematic review methods. Firstly, a scientometric review of COP publications is implemented to: 1) identify the most active researchers and institutions in COP field; 2) visualize the geospatial network of countries that have contributed to COP; 3) identify the most frequent keywords and co-occurrence networks; and 4) determine the high impact journals which have published COP papers. This method will reveal research frontiers in COP field and provide opportunities for collaboration among research personnel and research organizations. Secondly, a systematic review on COP studies is conducted with the aim of : 1) summarizing the existing literature related to COP; 2) identifying the types of problems in COP and methodologies applied to solve them; and 3) highlighting future research opportunities in COP problems in MiC. By integrating scientometric review with systematic review, researchers and practitioners can effortlessly identify the research trend and research frontiers of COP in MiC.

The rest of the paper is organized as follows; section 2 briefly illustrates the development of COP research and how previous researchers address different types of COP problems using a variety of research methodologies. Then, the methods used to extract relevant studies on COP and the mixed review method are illustrated in section 3. Section 4 discusses the results of the scientometric analysis of COP research. This includes citation networks of top journals and articles, collaboration networks of top researchers, institutions and countries and co-occurrence network of COP keywords. Section 5 provides the results of the systematic review of relevant COP studies based on COP problems and the solution methodologies. Also, section 5 includes a description of each COP problem, applied methodology and a pictorial analysis of the frequency of each problem and corresponding solution methodology in the literature. Based on the results obtained from sections 4 and 5, section 6 summarizes some future research opportunities in COP in MiC. Finally, conclusions and research limitations are discussed in section 7.

2. RESEARCH BACKGROUND

The tendency to adopt MiC for the fast delivery of projects where long construction time cannot be tolerated makes COP in such projects a key challenge. Stakeholders of COP, such as planners, construction engineers, crane operators and crane vendors, have limited time to make the decisions related to COP in MiC [7]. Usually, these stakeholders rely on their experience and some rules-of-thumb, which may lead to sub-optimal decisions in COP. Key performance indicators of MiC projects include the duration of the project, its cost, productivity and safety. Improper planning of crane operations can severely impact these indicators, and hence wipe away the merits of adopting MiC [18]. Therefore, mainstream research on COP in MiC is dedicated to providing its stakeholders with automated models for making informed COP decisions. Some of these decisions can be grouped under the category of crane layout problem. Here, planners, with support of crane vendors, are responsible for determining the number of required cranes, types, locations and supply sites of MiC modules. Many studies, such as [6], [7],

[19], [20], and [21] have addressed the crane layout problem by minimizing the hoisting time of MiC modules from supply points to demand points. Factors considered include making the operating lifting radius of the crane to cover all demand points and utilizing a crane whose capacity exceeds the weight of the heaviest modules. Besides the crane layout problem, crane operators have to put up a schedule to determine when each MiC module will be lifted and delivered to its destination. In such schedules, the crane operator has to consider the due date to transport each module to its destination and the precedence relationships between the MiC modules. This scheduling problem has been covered in some studies, such as [22], [23] and [24], with the objective of shortening the total hoisting time. To avoid potential collisions between lifted MiC modules and other physical obstacles during lifting operations, the crane operator needs to plan the motion trajectory of the lifted modules. Moreover, the operator must also control the crane in terms of the sequence and speed of radial, tangential and vertical movements. Refs. [8], [25] and [26] have proposed automated systems to support the crane operator in collision-free lift path planning. In addition to the previously mentioned problems, the structural stability of cranes has attracted the attention of some researchers, such as [27], [28] and [29]. These researchers have proposed approaches to help the construction engineer to check the stability of crane’s supporting system in MiC projects.

COP researchers have employed a wide variety of methodologies to address the previously mentioned COP problems in MiC. Both exact and heuristic approaches have been used to solve the majority of COP problems. As for the exact optimization methods, branch and bound algorithms have been applied by many researchers, such as [6] and [30]. Besides, [31] used dynamic programming to solve the crane layout problem. Metaheuristics, such as genetic algorithm (GA) and particle swarm optimization (PSO), have been used by [32] and [33], respectively, to obtain near-optimum solutions to the crane layout problem. Simulation modelling like discrete-event simulation (DES), system dynamics (SD) and agent-based simulation (ABS), have been adopted by [26], [34], and [35], respectively. These authors employ simulation modelling to solve the crane layout and the lift path planning problems in MiC. Some previous researchers realize the critical role of visualization in solving COP-related problems in MiC. Hence, 3D modeling, 4D modeling and virtual prototyping have been used by [36], [9] and [22], respectively, to detect potential spatial risks through the lifting paths. Last but not least, some researchers such as [37] and [38], have proposed approaches based on laser scanning to track the lifted objects and hence avoid possible collisions.

The above discussion shows that COP research in MiC has reached a high degree of maturity and a wide variety of solution methodologies have been proposed. Despite that, the literature lacks a holistic review devoted to COP in MiC. Therefore, this study aims at providing a science mapping and clustering of COP research based on types of COP problems and solution methodologies. This holistic review, therefore, provides researchers with potential research challenges in COP in MiC that are not readily available from previous studies.

3. RESEARCH METHODOLOGY

With a clear objective of classifying COP research to equip future researchers to conduct more efficient and intensive research in COP of MiC, a “mixed review method” has been adopted in this study. Fig. 1 shows a general outline of the research methodology. The mixed review method comprises both quantitative (scientometric approach) and qualitative (systematic approach) review methods. Thus, this approach combines the advantages of the two methods. Furthermore, the mixed review method is accepted by many authors due to its ability to eliminate biased conclusion and subjective interpretation while providing an in-depth understanding of domain knowledge and research trends [13]; [39]. Therefore, the mixed review method has been selected to achieve the objective of this study.

Fig. 1

3.1 Extraction and Evaluation of Bibliometric Data

The research methodology starts by extracting relevant studies to COP. In this section, keywords and search databases used to find relevant studies are stated. Also, this section includes the inclusion and exclusion criteria applied to filter the retrieved studies. Finally, a standard review protocol is explained to screen the retrieved studies.

3.1.1 Selection of database and keywords

Scopus, Web of Science and Google Scholar are the three common databases in construction management research. In this study, Scopus is used to extract research publications on COP in MiC because it has a broader coverage of bibliometric data than the other search engines [40]. In addition, Scopus is compatible with recent science mapping software, such as VOSviewer.

After selecting the search database, relevant keywords are identified. The most common and interchangeable keywords related to COP in MiC are used to extract a more comprehensive set of the bibliometric data on COP. The keywords used for the search include modular construction, crane and planning or operation. Given that keywords have a strong influence on the overall research outcome, efforts have been made to use these keywords and their alternatives which could aid in retrieving almost all journals and papers on COP in MiC.

3.1.2 Inclusion and exclusion criteria

Specification of inclusion and exclusion criteria is a primary step in any systematic review to filter the retrieved studies and keep only the relevant ones. In this study, the inclusion criteria include: 1) studies which focused on COP in construction projects; 2) studies which addressed COP problems by using quantitative methods; and 3) studies published in peer-review journals. The exclusion criteria are: 1) studies published in languages other than the English language; 2) studies which addressed mechanical control systems of cranes; 3) articles which studied site layout planning problem without considering COP aspects; 4) studies on COP of some crane types which were rarely used in construction sites, such as gantry cranes and mast cranes; and 5) studies without available full text.

3.1.3 Screening and evaluation of retrieved studies

As of March 2020, a total of 337 articles have been retrieved from the Scopus database. Then, the authors have followed the Preferred Reporting Items for Systematic Reviews and Meta-

Analyses (PRISMA) protocol for screening and evaluating the retrieved studies [41], as shown in Fig. 2. The first process of PRISMA protocol is to rapidly screen titles and abstracts of the 337 retrieved studies. Following this process, 213 irrelevant articles have been excluded. Then, the full text of each included article has been evaluated, and 99 articles have met the inclusion criteria. Next, backward snowballing search strategy has been employed to find other studies which have not been obtained from the Scopus search. The 99 included articles have been used as the start set of relevant studies for the backward snowballing search strategy [42]. In the backward snowballing, relevant articles in the reference list of each paper in the start set have been searched. The newly found articles from this process have constituted a new start set. This cyclic process has been iterated until no new papers were found. Thanks to this search strategy, 30 new relevant articles have been found, and hence the total number of eligible articles is 129 (99+30) articles.

Fig. 2

3.2 Mixed Review Method

The mixed review method recruits both quantitative and qualitative methodologies simultaneously within the same research [43]. With a focus on utilizing the strengths and minimizing the weaknesses of both methods [44], the mixed method has been the preferred choice of most researchers. This present study takes advantage of the mixed review method to obtain a detailed understanding of the reviewed topic. Hence, it is expected that the applied method will be helpful in identifying the presence of any paradox and contradictions in the findings. Scientometric review and systematic review arechosen as the quantitative and qualitative techniques, respectively.

3.2.1 Scientometric review

The scientometric review is a quantitative science mapping approach. It focuses on the visualization of structural and dynamic aspects of scientific research. These aspects include knowledge domain and relationships among keywords, researchers, institutions, countries, articles and journals. Also, the scientometric review serves as a salutary technique within the field of bibliometry [45]; [46]. Scientometric review utilizes text mining techniques [47]; hence, it overcomes the subjectivity associated with the findings of narrative and systematic reviews [48]. Subjectivity arises when the researcher extracts the data from the retrieved studies based on his or her understanding, and uses these data for the analysis. However, in the scientometric review, the data required for the analysis are extracted automatically from the included studies. Therefore, many researchers have adopted this technique to map out patterns and diagnose a large amount of bibliometric data in many research topics in the construction field. Examples of such include [49] in computer vision applications for construction and [50] in artificial intelligence in construction.

Having obtained the bibliometric data which satisfied the inclusion and exclusion criteria, the first step in a scientometric review is to select a science mapping software. The software is applied to visualize structural, dynamics and temporal patterns and trends in the scientific literature of a knowledge domain, as shown in Fig. 1(a). VOSviewer software is used for this purpose. VOSviewer software provides the platform to produce, visualize and explore bibliometric networks [45]. The 129 articles obtained from data extraction and evaluation process illustrated in section 3.1 are fed into VOSviewer. Subsequently, a scientometric analysis is conducted to study and visualize networks of keywords, researchers, institutions, countries, and articles in COP research.

3.2.2 Systematic review

The findings obtained from the scientometric review method, albeit useful for mapping the research field, do not provide a deep insight into the bibliometric data. A systematic review, on the other hand, focuses on providing a comprehensive view of existing research to identify gaps in the body of knowledge and anticipate future research directions [51]; [52]. Therefore, many researchers have adopted the systematic review method in different construction research areas. These include [2] in applied lean techniques in modular construction and [53] in the adoption of blockchain in the built environment.

After retrieving the 129 relevant articles obtained from data extraction and evaluation process, the first process in the systematic review is to extract the required data to conduct a two-dimensional classification of the COP research, as shown in Fig. 1 (b). The two-dimensional classification is aimed at categorizing the 129 articles based on the COP problems and the applied solution methodologies. Therefore, COP problems and applied solution methodologies are extracted from each of the 129 articles. Based on the two-dimensional classification of the 129 articles, research gaps in COP of MiC are highlighted for future research consideration.

4. RESULTS AND DISCUSSION OF SCIENTOMETRIC REVIEW OF COP IN MIC

Analysis and discussion of results encompass the annual publication trend, network analysis of research outlets, and assessment of contributions. Others are contributions of countries and researchers, top research centres or institutions and most cited articles in COP research. Bibliometric mapping techniques have been employed to elaborate more on the relationship and collaboration among institutions and countries.

4.1 Annual Publication Trend of COP Papers

Fig. 3 presents the annual COP research publication over the last four decades. The second-degree polynomial trend line on the figure manifests the accumulation of knowledge and development of COP research. This fast-growing trend indicates that research on COP in MiC has received considerable attention from the research community, especially during the last two decades. Between 1980 and 2000, there is, on average, less than one paper published on COP annually. A gradual increase in research publications can be seen in the third and fourth decades (2000-2010 and 2011-2020). This rises to about six published articles per year in those decades. An all-time peak of 12 publications is observed in 2018. The increase in publications is not surprising since the need for high rise buildings have increased globally as land prices escalate. Thus, the conscious effort on optimizing land use in various cities have resulted in the construction of high rise residential buildings using MiC method. This requires more cranes to lift modules to higher levels. Crane planning is an essential element in the planning process and represents a significant cost component during various MiC projects. Therefore, there has been a general need to perfect crane operations in MiC projects. Notwithstanding the overall gradual increase in research publications, a decline in the number of COP research publications can be seen in some specific years. Nonetheless, Fig. 3 demonstrates that efficient COP is becoming a critical factor for the successful delivery of MiC projects. This is explained by the numerous research works on COP in MiC to address many of its aspects by using a wide variety of available methodologies, as will be illustrated in section 5.

Fig. 3

4.2 Network Analysis of Journals Contributing to COP in MiC

Analysis of the journals, which publish articles related to COP in MiC, is a necessary step in the scientometric review process. This is important to identify the high impact journals, map their network, and hence guide readers to the key journals in this field [54]. Also, identification of the top COP research journals helps researchers in selecting the best journals for publishing their works. Furthermore, it assists institutions and libraries with limited resources to subscribe to key COP journals [55]. Fig. 4 shows citations network of seven top scientific journals that publish articles on COP. These journals have published at least three COP research articles and achieved at least 20 citations. These specifications have been exploited in VOSviewer software to generate the network shown in Fig. 4. It is worth mentioning that there are no standard rules to select the number of documents and citations in the VOSviewer's network analysis [48]. Besides, Table 1 summarizes the quantitative data of the network.

Fig. 4

Table 1

The networks generated in VOSviewer are distance-based [56]. For example, in Fig. 4, the distance between two journals indicates the relationship between the journals in terms of co-citation links. Also, the size of the node (journal) represents the number of citations achieved by the journal. For instance, *Automation in Construction; Journal of Construction Engineering and Management;* and *Journal of Computing in Civil Engineering* have larger nodes than the other journals, indicating their higher impact on COP research. In addition, the journals with the same colour belong to the same cluster, highlighting the frequency of co-citation of these journals in COP research articles. Besides, the thickness of the connection lines in the network indicates the citation linkage between the journals. For example, *Automation in Construction* has strong citation links with *Journal of Construction Engineering and Management; Journal of Computing in Civil Engineering;* and *Construction Management and Economics* in the COP research, as shown in Fig. 4. However, *Canadian Journal of Civil Engineering* has a weaker citation connection with the rest of the journals.

Table 2 ranks the seven top journals in COP research based on the number of published articles, number of citations and total link strength. The total link strength represents the number of links of a journal with the other journals. The results show that the most influential outlet for COP in MiC is *Automation in Construction* with a total link strength of 240 and 1196 citations. The leading journal, *Automation in Construction,* can be justified as a perfect fit for COP in MiC as existing literature seeks to automate the whole crane operations in MiC projects. Automation reduces human interference and minimizes errors.

4.3 Scientific Collaboration Networks in COP Research: Co-authorship Analysis

Understanding the current scientific collaboration networks in any research field can facilitate the identification of top researchers and laboratories in the field. This can promote collaboration in joint funding projects and communication between academics [48]; [50]. Ref. [57] demonstrates that collaborative works are often published in higher impact journals and receive more citations than individual research works. The co-authorship analysis reveals the collaboration network between different entities in any research field [54]. Therefore, the co-authorship networks of collaborative researchers from different countries and institutions in COP research field are presented and discussed in the next subsections.

4.3.1 Active countries in the COP research

Identification of the scientific collaboration network of countries can promote future collaboration and knowledge sharing. Fig. 5 shows the collaborating and the most influential countries in the COP research, while Table 2 lists the contribution of each of these countries. The network shown in Fig. 5 is generated in VOSviewer by selecting “co-authorship” and “countries” as the type of analysis and the unit of analysis, respectively. Besides, the “minimum number of documents of a country” and the “minimum number of citations of a country” are set to “4” and “10”, respectively. Again, there are no standard rules to set these conditions. 12 out of 26 countries satisfy the conditions and are included in Table 2. However, only 11 countries are shown in Fig. 5 with the exception of Singapore. This is because there are no cross-country studies between researchers in Singaporian research institutions and other researchers in other territories.

Fig. 5

Table 2

In Fig. 5, the node size reflects the number of citations achieved by studies in each country. For example, the United States, Canada and China are represented by bigger nodes than the other countries. This indicates that these countries contribute most to COP research. Researchers in the United States, China and Australia tend to collaborate more with other researchers in different territories, as demonstrated in the total link strength of each country in Table 2. Researchers in Canadian research institutions, despite their significant contribution to COP research, have fewer cross-country collaborators. However, cross-country studies between researchers in the United States or China and researchers in different territories are higher.

4.3.2 Active institutions in the COP research

Knowledge of the collaboration network of institutions, which invest more in COP research is useful to industrial practitioners seeking innovative solutions to COP problems [48]. Table 3 shows the top leading institutions in COP research. Table 3 is produced in VOSviewer by setting the “minimum number of documents of an organization” and the “minimum number of citations of an organization” to “2” and “10”, respectively. Nine organizations meet the requirements, and are listed in Table 3.

Table 3

The results in Table 3 indicate that research centres with the highest contribution to COP research in MiC include University of Alberta, Gyeongsang National University and Georgia Institute of Technology. The margin between the number of studies conducted in the University of Alberta and in other universities clearly indicates her leading role in COP research in MiC. Interestingly, PCL Industrial Management Inc. and NCSG Engineering Ltd., albeit non-academic institutions, are 6th and 9th, respectively, among the top nine institutions. This shows that COP research contributes to the industry and tackles real-world problems in the field. As for the collaboration between institutions, the results suggest that these two companies are more collaborative in conducting COP research than other academic institutions.

4.3.3 Active researchers in the COP research

Visualization of scientific collaboration network of researchers in COP field promotes collaboration and helps in sharing of knowledge and ideas [50]. In VOSviewer, by setting the “minimum number of documents of an author” and the “minimum number of citations of an author” to “3” and “10”, respectively, 34 out of 260 researchers meet these conditions. They are listed in Table 4. These researchers are shown in the citation density map in Fig. 6. In this figure, each group of collaborative researchers constitute a cluster.

Fig. 6

Table 4

Fig. 6 shows three clusters of collaborative researchers. The first cluster of collaborative researchers includes Dienstknecht M. and Briskorn D. from the Bergische Universität Wuppertal, Germany. The second cluster contains Gao S., Wu D., Wang X. and Lee D. from the Dalian University of Technology, China. The third cluster includes Taghaddos H., Hermann U., Al-Hussein M., Bouferguene A. and Kosa J. The last cluster consists of collaborative researchers from three different institutions, which are University of Alberta, PCL Industrial Management Inc. and NCSG Engineering Ltd., all within the Canadian territory. Such collaboration between professionals in the academia and industry may be responsible for this cluster being the most influential one within the network.

The top five researchers in terms of the total number of citations are Al-Hussein M., Varghese K., Tam C.M., Kang S.-C. and Miranda E.. However, normalization of the total number of citations results in different order of top five researchers. Normalization mitigates the impact of the fact that older articles have had more time to be cited in comparison with recent articles [56]. Using the normalized citations metric, the top five researchers are Miranda E., Moselhi O., Taghaddos H., Tantisevi K. and Al-Hussein M. By examining the links between the top researchers in COP, the most collaborative research couples are (Dienstknecht M. & Briskorn D.), (Kang S.-C. & Miranda E.) and (Li H. & Skitmore M.) with a link strength of “3” for each couple.

4.4 Article Co-citation Analysis

There is a wide consensus in the scientific community that the number of citations received by an article is an indication of its contribution to the field of study. This is not always the case, especially for recent publications [48]. Top-cited articles in COP research and their citation networks are provided in this section. By setting “the minimum number of citations of a document” to “20”, 54 out of 129 articles meet the threshold and are connected with one another. Fig. 7 shows the density map of these articles generated by VOSviewer. However, Table 5 summarizes the total number of citations, number of links and normalized number of citations received by the 20 top-cited articles in COP research. The time span of these articles ranges from 1996 to 2015. The five most cited articles are [58], [32], [59], [5] and [60]. Three of these studies address problems related to tower cranes [5], [32] and [58], while the others focused on problems of mobile cranes. Despite that these studies are old, they are considered to be a stepping stone for early-stage researchers who are interested in COP research. Also, normalized citations metric was used to correct for the fact that older studies have had more time to be cited in comparison with recent studies. Normalized citations represent the number of citations received by an article divided by the average number of citations of all articles published in the same year [56]. The five top articles in terms of normalized citations are [61], [6], [62], [32] and [63]. Interestingly, the majority of these papers are related to tower cranes, except [62]. The number of internal citations between the studies listed in Table 5 shows that three studies receive highest citations from the 54 articles. These articles [5], [60] and [64] meet a minimum threshold of 20 citations. Their citations are 18, 18 and 14 citations, respectively, as shown in the number of links in Table 5. A classification and a summary of each of the studies mentioned above are provided in the supplementary document.

Fig. 7

Table 5

4.5 Co-occurrence Network of COP Keywords

Co-occurrence network of keywords can provide a mental map of research topics in any field [48]. Moreover, the network of keywords can help researchers to: 1) identify the relationships between the research topics and the research methodologies used by previous researchers; 2) understand the mainstreams of any research field using the clustering function in VOSviewer and 3) identify the frequency of addressing the research topics by specific methodologies, and hence pick some research gaps. The network of keywords provides the researcher with the above-mentioned information without the need to read the whole papers. Furthermore, this information is free of the subjectivity characterized by the conclusions provided in the narrative and systematic reviews. VOSviewer used the terms that appeared in the titles, abstracts and keywords of the 129 included papers to generate the keywords co-occurrence network shown in Fig. 8. Each node in Fig. 8 represents a keyword, and its size reflects how many times this keyword is repeated in the titles, abstracts and keywords of the included papers. However, the thickness of the curved line between two keywords reflects how many times these keywords have been used together. By setting “the minimum number of occurrences of a keyword” to “5”, 57 keywords meet this threshold, and they can be used to build the network. However, general terms, which do not add much to the understanding of the main research topics in COP research, are removed to simplify the network. Such terms include "cranes", "construction", "construction industry", "crane", "construction management" and "civil engineering", In addition, Fig. 8 shows only the strongest 200 links in the network to make it clearer. Analysis of the co-occurrence network of keywords, shown in Fig. 8, can lead to the following findings.

Fig. 8

(1) "tower cranes" (37 occurrences) are repeated more than "mobile cranes" (24 occurrences) in the literature. This indicates that problems related to tower cranes draw greater attention from researchers than the problems of mobile cranes. Figs. 9(a) and 9(b) show the most frequent co-occurrence keywords with "mobile cranes" and "tower cranes", respectively. In Figs. 9(a) and 9(b), the link strengths between "motion planning" and "mobile cranes" and between "motion planning" and "tower cranes" are 2.35 and 0.5, respectively. These values highlight that motion planning problem of mobile cranes are often addressed more than that of tower cranes. Other problems are shown to co-occur more with only one crane type. For example, "productivity" and "location" are linked to "tower cranes" only, as shown in Fig. 9(b). However, "crane selection" and "cables" are connected to the network of "mobile cranes", as shown in Fig. 9(a). Similarly, some research methodologies are linked more with only one crane type. For instance, "visualization" and "three dimensional computer graphics" are shown in the network of mobile cranes, as demonstrated in Fig. 9(a). On the other hand, "integer programming" and "decision support system" are repeated with "tower cranes". Interestingly, "tower cranes" and "mobile cranes" do not co-occur with each other. This suggests that few studies have addressed COP problems arising from using tower and mobile cranes in the same construction site. This finding is demonstrated by locating "tower cranes" and "mobile cranes" in two clusters.

(2) "optimization" (30 occurrences) and "visualization" (14 occurrences) are the top research methodologies repeated in COP research. Figs. 9(c) and 9(d) show the network of

keywords that co-occur with “visualization” and “optimization”, respectively. Fig. 9(c) shows that the “visualization” is repeated more with “mobile cranes” than with “tower cranes”. Also, the visualization network gives an idea about the applied visualization techniques through the links with “three dimensional computer graphics” and “three dimensional”. Furthermore, Fig. 9(c) highlights the importance of visualization in the automation of COP through its link with “robotics”. In Fig. 9(d), the link strengths between “optimization” and “tower cranes” and between “optimization” and “mobile cranes” are 3.96 and 0.87, respectively. They indicate that optimization techniques are popular for solving problems of tower cranes than that of mobile cranes. Also, Fig. 9(d) reveals the optimization techniques used in the literature, such as “integer programming”, “genetic algorithms” and “algorithms”. Moreover, Fig. 9(d) shows that optimization has been used to solve some problems in COP, such as “location”, “motion planning”, “site selection” and “accident prevention”.

(3) The most frequent types of projects that appear in the network are “tall buildings” (10 occurrences) and “modular construction” (6 occurrences). Fig. 9(e) shows the network of the keywords associated with “modular construction”. This network indicates that mobile cranes are frequently used in MiC projects than tower cranes. It is most probable the majority of these projects are low rise buildings. This finding is backed by the absence of connections between “modular construction” and “tall buildings”. Moreover, these keywords are located in two clusters. Expectedly, “tall buildings” are connected to “tower cranes”, as shown in Fig. 9(f), which shows the keywords network of “tall buildings”. Also, Fig. 9(f) shows that COP problems related to tall buildings are frequently solved by optimization methods.

Fig. 9

5. RESULTS AND DISCUSSION OF SYSTEMATIC REVIEW OF COP IN MIC

Findings from the scientometric review can only provide the reader with a high-level clustering of COP research. This, however, cannot help in the identification of specified research gaps in COP in MiC. Therefore, the 129 articles used for the scientometric review are subjected to a systematic review to provide a comprehensive literature classification of COP research. The introduction, methodology, conclusion and for most cases, the whole body of the 129 articles are studied. These articles are classified based on two-dimensional classification. These two dimensions are problem type and research methodology. Each dimension consists of several subcategories. For example, crane layout, lift path planning, scheduling of crane tasks, crane stability and integrated problems are five types of problems addressed in the 129 papers. These problems have been solved by six types of research methods. These include optimization, visualization, simulation, positioning and tracking systems, artificial intelligence and hybrid methodologies. The rationale behind using this two-dimensional classification is to provide an insightful description of the mainstream research on the COP. Therefore, it is to highlight the research gaps in COP in MiC. The results of classification analysis are presented in the next subsections in terms of tables and graphs to facilitate discovering trends and research gaps in COP in MiC. In addition, illustration of each subcategory of the two classification dimensions is also provided. And finally, a brief summary of the contribution of each of the 129 papers is provided in the supplementary document.

5.1 Classification Based on Type of Problems

The mainstream research on COP can be classified into five categories. Each category represents a problem type related to COP in MiC. The five problem types are crane layout, lift path planning, scheduling of crane tasks, crane stability and integrated problems. A brief definition of each problem type, solution methodologies, and research gaps pertaining to each problem type are summarized in the following subsections.

5.1.1 Crane layout

The crane layout problem is part of the facility layout problem in construction sites. The crane layout problem aims at obtaining the optimum number of cranes, crane type (tower or mobile cranes), crane model, and crane locations. Furthermore, the problem seeks to optimize locations of supply points and allocate these supply points to demand points. The objective of this problem is to minimize the transportation time of MiC modules from supply points to demand points. Besides these objectives, others covered in the literature include minimization of hiring, operating, assembly, dismantling and relocating costs of cranes. Another objectives are maximization of crane's utilization and minimization of CO_2 emissions from crane operations. Many factors should be considered when solving the crane layout problem. These include setting the operating lifting radius of the crane to cover all demand points and selecting a crane capacity that can bear the heaviest modules. Finally, the capacity of supply points should be considered. For mobile cranes, additional factors related to its manoeuvrability should be considered. These factors comprise the clearance distance required for its swinging counterweights, extended boom and outrigger. Safety factors should also be considered, such as collision-free lift path and crane covering of pathways used by equipment and workers.

Forty-eight of the 129 papers address the crane layout problem, which demonstrates the importance of this problem. Thirty-five of them are related to tower cranes, while the others are related to mobile cranes, as shown in Fig. 10(a). The diversity of solution methodologies alludes to different approaches adopted by previous researchers. As for stand-alone methodologies, optimization is found to be the most frequent methodology, followed by artificial intelligence (AI), simulation and visualization methods, as shown in Fig. 10(a). However, positioning and tracking systems, such as radio-frequency identification (RFID), ultra-wideband (UWB), global positioning system (GPS), geographic information system (GIS), etc., have not been utilized to solve this problem. Hybrid methodologies, which is a combination of multiple methodologies, are the second most frequent solution methodology after optimization. This also demonstrates the complexity of this problem and the need for hybridizing multiple methods to handle its various aspects.

The research gaps of previous studies on the crane layout problem can be summarized in the following points:

1. The layout of an MiC site is dynamic based on the progress of its construction activities. Thus, crane layout decisions made at the preliminary stages may not be feasible for the later stages. Only a few studies have considered the dynamic site layout when solving the crane layout problem, such as [65].

2. The tendency to adopt fast-track building in MiC projects makes the use of multiple cranes inevitable. Only a handful of studies have tackled this challenge, e.g. [66] and [67].

3. The environmental and social impacts resulting from the decisions related to the crane layout problem are rarely considered in the literature. Few studies have assessed the ecological footprint and energy consumption of crane operations, such as [21] and [68]. However, other effects, like the impact of the location of supply points on traffic condition in congested urban areas, is scarcely studied.

4. Majority of the studies on crane layout problem assume that the velocities of hoisting, slewing and trolleying are constant. According to [69], this assumption ignores the fact that the velocity of each of these movements increases gradually from zero to its maximum value. And before reaching the crane destination, it decreases from the maximum to zero again. Such a small error can significantly impact the reliability of the suggested models because it accumulates for a repetitive process, such as crane operations.

Fig. 10

5.1.2 Lift path planning

The lift path planning problem can be defined as obtaining the shortest route between two points without colliding with obstacles located between them. This problem is well-established in robotics, and it has other names such as motion planning and pathfinding. The lift path planning for crane operations in MiC is paramount for many reasons. Firstly, as crane operations are repetitive, using longer paths due to improper planning of paths between supply and demand points can significantly prolong the duration of an MiC project. Hence, the privileges of using MiC are lost. Secondly, obtaining collision-free lift paths can protect the project from the consequences of fatal accidents. However, obtaining shortest and collision-free lift paths for crane operations is not an easy task in a congested and dynamic MiC site. For example, erected modules may become obstacles for the upcoming modules [70]. As a result, adaptive lift path planning needs excessive communication among construction team members with the aid of motion sensors and tracking of lifted modules, [71]; [72].

Fifty-six out of the 129 papers of COP have handled the lift path planning problem, which makes it the most frequent problem studied separately. Thirty-four of them are focused on mobile cranes, while the others are related to tower cranes, as shown in Fig. 10(b). These percentages show that the lift path planning for mobile cranes is more addressed than that of tower cranes. According to Fig. 10(b), hybrid methodologies are the most common solution approach, indicating the complexity of this problem. Positioning and tracking systems play a pivotal role in handling this problem. Also, visualization is often used to solve this problem compared to optimization and AI. Optimization in this problem includes motion planning algorithms such as the A* algorithm, the configuration space (C-space) and rapidly-exploring random trees (RRT). Finally, simulation is the least common methodology used in this problem. As shown in Tables I and II in the supplementary document, simulation is reported in only three papers in combination with other methodologies.

Despite the contribution of the previous studies on the lift path planning of crane operations, there is still room for further improvement. Solving the lift path planning problem for multiple cranes working in overlapped work zones is more complicated than using a single crane. A few studies have addressed the lift path planning in case of multiple cranes, such as [73] and [74].

5.1.3 Scheduling of crane tasks

This problem can be defined as the assignment of MiC modules to a specific pick or supply area. A particular crane is allocated to transport these modules to their destinations. Also, for each crane, the order of which its assigned modules are lifted has to be defined. Usually, the crane operator makes these decisions based on his experience or some rules of thumb. These include

First Come First Served (FCFS), in which the crane operator performs the lifting tasks in the order of receipt. However, such heuristics often lead to sub-optimal solutions. Therefore, the researchers address this problem with the objective of reducing the total transportation time and balancing the workload among cranes. Other objectives include reducing crane idleness and waiting time incurred by crews who are waiting for modules in the demand areas. The obtained solutions have to satisfy some requirements. These include the maximum capacity of each supply area, precedence relationships between modules and due date to transfer each module. In addition, the obtained solutions should be checked against potential collisions.

Only seven of the 129 papers handle this type of problem, with a focus on tower cranes. One article, however, reports on mobile cranes, as shown in Fig. 10(c). Again, visualization is applied to solve this problem more than optimization. In this problem, visualization is used to validate the sequences of crane tasks to avoid collisions. On the other hand, optimization is used to find the optimum or near-optimum sequences of crane tasks. For example, [24] integrate simulation with optimization to solve this problem with considering the tower crane productivity. The few numbers of studies on crane tasks scheduling, in comparison with the other problems, make this problem a potential point for future research. There is also the possibility to add to knowledge in this area by using different methodologies.

Some research gaps related to this research point are summarized as follows:

1. Real-life crane operations in MiC are exposed to a wide variety of different uncertainties that may invalidate the lifting schedules, even the optimized ones. To the best of the authors' knowledge, no study has suggested a near real-time rescheduling approach to mitigate the impact of uncertainties or disturbances. Examples of disturbances that can negatively impact on the performance of crane operations in MiC include arrival delay of modules and intermittent requests of lifting tasks in the construction site.

2. Scheduling of crane tasks for multiple cranes is more challenging than that of a single crane, as the problem becomes more complicated than that of a single crane. Only [24] have addressed this problem in the case of multiple cranes.

3. A common limitation among the previous studies on this topic is that the obtained schedules of lifted materials are isolated from the project schedule.

5.1.4 Crane stability

Stability of cranes is one of the most critical safety concerns in COP of MiC. The decisions related to the crane stability problem include the design of the supporting system of mobile cranes, design of foundation of tower cranes and design of lateral support system of tower cranes [27]; [75]. Many factors have to be considered in these decisions, which include the load of MiC modules, the jib length of tower cranes, and the boom length of mobile cranes. Others are the self-standing height of tower crane, ground bearing capacity of crane location and loading capacity of lifting cables and hooks. According to [28], these decisions are made based on either the experience of crane vendors or not considered at all. Each of these may lead to economically infeasible designs or fatal accidents, respectively.

Only nine papers in the COP literature address the crane stability problem. Five of them are related to mobile cranes, while the others are related to tower cranes, as shown in Fig. 10(d). Structural analysis methodologies, such as finite element models, are the most common methodology, as shown in Fig. 10(d). Some researchers use this approach to study the structural behaviour of crane components, such as its joints under different loading conditions [76]. Also, optimization is applied to find the optimum or near-optimum design of crane supports in terms of economic feasibility and structural stability [28].

Some research gaps related to the crane stability are highlighted in the following paragraphs:

1. There is an apparent relationship between the crane layout problem and the crane stability problem. This is because the decisions related to the crane stability are dependent on the crane layout decisions. For example, the crane location affects the design of crane supporting systems

and design of crane foundation. Few studies consider this relationship, for instance, [27] and [77]. Also, inspection of the crane stability in real-time has not been examined in the studied literature. In addition, providing the crane operator with proactive actions to stabilize the crane in the face of disturbances, like wind, overload, eccentricity of the lifted module, and collisions has not been considered in the previous studies.

2. Majority of cranes are manually operated nowadays. Therefore, designing effective control systems to eliminate swinging of MiC modules during lifting operation is vital. This ensures that the required levels of safety and productivity, especially for high-rise buildings, are achieved. Refs. [78] and [79] design and demonstrate an anti-sway controller to suppress payload swings in harsh and dynamic environments, e.g. offshore. The authors consider the unavailability of velocity signal feedback and actuator constraints in their design. Such innovative control systems can be adapted to enhance the safety of MiC lifting operations.

5.1.5 Integrated problems

Studies, which address more than one of the previously mentioned problems simultaneously, are put in the category of integrated problems. The researchers in the COP field realize the inevitability of solving multiple COP problems simultaneously to provide holistic solutions for real-life crane operations in MiC. For example, [9] and [36] provide mobile crane operators in MiC projects with an assessment tool. This tool can evaluate the feasibility of predefined lift paths and other related crane layout decisions, such as pick area location and crane type. For tower cranes, [80] develop a binary mixed-integer linear programming (MILP) model. The MILP model finds the optimum crane location and the optimum sequence of crane tasks to minimize material transportation time.

Nine papers out of the 129 articles address multiple COP problems. Majority are related to mobile cranes, as shown in Fig. 10(e). More than half of these studies adopt hybrid methodologies to solve such integrated problems. Optimization and visualization solution methodologies come in the second and third positions, respectively. Other methodologies, such as artificial intelligence and positioning and tracking systems, have not been used to solve this kind of problems in MiC.

Based on the previous analysis, some research gaps can be identified. Addressing multiple COP problems simultaneously, especially with tower cranes in MiC, is hardly reported. As illustrated before in section 5.1.4, the problems of determination of crane location and the crane stability are interrelated. Also, integration of the lift path planning problem, the scheduling of crane tasks problem and determination of locations of supply areas are necessary to provide a comprehensive COP in MiC. Despite the importance of addressing these types of integrated problems, only a handful of studies have studied them. Hence, they can be candidates for future research.

5.2 Classification Based on Applied Methodologies

Six types of methodologies have been applied to solve the five problems mentioned above in the 129 papers on COP. These methodologies are optimization, visualization, simulation, positioning and tracking systems, artificial intelligence and hybrid methodologies. Structural analysis is applied to solve one type of COP problems (crane stability problem), therefore, it is not included in this section. A summary of each solution methodology, statistics on its implementation, and research gaps related to each methodology is provided here.

5.2.1 Optimization

Optimization algorithms are used to find the optimum or near optimum solutions to a single-objective or multi-objective optimization problems without violating the defined constraints. The crane layout, the scheduling of crane tasks and the lift path planning problems are classified as Non-deterministic Polynomial-time (NP) hard problems. This classification is according to [6], [23] and [7], respectively. These problems are solved by using either exact or approximate optimization approaches. The main difference between these two approaches is that the exact approaches (e.g. Branch & Bound and dynamic programming) do find the global optimum solutions. However, there is no guarantee of a global solution when using the approximate approaches, such as heuristics and metaheuristics.

Thirty-three of the 129 papers of COP use optimization to achieve their research objectives. In addition, optimization is combined with other methodologies to solve COP problems. This will be illustrated in section 5.2.6. This demonstrates the contribution of optimization approaches to the COP research field in MiC. As shown in Fig. 11(a), solution to all types of COP problems is obtained by optimization, albeit with different percentages. The crane layout problem is addressed by the majority of the 33 papers on optimization. The same number of papers use optimization to solve the lift path planning and the integrated problems, ranking them in the second position after the crane layout problem. Similarly, scheduling of crane tasks and crane stability problems are solved by optimization. In addition to that, the 33 papers, which adopt optimization, are further classified into five categories. The first three categories represent the papers which use exact approaches, namely Branch & Bound, Branch & Cut and dynamic programming. The last two categories contain the papers which apply approximate approaches, such as heuristics and metaheuristics. It is worth mentioning that motion planning algorithms such as A* and Rapidly-exploring Random Tree (RRT) algorithms are considered as heuristics. However, metaheuristics include algorithms like Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), etc. As shown in Fig. 11(a), the majority of authors of the 33 papers have preference for approximate approaches over exact ones. This can be attributable to the fact that the approximate approaches can find good-quality solutions in a relatively short time in comparison with the exact methods. Interestingly, all exact approaches are used to solve the COP problems related to tower cranes only. On the contrary, all optimization problems related to mobile cranes are solved by using heuristics, except one paper which uses GA [59]. GA is the most frequent used metaheuristics in COP research area, followed by PSO. With the exception of two papers on SA, all the metaheuristics used to solve the COP problems are population-based metaheuristics, such as GA and PSO. In this type of meta-heuristics, the search process is started with a set of randomly generated solutions, and these solutions are improved during subsequent search processes.

Based on the previous analysis, some research gaps can be identified as:

1. Dynamic programming has been used only once to solve the crane layout problem of tower cranes [31]. However, this approach has been successfully used to find the global optimum solution of problems similar to COP problems in MiC. These include the flow shop sequencing problems with due dates [81] and the motion planning problems [82]. Hence, dynamic programming may be applied to solve the scheduling of crane tasks and the lift path planning problems in MiC.

2. Despite that GA and PSO are used by the majority of researches to solve the COP problems, these metaheuristics are condemned for having many parameters to be tuned and for taking too long to evaluate a population of solutions [83]. Therefore, testing other metaheuristics, especially single solution-based metaheuristics, such as simulated annealing, tabu search and variable neighbourhood search, can shorten the computation time.

3. Hybridizing multiple metaheuristics or hybridizing metaheuristics with local search methods like Hooke–Jeeves method and Nelder-Mead simplex method can help to improve the performance of metaheuristics. Only [33] have used hybrid metaheuristics to solve COP problems. Hence, developing hybrid metaheuristics dedicated to solving COP problems in MiC is a candidate future research point.

4. As many COP problems in MiC need solutions within a short computational time, using High-Performance Computing (HPC) and parallel metaheuristics are justified for future research.

Fig. 11

5.2.2 Visualization

Visualization techniques, such as 3D modeling, 4D modeling, virtual prototyping, virtual reality and augmented reality play an indispensable role for solving many of COP problems in MiC. These techniques have been applied to detect potential spatial risks to avoid collisions and thus, increase safety at job sites. Also, these techniques can significantly improve communication among participants of crane operations and facilitate the comprehension of lift plans.

Visualization is reported as a primary methodology in 19 of the 129 COP studies. As shown in Fig. 11(b), visualization has been exploited to solve a variety of COP problems in MiC except the crane stability problem. The lift path planning problem is the commonest COP problem addressed by visualization techniques. This is followed by the problems of crane layout and scheduling of crane tasks. Regarding the usage of visualization techniques, 3D models are the most common visualization technique used in 63% of the 19 papers, followed by 4D models (26%) and virtual prototyping (11%).

Based on the previous statistics, it can be noted that new visualization techniques, such as virtual prototyping, virtual reality and augmented reality, are rarely adopted to solve COP problems in MiC. Such new technologies can contribute to this research field by providing crane operators with a risk-free training tool that is very close to a real working environment. This improves their awareness of their surroundings, increases their productivity and minimizes/eliminates collisions.

5.2.3 Simulation

Simulation modeling is used to represent a system whose states are changed based on some rules and interactions between its parameters. Researchers resort to simulation modeling when simulation of the system through analytical methods is very complex or even impossible [18]. Therefore, previous researchers have utilized this technique to solve some of the COP problems in MiC. Simulation modeling techniques are Discrete-Event Simulation (DES), System Dynamics (SD) and Agent-Based Simulation (ABS). Besides these techniques, Monte Carlo simulation is considered as a simulation technique in this study. Each simulation technique has its scope, merits and limitations.

Only five of the 129 papers on COP adopt simulation modeling as the main methodology to solve crane layout problem of tower cranes and scheduling of crane tasks. However, simulation is integrated with other methodologies to solve other COP problems, as will be illustrated in section 5.2.6. As shown in Fig. 11.c, DES is the most frequent simulation modeling technique used in COP research, followed by Monte Carlo and SD, which have similar usage statistic. It is worth noting that ABS is used only once with optimization, as a hybrid methodology to solve the crane layout problem. The authors consider the impact of conflicts among multiple tower cranes on total time and cost [35]. Further analysis reveals that more papers hybridize simulation modeling with other methodologies than papers using simulation as their sole methodology. Therefore, it can be concluded that researchers used simulation as an evaluation tool, and hence they often integrated it with other methodologies. However, hybridization of multiple simulation techniques, as long as each one is used properly, can leverage the ability of simulation modeling. For example, DES can consider the stochastic waiting time of lifting modules in supply areas, while SD can handle some uncertainties in MiC sites such as weather impact and fatigue of the crane operator. Also, ABS can be used to represent behaviour interactions among participants in crane lift operations in MiC sites.

5.2.4 Positioning and tracking systems

Positioning and tracking systems, such as RFID, GPS, laser scanning, sensors, photogrammetry technologies, etc., are used in COP research. These systems help to improve the safety of crane operations in MiC, especially for blind lifting. Seventeen of the 129 papers on COP adopt these technologies to improve the safety of proposed lift path plans by motion tracking of lifted modules and crane body components. In these papers, the researchers use both individual and a combination of laser scanning and other positioning and tracking systems, as shown in Fig. 11(d). However, the performance of laser scanning is affected by dust, weather conditions, vibration and congestion in MiC sites, according to [71]. Based upon that, some research gaps related to the application of positioning and tracking systems to solve the COP problems in MiC can be outlined. Firstly, it can be noted that using positioning and tracking systems is only limited to addressing the lift path panning problem. However, such technologies can be used to solve other COP problems, for instance, the crane layout and the crane stability problems. For these problems, sensors can be used to detect unstable events in crane operations, such as eccentricity of MiC modules, crane tip-over and fatigue in crane boom or crane jib. Secondly, new technologies of positioning and tracking systems need to be tested and compared with the traditional positioning and tracking systems to solve COP problems in MiC. Examples of such new technologies include RFID, Unmanned Aerial Vehicle (UAV)-based Light Detection and Ranging (LiDAR) and UAV (such as drones)-based cameras. It is worth mentioning that [84] propose a UAV-based 3D model to help in hoist planning and site layout planning.

5.2.5 Artificial intelligence

Artificial intelligence techniques, such as Artificial Neural Network (ANN), expert systems and fuzzy logic systems, have been used to tackle some of the COP problems in MiC. This is ascribed to the capability of these techniques to process subjective information in a consistent manner. They have been utilized to help in decision making of crane selection in the crane layout problem and increasing safety in the lift path planning problem. Despite that, artificial intelligence is applied only in six papers out of the 129 papers on COP. As shown in Fig. 11.e, ANN, expert systems and fuzzy logic have similar usage statistics in the literature. Safety and productivity may be improved in MiC projects by operating cranes autonomously. Hence, [85] argue that reinforcement learning, as an artificial intelligence technique, will play an important role to achieve this aim.

5.2.6 Hybrid methodologies

The hybrid methodologies refer to a combination of the methodologies mentioned above. The rationale behind the hybridization of multiple methodologies is that each methodology has its limitations which can be overcome by integrating it with other methodologies. Therefore, 43 out of the 129 papers of COP take advantage of hybrid methodologies. This suggests that previous researches are more inclined to using multiple methodologies in the COP field. Fig. 11.(f) shows that all COP problems are addressed by using hybrid methodologies. The lift path planning is the most common COP problem solved with hybrid methodologies. Next in line are the crane layout problem and the integrated problems, in that order. However, the problems of crane stability and scheduling of crane tasks are the least frequent problems solved by the hybrid methodologies.

Optimization and visualization (O & V) is the most frequent combination of methodologies (45%) used in COP field. Thereafter, a combination of visualization and positioning and tracking systems (V & PTS) and optimization and simulation (O & S) account for 14% and 10%, respectively, in the papers. Moreover, some researchers combine three methodologies, such as optimization, visualization and simulation (O & V & S) and optimization, visualization and positioning and tracking systems (O & V & PTS), to capture the complexity of the COP problems. Interestingly, some methodologies such as simulation and visualization are used more in combination with other methodologies than using them individually to solve the COP problems.

Based on the previous analysis, some future research points related to using hybrid methodologies to solve the COP problems in MiC are summarized as follows:

1. Addressing emergent COP problems in MiC, such as autonomous lift path planning, needs a combination of new methodologies. Candidate methodologies include agent-based simulation, deep reinforcement learning and positioning and tracking systems, which can cope with the dynamic environment of MiC sites.

2. Using augmented reality with optimization methods can be used to support real-time decision making in some problems (e.g. scheduling of crane tasks) especially in case of disturbances occurring at the MiC site.

3. Despite the computational power of modern computers, integrating multiple methodologies may be computationally expensive. Thus, it is expected that researchers will resort to HPC and cloud computing to overcome this issue.

To conclude and summarize the previous discussion, Fig. 12 shows a two-dimensional classification matrix of the 129 papers on COP. The matrix rows represent the COP problems, while its columns represent the methodologies used to solve these problems. Each cell of this matrix represents the number of papers which address a specific problem solved by a particular methodology. To better visualize the matrix, a colour map is used. In this colour map, the high values are assigned green colour; low values the yellow colour, and zero value is marked in red colour. This can give an overview of the mainstream research on COP, and hence guide researchers towards COP problems in MiC that need further studies. These problems are crane stability, scheduling of crane tasks and the integrated problems. Also, Fig. 12 indicates that some methodologies (e.g. simulation and artificial intelligence) have not received adequate research attention for solving COP problems in MiC.

In addition to that, Fig. 12 provides a graph of the research trend for each COP problem and the applied methodologies. The vertical axis of the graph represents the number of published papers, while the horizontal axis represents the publication year. Each graph is accompanied by a third-degree polynomial trend line which manifests the accumulation of knowledge and development of each COP problem and the applied methodologies.

Fig. 12

The slope of research trends in lift path planning problem and scheduling of crane tasks problem have flattened over the last years. However, the slope of the crane stability problem is increasing at a constant rate. Further research attention may be turned to crane layout problem and integrated problems as indicated by the fast-growing number of papers on these problems. For solution methodologies, simulation and artificial intelligence decline in usage during the last years. Lately, the adoption of the positioning and tracking systems and visualization has slightly reduced. Nonetheless, optimization and hybrid methodologies have been frequently utilized. Therefore, it is anticipated that future researchers will keep on integrating multiple methodologies with optimization to address COP problems in MiC.

6. FUTURE RESEARCH OPPORTUNITIES IN COP OF MIC

Based on the research gaps identified by conducting the systematic and scientometric reviews of COP in the previous sections, some research directions can be derived for future research consideration. Fig. 13 shows four main research opportunities for COP in MiC derived from research gaps in this field, which are summarized in the following points:

Fig. 13

1. Since MiC sites are dynamic in nature where site facilities and site space are changing during the project duration, the crane layout decisions made at earlier construction stages may be infeasible in later construction stages. The dynamic nature of MiC sites can also impact motion planning of lifted objects, especially in congested construction sites, where multiple overlapped cranes represent dynamic obstacles to each other. Usually, planners tend to underestimate this problem due to its complexity. Despite that, few studies have considered the dynamic site layout when solving the crane layout and the lift path planning problems, especially for tower cranes. Therefore, there is a need for automated models, which can assist planners in making decisions related to these problems to increase the productivity and safety aspects in MiC sites. Dynamic programming, virtual reality and ABS may be used to tackle this issue.

2. With the eagerness to accelerate construction schedules through the adoption of MiC, using multiple cranes in MiC sites becomes prevalent [86]. This adds to the complexity of some COP problems in MiC, such as the crane layout, the lift path planning and the scheduling of crane tasks problems. Nevertheless, few studies have addressed these problems in multi-crane MiC sites. COP of tower cranes in high-rise MiC projects is rarely tackled in the literature as well. Hence, future studies can address these problems with the aid of integrated methodologies, such as hybrid metaheuristics, ABS, virtual reality and high-performance computing.

3. Crane operations in MiC are exposed to a wide variety of risks that are hard to control, such as weather conditions, crane failures, human errors, scope change, rework, etc. Nonetheless, the vast majority of the previous studies on COP field provide static solutions to these problems while ignoring the dynamic disturbances of COP in MiC. Consequently, it is recommended that systematic risk management procedure is needed to evaluate the impact of different risks on key performance measures, e.g. productivity and safety of COP in MiC. Also, this procedure is required to assess the efficiency of precautions taken to mitigate the impact of risks. The last objective of this procedure is to optimize the response actions, including rescheduling of crane tasks (scheduling of crane task) or rerouting of lifted modules (lift path planning problem). Also,

providing the crane operator with real-time inspection of crane stability may enable him/her to take appropriate proactive actions to avoid accidents. This is considered an integral part of the optimization of response actions. Methodologies, such as fuzzy logic systems, simulation modeling, sensors, augmented reality and parallel metaheuristics, are beneficial for this purpose.

4. With the tendency to revolutionize the construction industry with robots to improve its productivity and safety, dreams of autonomous cranes become a reality. These cranes will be armed with accurate positioning and tracking systems, such as camera or LiDAR sensors to mind its surroundings. Also, these cranes will have the capability to learn from experience like humans by using speech recognition and deep reinforcement learning. Furthermore, these cranes are supposed to communicate with other entities in MiC sites through the Internet of Things (IoT). For instance, a delivery truck may communicate with a crane for unloading modules or a different crew may ask for crane support. Moreover, these cranes are expected to have the ability to lift modules in harsh visual conditions, such as fog, night operations or blind lifts with the ability to avoid collisions. The automated crane layout planning, which considers the sustainability aspects like environmental factors (greenhouse gas emissions) and social factors (noise) will complete the whole picture. Simulation modeling and virtual prototyping will play an essential role in the development phase. However, information exchange and interoperability between the different methodologies and applications still require further study.

7. CONCLUDING REMARKS

This research provides insights into trends and developments of COP in MiC by analysing relevant COP research papers. Collectively, 129 relevant papers are analysed in this study by utilizing a mixed review method by integrating scientometric review and systematic review. This method provides a comprehensive review of the topic under study with minimal subjective judgment.

Analysis of the annual publication trend shows that research on COP in MiC has received considerable attention from the research community with an increasing trend over the last two decades. The results of the scientometric review indicate that: 1) *Automation in Construction*, *Journal of Construction Engineering and Management, Journal of Computing in Civil Engineering, Construction Management and Economics and Computer-aided Civil and Infrastructure Engineering* are the top five journals in terms of the number of articles, number of citations and total link strength in COP research; 2) based on the number of studies and number of citations, the United States, Canada and China have made significant contributions to COP research in MiC. However, the collaboration network between countries contributing to COP research reveals a lack of cross country comparative studies between Canada and the other countries; 3) the network analysis of institutions which invested more in COP research shows that the University of Alberta is the most influential institution contributed to COP research. The superiority of the University of Alberta is backed by the wide gap between its research output and those of the second (Gyeongsang National University) and third institutions (Georgia Institute of Technology). Also, the collaboration between the University of Alberta and two companies working on COP in MiC highlights the significance of collaboration with industry professionals; 4) the co-authorship analysis reveals that the three top researchers in COP research are Al-Hussein M., Varghese K. and Tam C.M., based on the number of citations. However, using the normalized citations metric, the three top researchers are Moselhi O., Taghaddos H. and Tantisevi K.. In addition, the collaboration network between the top researchers indicates that the most collaborative research couples are (Dienstknecht M. & Briskorn D.), (Kang S.-C. & Miranda E.) and (Li H. & Skitmore M.); 5) the article co-citation analysis suggests that 20 articles have been cited between 49 and 95 times over the last four decades. The top five of these articles include [58], [32], [59], [5] and [60]; and 6) analysis of the co-occurrence network of keywords reveals that “tower cranes” is repeated more than “mobile cranes”, highlighting that previous researchers have focused more on problems related to tower cranes. Also, “optimization” and “visualization” are the most frequent research methodologies repeated in keywords of the retrieved articles. Interestingly, the keywords network shows that “modular construction” is connected more to “mobile cranes” in comparison with “tower cranes” or “tall buildings”, indicating that there is a research gap in COP in high-rise modular buildings.

On the other hand, the systematic review analysis provides a more comprehensive view of existing COP research for classification purpose. Hence, research gaps are identified, and future research directions are proposed. The findings obtained from the systematic review analysis are as follows: 1) the number of articles on tower cranes is higher than that of mobile cranes. This finding corroborates the observation obtained from the keywords network in the scientometric analysis; 2) there are five types of problems addressed in COP research. These problems include crane layout, lift path planning, scheduling of crane tasks, crane stability and integration between these problems; 3) The lift path planning problem is the most frequent problem addressed in COP literature, followed by crane layout, integrated problems, crane stability and scheduling of crane tasks; 4) these problems have been solved by six types of methodologies, which are optimization, visualization, simulation, positioning and tracking systems, artificial intelligence and combinations of these methodologies; 5) the most frequent methodologies used to solve the different problem types are: optimization for crane layout problems, hybrid methodologies for the lift path planning problem, visualization for the scheduling of crane tasks, finite element models for the crane stability problems and hybrid methodologies for integrated crane problems; 6) overall, hybrid methodologies are the most frequent methodologies used to solve the COP problems in MiC, followed by optimization, visualisation, positioning and tracking systems, artificial intelligence, and simulation; 7) the most frequent solution techniques used in these methodologies are: approximate approaches (especially, GA) in optimization, 3D BIM in visualisation, sensors in positioning and tracking systems, ANN in artificial intelligence, DES in simulation and combinations of optimization and visualization approaches in hybrid methodologies; 8) Both crane layout problem and integrated problems are experienced a fast-growing research trend during the last years, indicating that they could gain further attention in future studies. Similarly, the fast-growing trends of using optimization and hybrid methodologies suggest that researchers will keep on using these methodologies to address COP problems in MiC.

Based on the identified research gaps for each COP problem and each applied methodology, four future research opportunities in COP in MiC are proposed. These represented abandoned, yet critical points in COP of MiC. Firstly, the dynamic site layout of MiC projects should be considered when solving the problems of crane layout and lift path planning. Virtual reality and ABS are good candidate solution methods to build automated models for this purpose. Secondly, with the tendency to use multiple cranes to expedite the construction of high-rise modular buildings, developing hybrid metaheuristics and using high performance computing are required to reduce the computation time when solving the problems of lift path planning and scheduling of crane tasks in real-time. Thirdly, a systematic risk management procedure is needed to identify and assess different risks that impact the safety and productivity of cranes. Then, a resilient risk response approach should be developed to find the optimum rerouting of lifted modules or rescheduling of crane tasks to mitigate risk events. Finally, future researchers can benefit from the new advancement of IoT, LiDAR sensors and deep reinforcement learning to develop and test autonomous crane systems.

Despite the contributions of this present research, some limitations are highlighted. Firstly, it is possible that the authors might miss some studies on COP despite using comprehensive search strategies to retrieve relevant studies to COP. Secondly, articles published in languages other than the English language were excluded. However, the results of this study can adequately reflect the trend in COP research related to MiC. Thirdly, the classification of papers based on COP problems and applied methodologies is mostly dependent on the subjective judgments of the authors.

The information presented in this paper is valuable to both industry practitioners and researchers who are interested in MiC. Industry practitioners are provided with an identification of different problems related to COP in MiC and how researchers have addressed these problems. This would foster more collaboration between practitioners and researchers to promote innovation. Researchers, in particular, may benefit from research directions to nourish the existing body of knowledge on COP in MiC.

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https://doi.org/10.1016/j.jclepro.2019.05.229.

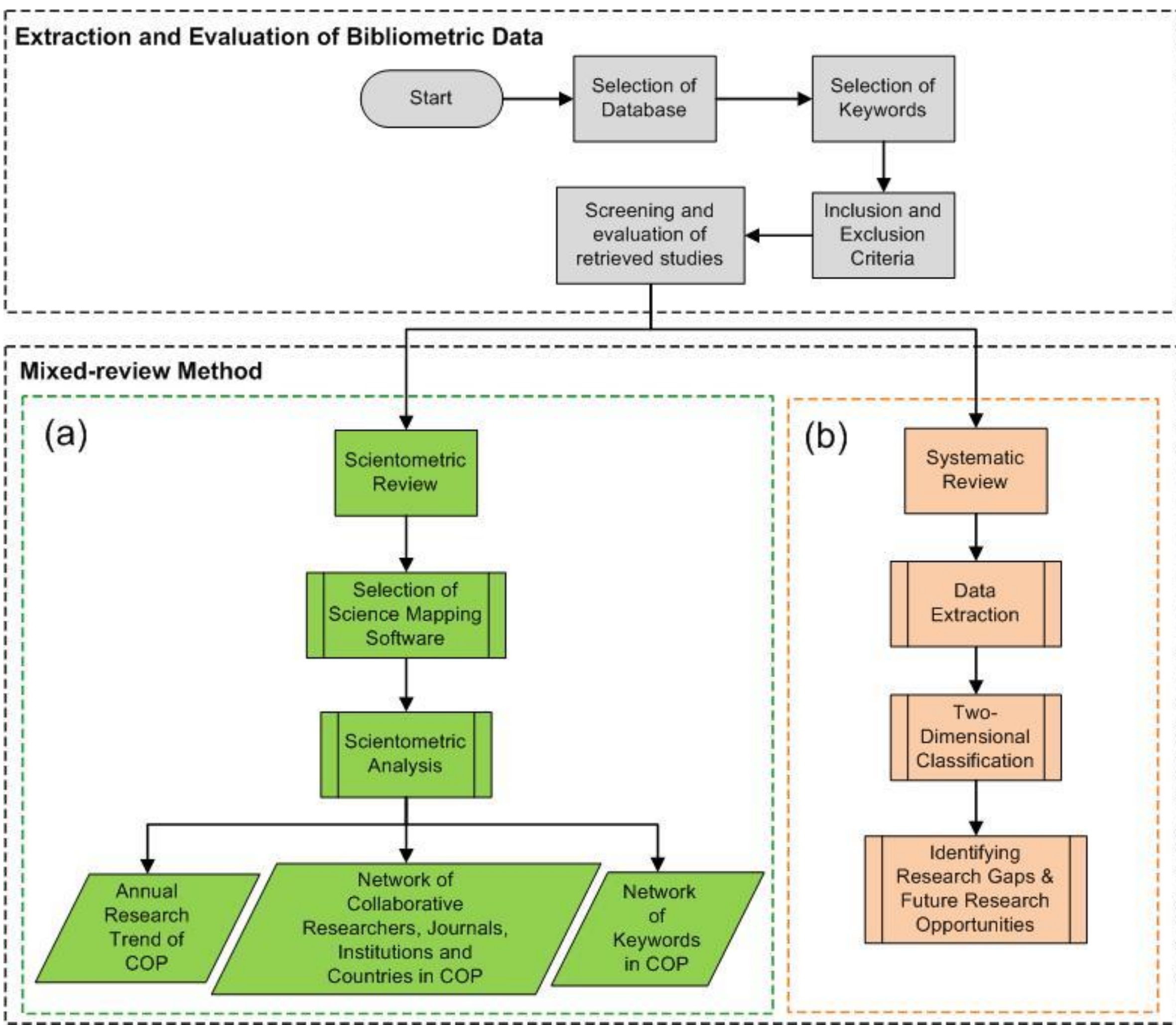


Fig. 1: General methodology for the literature review.

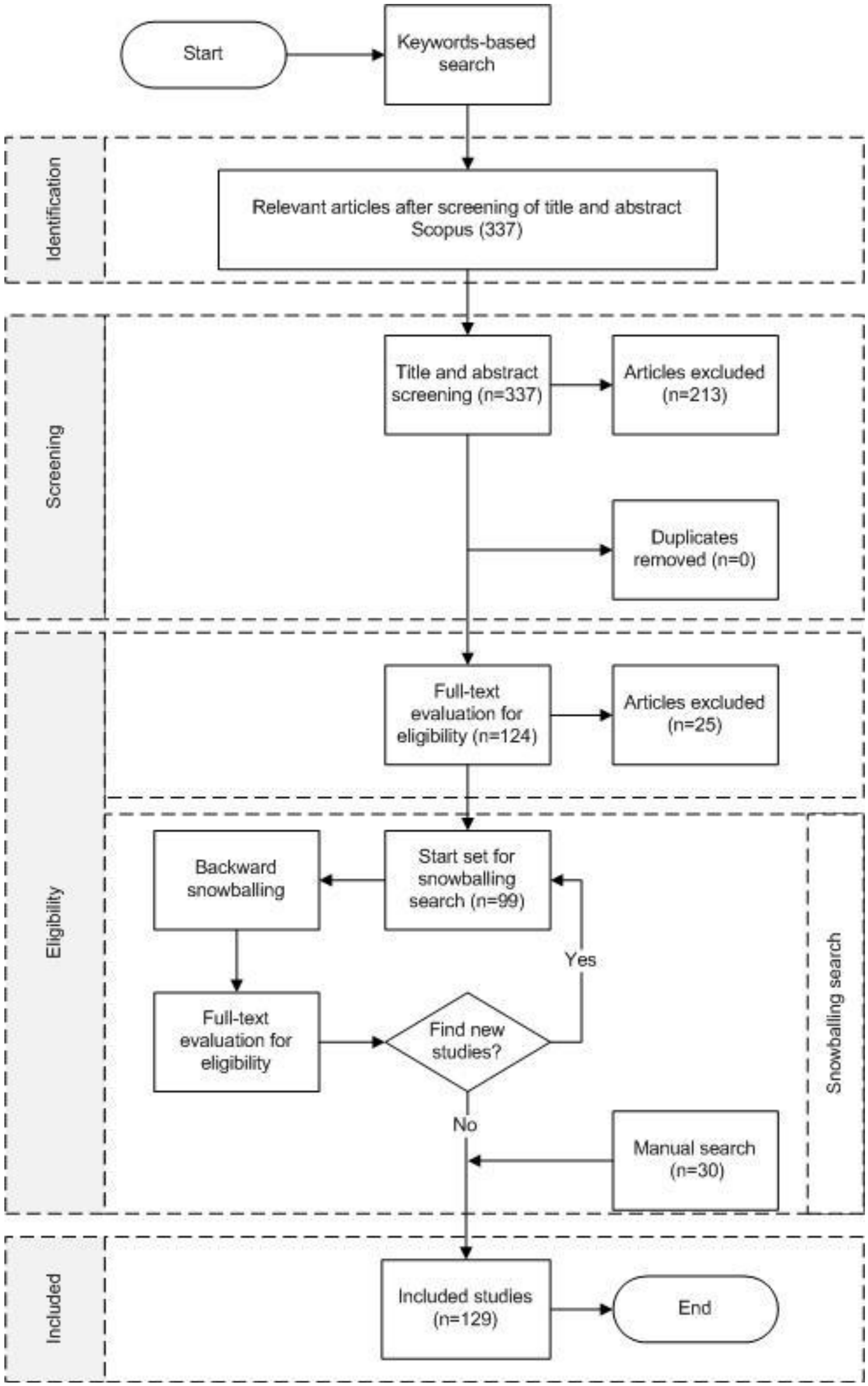


Fig. 2: PRISMA flow diagram of studies' screening and selection.

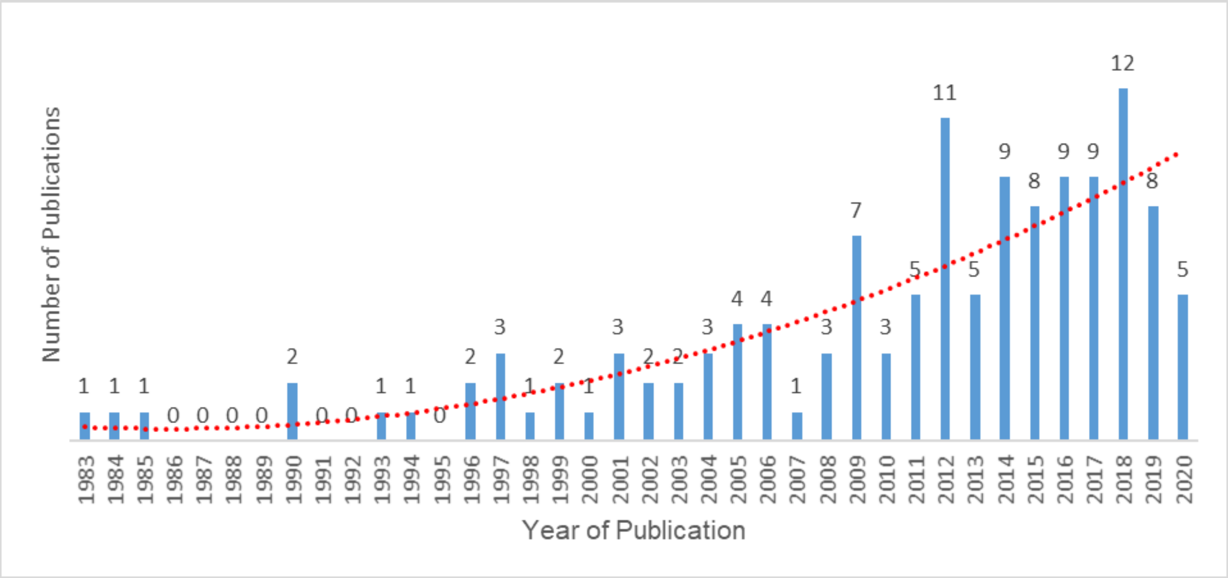


Fig. 3: Annual crane operation and planning (COP) research publication.

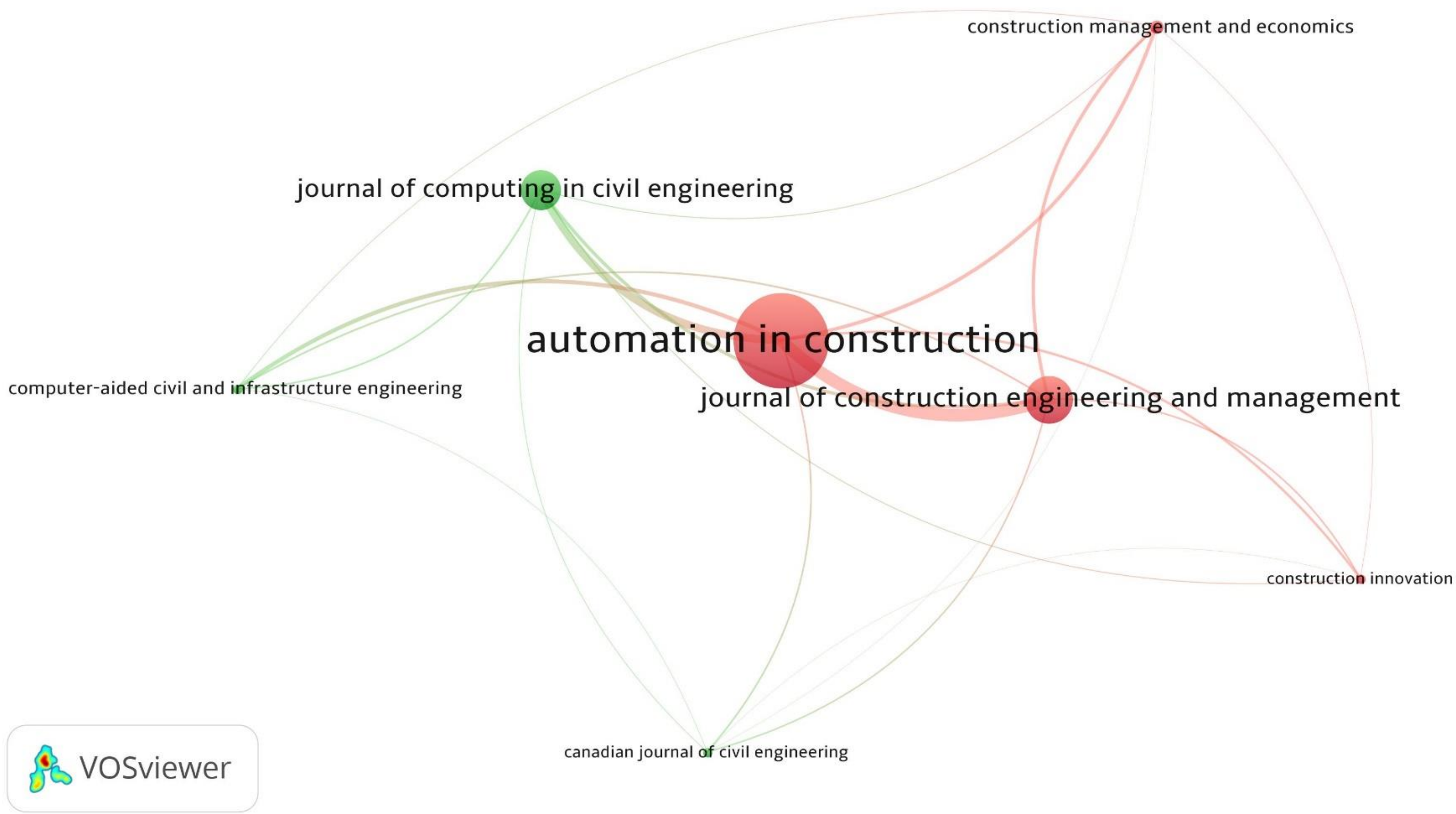


Fig. 4: Network of high impact journals on COP in MiC.

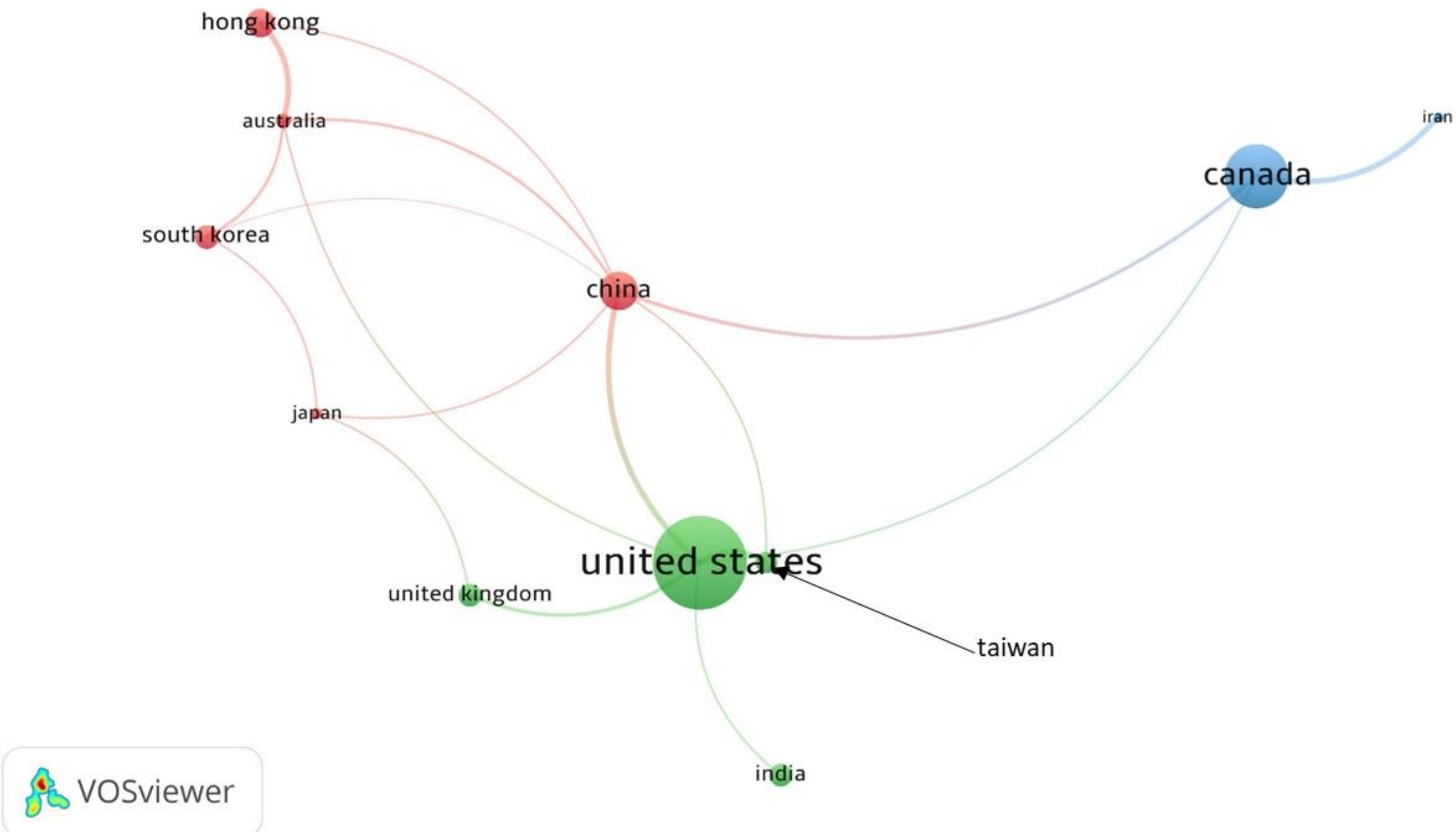


Fig. 5: Collaboration network of countries contributing to COP research.

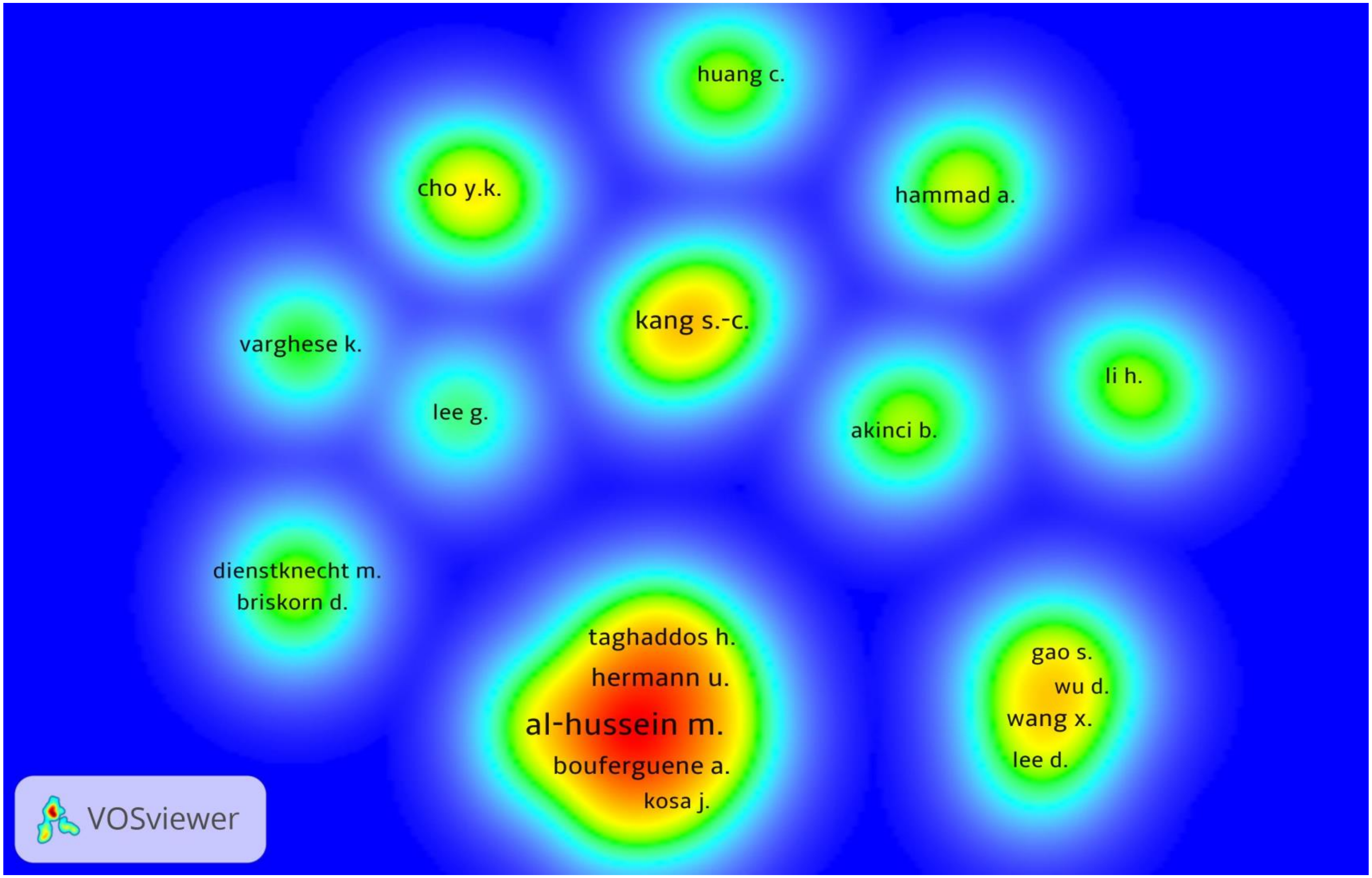


Fig. 6: Co-authorship citation density map of top researchers in COP research.

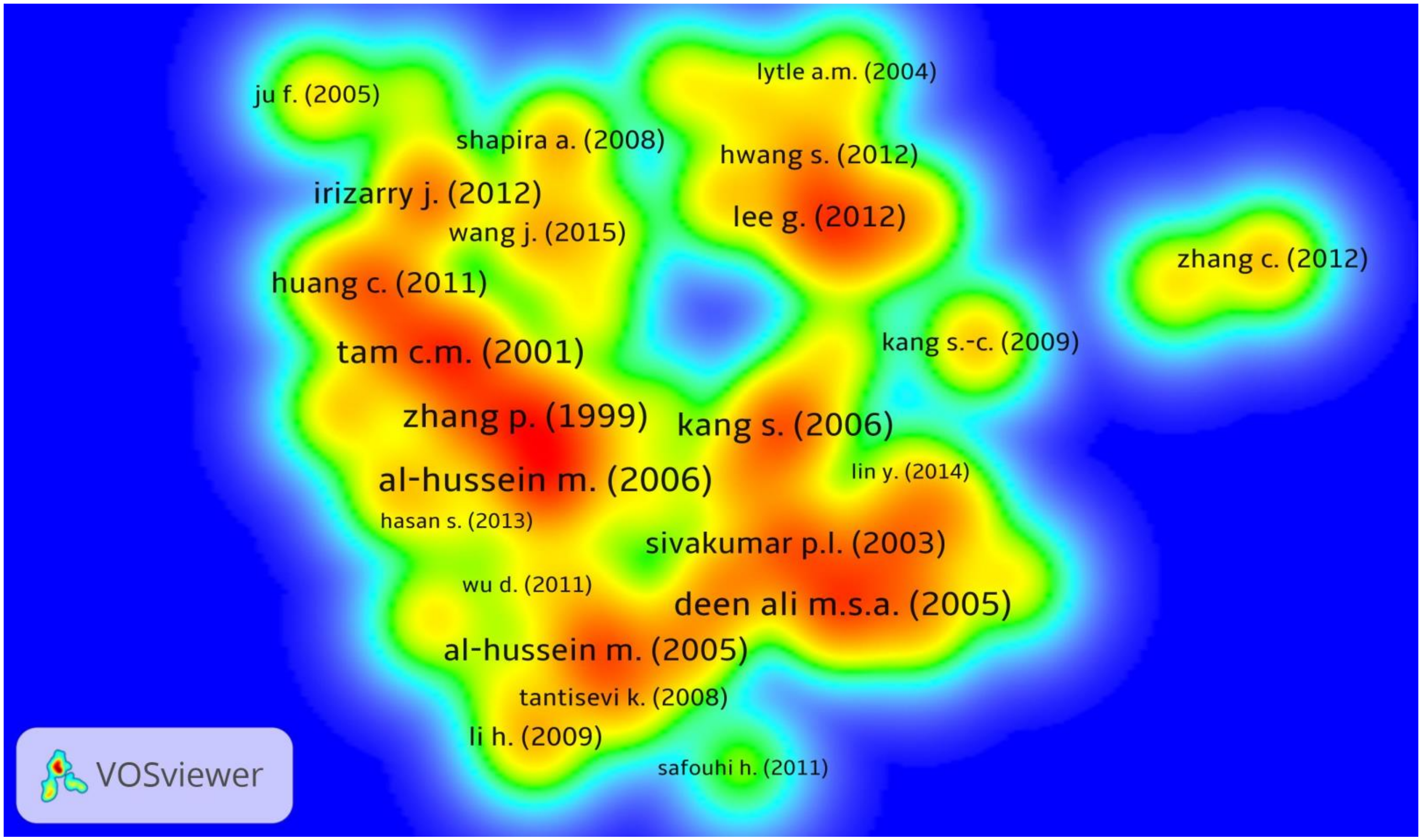


Fig. 7: Density map of documents citation network analysis.

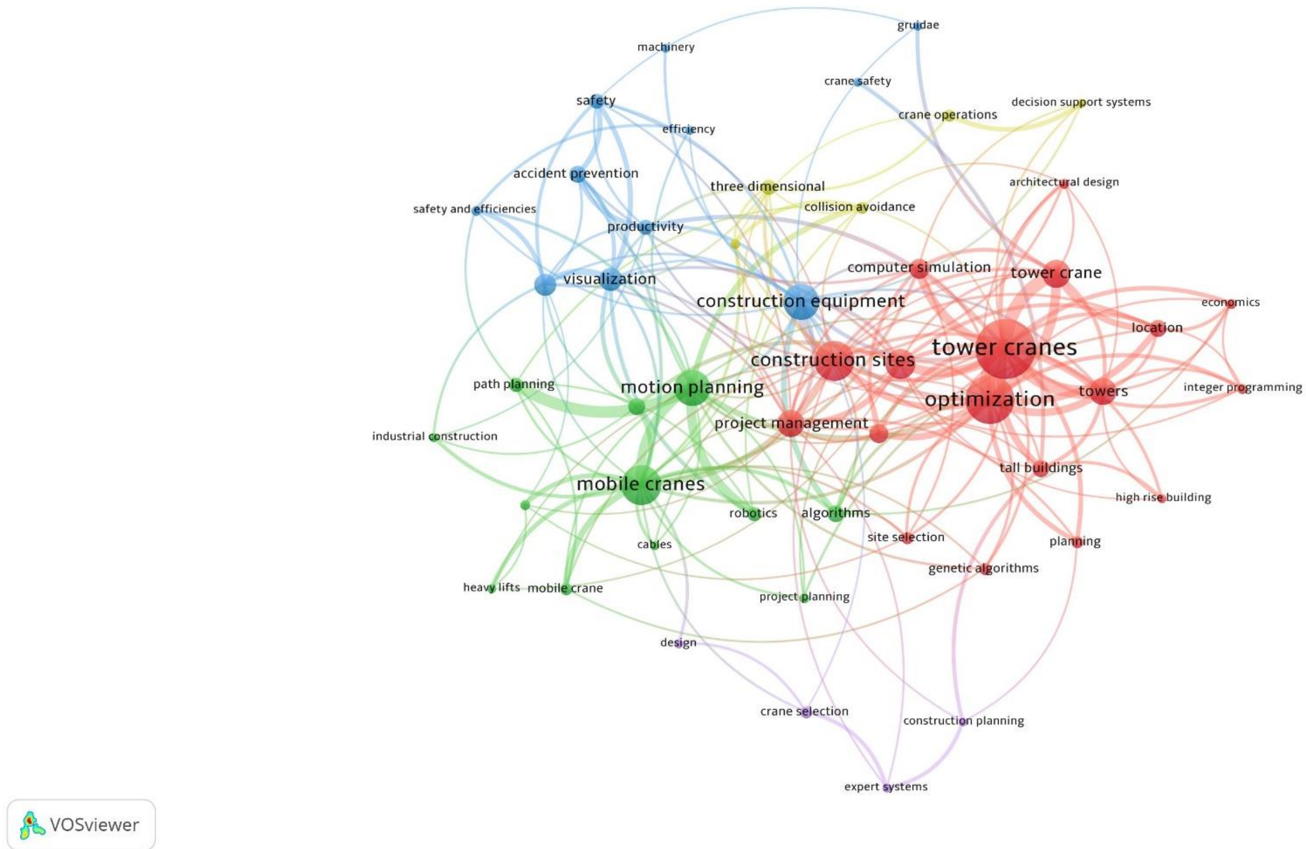
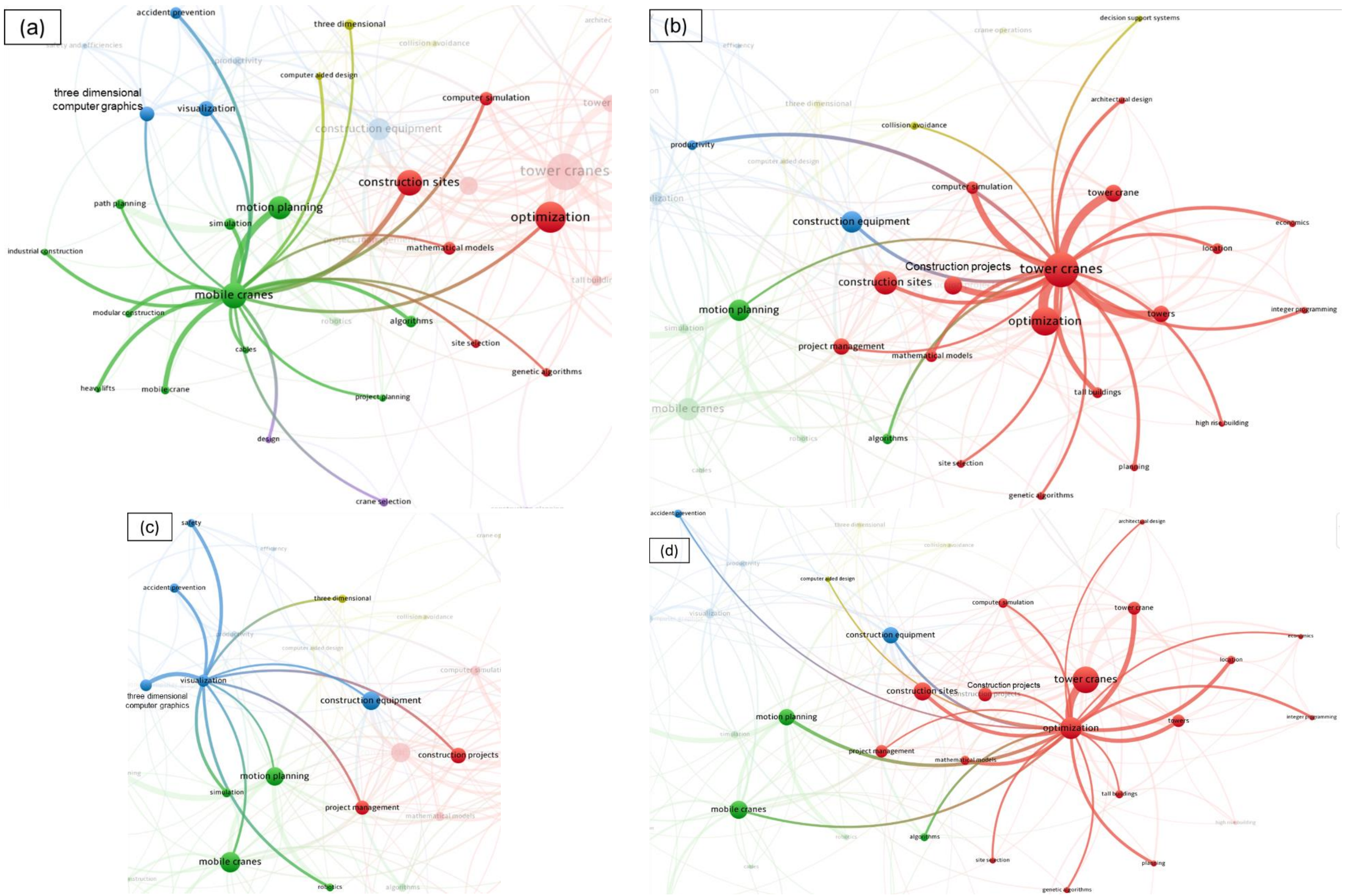
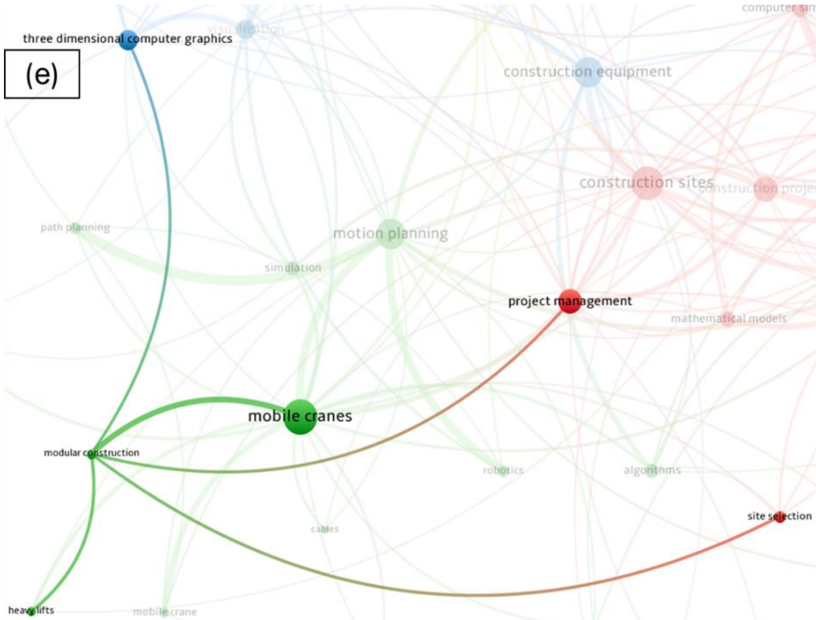


Fig. 8: Co-occurrence network of keywords in COP research.


(a)
accident prevention
three dimensional
three dimensional computer graphics
visualization
computer aided design
computer simulation
construction equipment
tower cranes
construction sites
motion planning
optimization
path planning
simulation
industrial construction
mathematical models
mobile cranes
modular construction
algorithms
site selection
cables
genetic algorithms
heavy lifts
mobile crane
project planning
design
crane selection
(b)
decision support systems
architectural design
collision avoidance
productivity
computer simulation
tower crane
economics
construction equipment
location
Construction projects
tower cranes
construction sites
motion planning
optimization
towers
integer programming
project management
mathematical models
tall buildings
high rise building
algorithms
site selection
planning
genetic algorithms
(c)
safety
accident prevention
three dimensional
visualization
three dimensional computer graphics
construction equipment
construction projects
motion planning
simulation
project management
mobile cranes
robotics
(d)
accident prevention
architectural design
computer aided design
computer simulation
tower crane
construction equipment
location
Construction projects
tower cranes
construction sites
motion planning
optimization
towers
integer programming
project management
mathematical models
tall buildings
mobile cranes
algorithms
site selection
planning
genetic algorithms



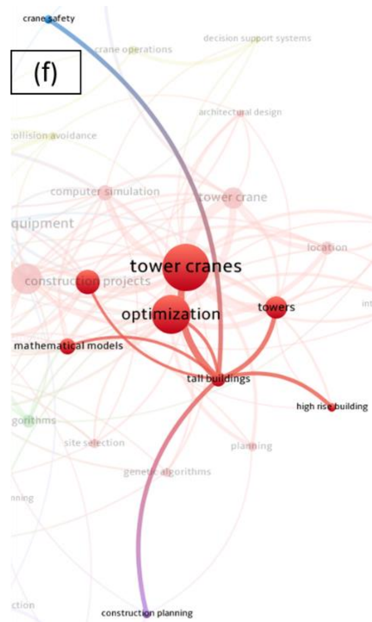
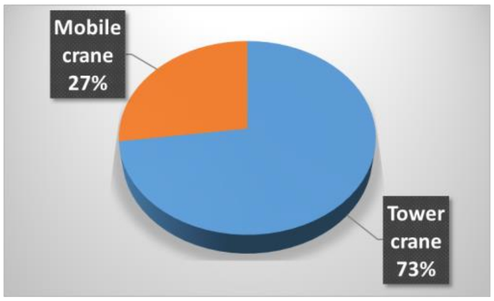
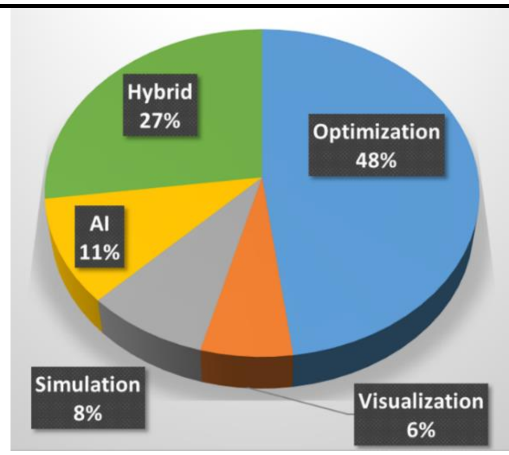


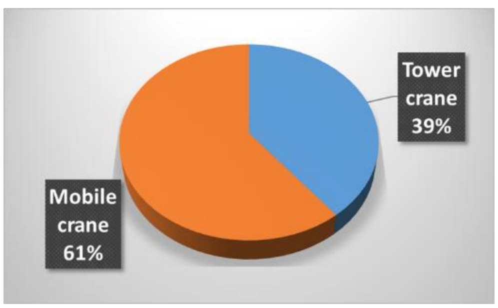
Fig. 9: The keyword networks of: (a) mobile cranes; (b) tower cranes; (c) visualization; (d) optimization; (e) modular construction; (f) tall buildings.

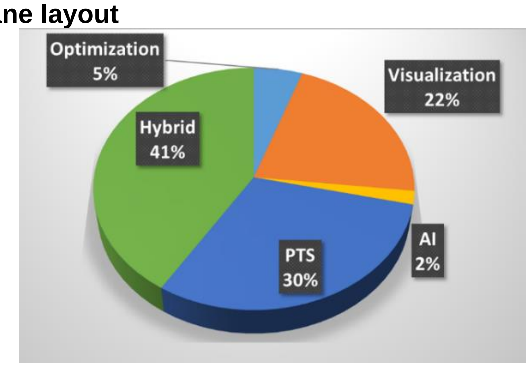
Percentage of papers related to the tower and mobile cranes for each problem type	Percentage of papers solved by different research methods for each problem type



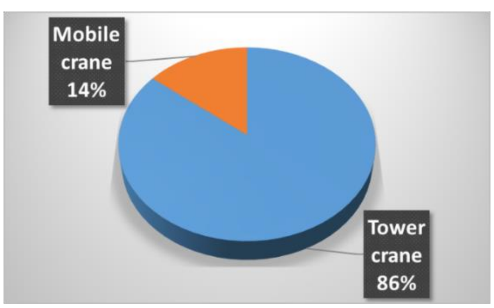


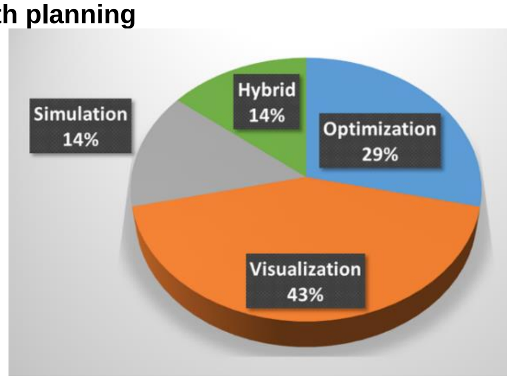
(a) Crane layout



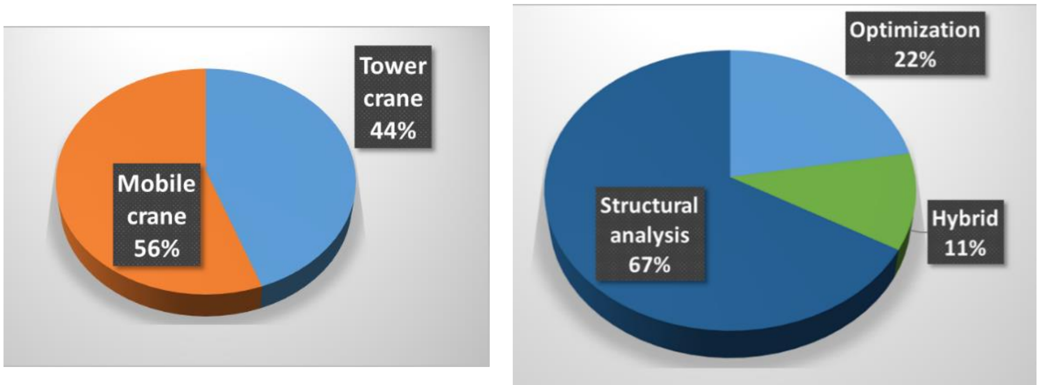


(b) lift path planning

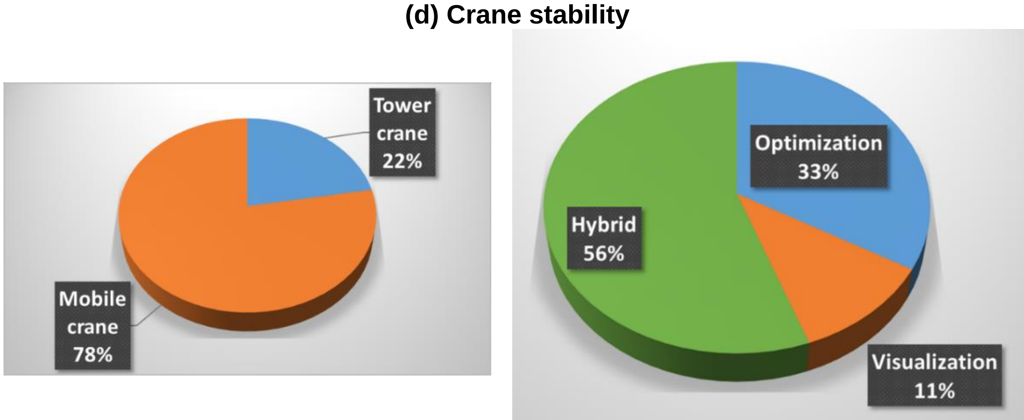




(c) Scheduling of crane tasks



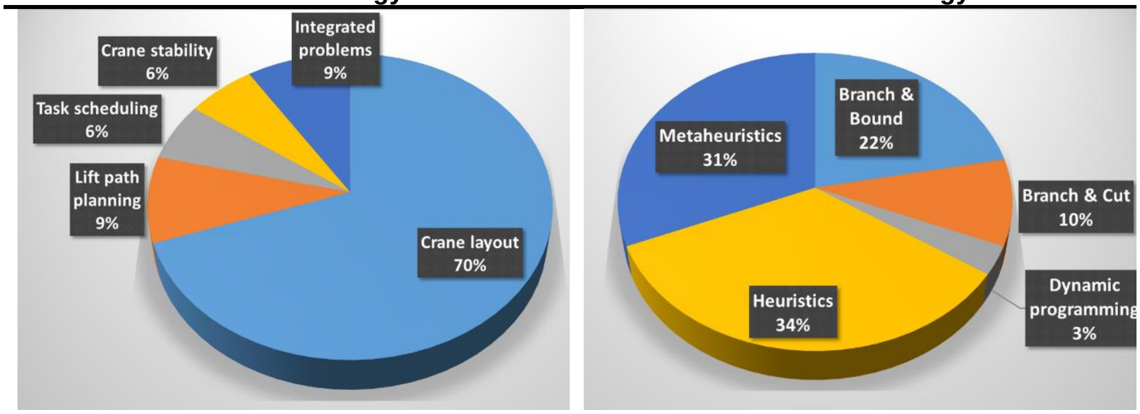
(d) Crane stability



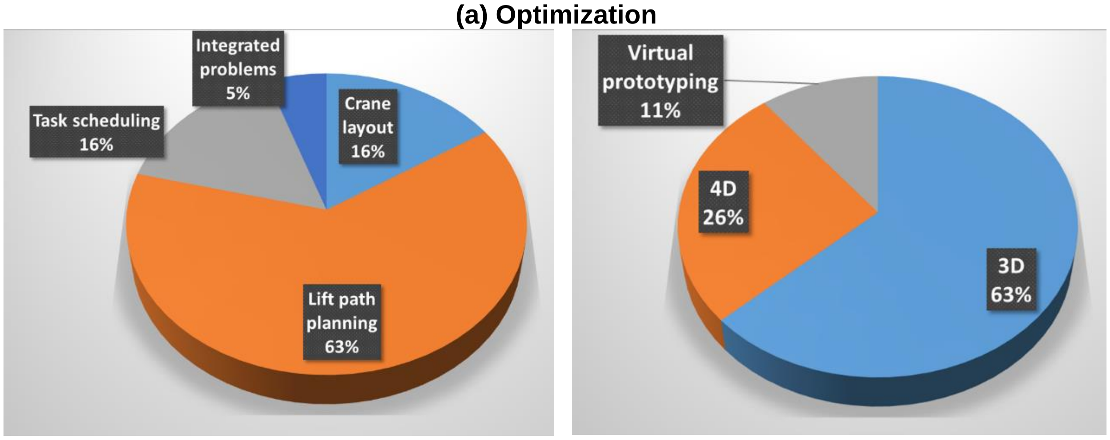
(e) Integrated problems

Fig. 10: Classifications of COP papers based on problem types.

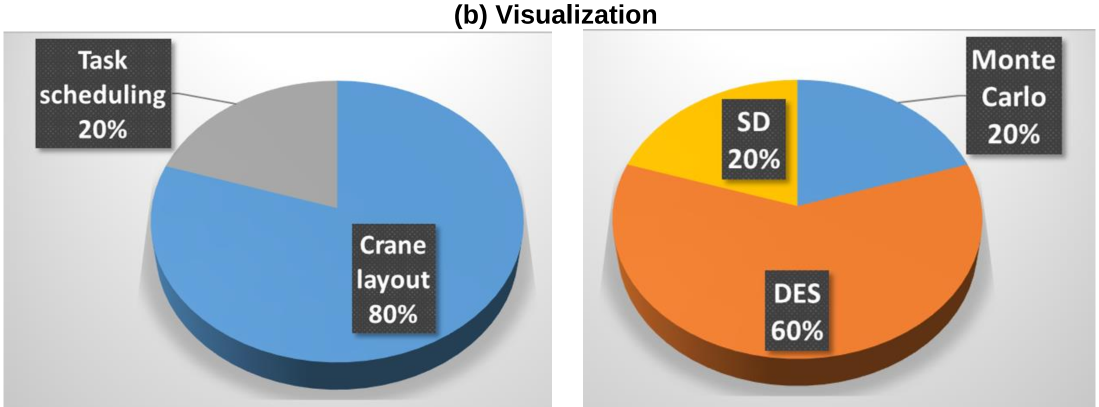
Percentage of COP problems solved by each methodology	Percentage of applied techniques under each methodology



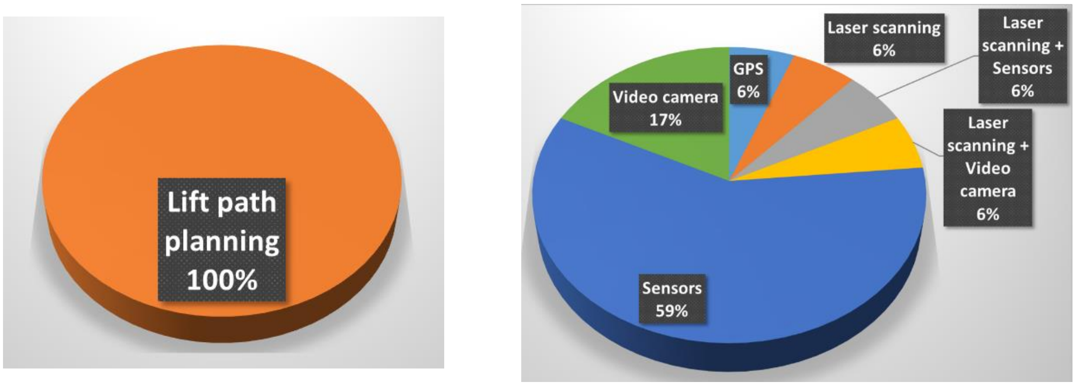
(a) Optimization



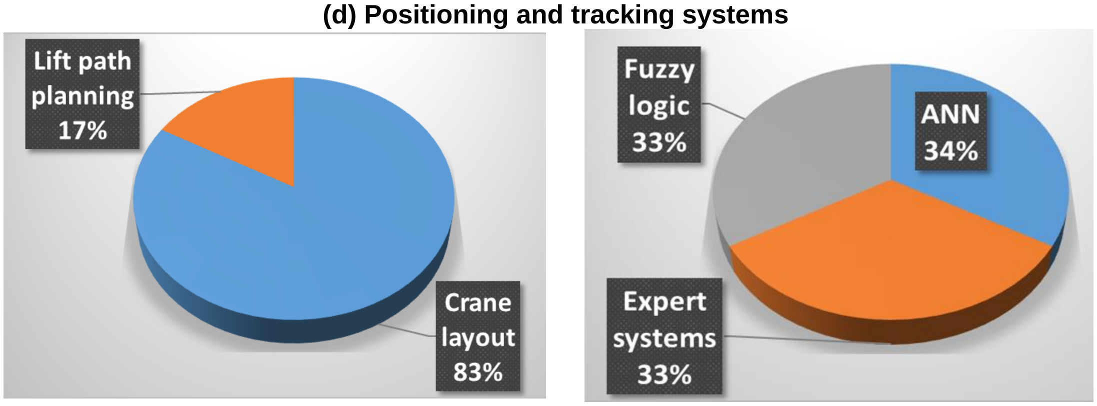
(b) Visualization



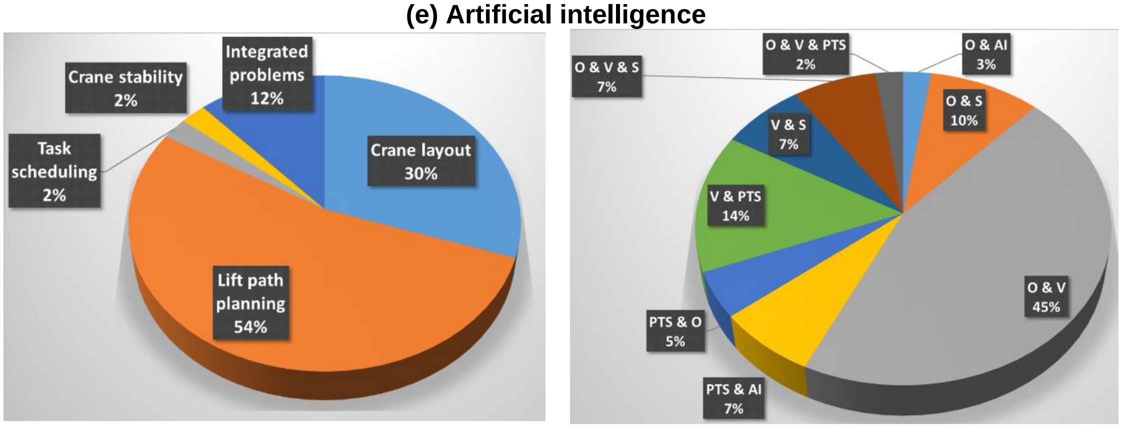
(c) Simulation



(d) Positioning and tracking systems



(e) Artificial intelligence



(f) Hybrid methodologies*

Fig. 11: Classifications of COP papers based on applied methodologies.

***** (O & AI: Optimization and Artificial Intelligence; O & S: Optimization and Simulation; O & V: Optimization and Visualization; PTS & AI: positioning and tracking systems and Artificial Intelligence; PTS & O: positioning and tracking systems and Optimization; V & PTS: Visualization and positioning and tracking systems; V & S: Visualization and Simulation; O & V & S: Optimization, Visualization and Simulation; O & V & PTS: Optimization, Visualization and positioning and tracking systems).

COP problems \ Methodologies	Optimization	Visualization	Simulation	Positioning and tracking systems	Artificial intelligence	Hybrid methodologies
Crane layout	23	3	4	0	5	13
Lift path planning	3	12	0	17	1	23
Scheduling of crane tasks	2	3	1	0	0	1
Crane stability	2	0	0	0	0	1
Integrated problems	3	1	0	0	0	5

Fig. 12: Research trends and 2D classification matrix of COP in MiC based on research topics and applied methodologies.

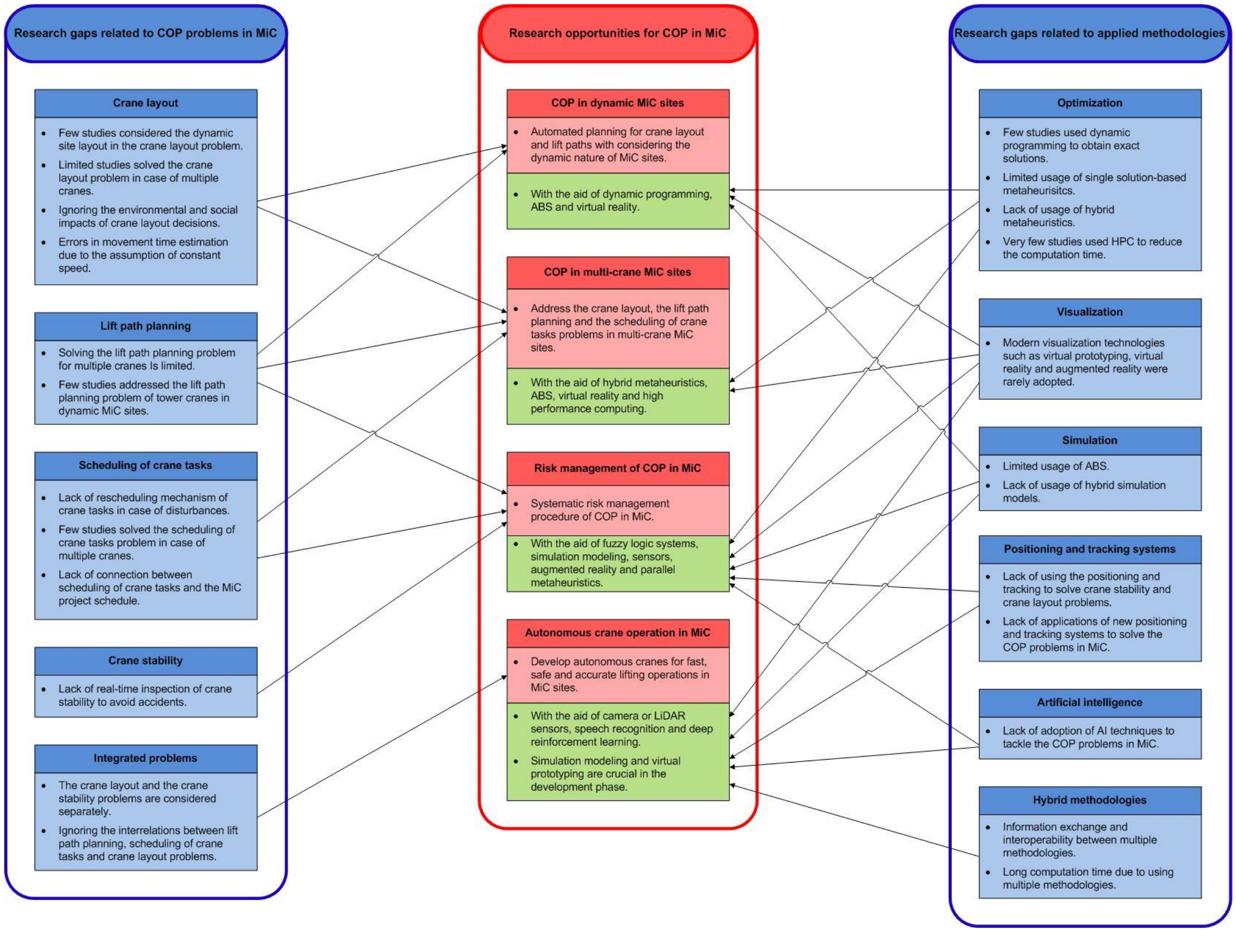


Fig. 13: Future research opportunities to COP in MiC.

Source	No. of studies	Total citations	Total Link Strength
Automation in Construction	48	1196	240
Journal of construction engineering and management	21	604	174
Journal of computing in civil engineering	16	508	100
Construction management and economics	6	177	52
Computer-aided civil and infrastructure engineering	3	115	48
Construction innovation	3	40	28
Canadian journal of civil engineering	3	21	22

Table 1: Bibliometric ranking of journals based on citation sources.

Country	No. of studies	Total citations	Total Link Strength
United States	34	922	11.00
Canada	28	633	6.00
China	20	382	10.00
Hong Kong	7	280	4.00
South Korea	10	235	3.00
United Kingdom	6	228	3.00
India	4	227	1.00
Taiwan	8	217	4.00
Australia	8	147	7.00
Japan	8	114	3.00
Singapore	4	51	0.00
Iran	5	12	3.00

Table 2: Top countries collaborating in COP research.

Rank	Institution/University	Country	No. of studies	Total citations	Total link strength
1	University of Alberta	Canada	13	121	9
2	Gyeongsang National University	South Korea	2	117	0
3	Georgia Institute of Technology	United States	5	92	4
4	Carnegie Mellon University	United States	2	74	0
5	National Taiwan University	Taiwan	2	66	0
6	PCL Industrial Management Inc.	Canada	2	24	1
7	North Carolina State University	United States	2	22	0
8	Hubei Engineering Research Center for Virtual, Safe and Automated Construction (VISAC)	China	2	10	0
9	NCSG Engineering Ltd.	Canada	2	10	2

Table 3: Top nine research centres publishing COP-related papers in MiC.

Author	No. of articles	No. of citations	Total link strength	Normalized citations	Author	No. of articles	No. of citations	Total link strength
Al-Hussein M.	20	443	18	18.97	Taghaddos H.	5	77	5
Varghese K.	4	227	0	4.99	Hung W.-H.	3	73	3
Tam C.M.	3	211	1	5.62	Hasan S.	5	69	5
Kang S.-C.	7	182	6	6.33	Li H.	3	69	3
Miranda E.	4	177	3	65.5	Skitmore M.	3	69	3
Hammad A.	4	163	3	3.96	Huang C.	3	66	1
Alkass S.	4	143	4	3.81	Fang Y.	4	62	4
Moselhi O.	4	143	4	65.5	Gao S.	3	60	3
Zhang C.	3	127	3	3.08	Lin Y.	3	60	3
Hermann U.	8	119	7	6.71	Wu D.	3	60	3
Lee G.	3	118	0	3.35	Olearczyk J.	4	55	4
Wang X.	5	114	4	4.72	Han S.	5	34	5
Akinci B.	3	112	3	2.64	Kosa J.	3	26	3
Tantisevi K.	3	112	3	65.5	Mohamed Y.	3	14	2
Bouferguene A.	10	111	10	8.65	Lee D.	3	13	1
Cho Y.K.	5	110	4	9.7	Briskorn D.	3	10	3
Lei Z.	4	80	4	3.87	Dienstknecht M.	3	10	3

Table 4: Top researchers whose studies recorded high citations in COP research.

Article	Title	No. of citations	No. of links	Normalized citations
(Al-Hussein et al., 2006)	Integrating 3D visualization and simulation for tower crane operations on construction sites	95	8	1.7
(Tam et al., 2001)	Genetic algorithm for optimizing supply locations around tower crane	88	13	2
(Ali et al., 2005)	Collision free path planning of cooperative crane manipulators using genetic algorithm	87	5	1.65
(Zhang et al., 1999)	Location optimization for a group of tower cranes	87	18	1.36
(Kang and Miranda, 2006)	Planning and visualization for automated robotic crane erection processes in construction	84	18	1.51

(Al-Hussein et al., 2005)	Optimization algorithm for selection and on-site location of mobile cranes	77	10	1.46
(Sivakumar et al., 2003)	Automated path planning of cooperative crane lifts using heuristic search	74	11	1.13
(Irizarry and Karan, 2012)	Optimizing location of tower cranes on construction sites through GIS and BIM integration	72	11	1.75
(Lee et al., 2012)	A BIM- and sensor-based tower crane navigation system for blind lifts	68	14	1.65
(Huang et al., 2011b)	Optimization of tower crane and material supply locations in a high-rise building site by mixed-integer linear programming	66	7	2.75
(Chang et al., 2012)	A fast path planning method for single and dual crane erections	58	6	1.41
(C M Tam and Tong, 2003)	GA-ANN model for optimizing the locations of tower crane and supply points for high-rise public housing construction	57	10	0.87
(Tantisevi and Akinci, 2007)	Automated generation of workspace requirements of mobile crane operations to support conflict detection	55	4	1
(Zi et al., 2015)	Localization, obstacle avoidance planning and control of a cooperative cable parallel robot for multiple mobile cranes	55	0	2.11
(Yang et al., 2014)	Vision-based tower crane tracking for understanding construction activity	54	0	2.91
(Reddy and Varghese, 2002)	Automated path planning for mobile crane lifts	54	8	1.15
(Lin and Haas, 1996)	Multiple heavy lifts optimization	51	12	1.36
(Lee et al., 2009a)	A laser-technology-based lifting-path tracking system for a robotic tower crane	49	9	1.64
(Shapira et al., 2008)	Vision system for tower cranes	49	8	1.29
(Zhang and Hammad, 2012b)	Improving lifting motion planning and re-planning of cranes with consideration for safety and efficiency	49	10	1.19

Table 5: Top-cited articles in COP research.