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A SYSTEM BOUNDARY-BASED CRITICAL REVIEW ON CRANE SELECTION IN BUILDING CONSTRUCTION

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Abstract

This study presented a system boundary-based review to systematically investigate the existing research on crane selection in building construction. The system boundary model comprised 9 boundary elements, namely year, location, research source, project height, project typology, crane type, selection constraint, selection criteria, and selection method. Three detailed analyses were carried out with reference to the boundary elements. Firstly, distribution analysis reflected an increasing research trend in crane selection worldwide. Secondly, regression analysis, considering 25 real cases, indicated that tower crane is better suited for high-rise building construction. Thirdly, systematic analysis identified a total of 19 constraints, 71 criteria, and 8 methods adopted for crane selection. Subsequently, the relationships between crane selection constraints and criteria were revealed. Furthermore, this study disclosed the selection differences between tower and mobile cranes, and the best practices in crane type and model selection. The main future research opportunities include i) using advanced AI technologies for crane type selection; ii) developing simulation models for tower crane model selection; iii) establishing a hybrid method for crane selection; and iv) extending the selection considerations to a larger spatio-temporal and functional scope.

Keywords: crane selection, system boundary, building construction, review

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1. INTRODUCTION

Crane is a key element used in building construction projects owing to its role as the primary lifting equipment. Crane has a huge impact on construction in terms of cost, safety, and efficiency. These factors largely determine the success of a project [1-3]. Thus, proper selection of crane is one of the critical decisions facing construction managers. The crane selection problem mainly involves two issues: 1) selection of crane type and 2) selection of crane model. Owing to the importance of these issues, significant scholarly endeavors have been devoted to realizing a feasible solution. These include consideration of various site settings and use of a variety of research approaches, such as expert interviews, simulation, optimization algorithms, and fuzzy theory [4-7]. Despite these research efforts, several key inquiries require further investigation: 1) Is there any best practice in crane selection? 2) What are the latest research trends and future research opportunities in this domain? 3) What are the most important considerations for determining the most appropriate crane? Therefore, this study, via an innovative system boundary review method, addresses these inquiries to benefit both the industry and academia.

A system is typically defined as a set of entities and their relationship with one another [8], for example, ecological systems. A system should only be understood considering specific spatio-temporal circumstances [9,10]. The “system boundary” method is one such approach for characterizing a system [11]. This method is typically defined as “a distinction made by an observer which marks the difference between an entity he takes to be a system and its environment” [11]. The methodology of system boundary has advanced considerably in many disciplines including social science [12], manufacturing engineering [13], and sustainable construction [14]. Even in the context of crane selection research, system thinking is not new. Crane selection activities involve complex relationships among people (i.e. managers), objects (i.e. crane types), and environment (i.e. construction site). Consequently, crane selection models have been developed in the past using system thinking, such as LOCRANE [15], CRANES [16], and D-CRANE [7]. This present research applies a systematic boundary method to reveal the complex relationships existing in previous research studies focusing on crane selection in building construction. The main aims of our study include 1) revealing the history of crane selection research and its trend; 2) identifying the critical crane selection methods, constraints, and required data items; 3) exploring the best practice in crane selection; 4) illuminating the differences between the selection of tower and mobile cranes; and 5) highlighting the future research opportunities.

The remainder of the paper is organized as follows. Section 2 presents the research scope and methodology. Literature identification is covered in Section 3, while Section 4 focuses on the development of the system boundary model. Section 5 shows the analysis processes and results based on the developed model. Several key concerns of the crane selection domain are discussed in Section 6. Finally, Section 7 provides conclusions and future works.

2. RESEARCH SCOPE AND METHODOLOGY

2.1 Research scope

In order to limit and clarify the research scope, only the research studies that simultaneously focused on “crane selection”, “dominant crane types” and “building construction” were considered.

2.1.1 Crane selection scope

Existing literature on cranes included structural design, type and model selection, location determination, and safety monitoring [17-19]. Our study is limited to the selection of crane (type and model) only. Finding the relevant pure crane selection studies was challenging as crane selection research largely interacts with other research aims such as crane location [20,21]. Therefore, the scope of the present study was limited by the following if-then rules:

If [the study concentrated only on crane selection]

Then it was *within* the scope,

Elseif [the study contained crane selection contents]

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    Then crane selection related content was within the scope,
Else
    The study was outside the scope.
Endif
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2.1.2 Crane type scope

Numerous crane models have been designed and produced by crane manufacturers to suit various working conditions. Mobile and tower cranes, as the dominant types [22,23], were *within* the research scope. The mobile crane is capable of moving under its own power without being restricted to predefined routes [5]. Mobile cranes include crawler-mounted, truck-mounted, and wheel-mounted cranes. Conversely, the tower crane has a fixed vertical mast that is equipped with a rotating boom and a winch for hoisting and lowering load [23]. Tower cranes combine different types of towers (e.g. mono and telescopic), jibs (e.g. horizontal trolley and luffing), and bases (e.g. static and rail-mounted).

2.1.3 Building construction scope

Construction project types could be broadly classified into building construction and infrastructure construction [24]. Building construction was considered to be *within* the research scope due to the close relationship between construction efficiency and cranes for the vertical transportation of materials/modules. Cranes are nearly imperative for most building construction projects regardless of their type and scale.

2.2 Research methodology

Figure 1 shows an overview of the review process. The review consisted of three main stages: literature collection, literature analysis, and discussions of results. To begin with, a systematic literature identification and further classification of the identified articles were conducted in the first and second steps, respectively (*see Figure 1 for details of the 9 steps involved*). In the third step, a system boundary model was developed to reveal the current status of research on crane selection. The model utilized three types of analytical means (distribution, relationship, and systematic analyses) to examine nine proposed boundaries: 1) year, 2) location, 3) research source, 4) project height, 5) project typology, 6) crane type, 7) selection constraint, 8) selection criteria, and 9) selection method. In the fourth step, distribution analysis focused on boundaries 1-3 to explore publication trends. Fifthly, a relationship analysis examined boundaries 4-6 to investigate the relationships between building height and crane type, and building type and crane type. Step six applied a systematic analysis on boundaries 7-9 to identify the existing crane selection constraints, criteria, and methods. Additionally, the systematic analysis also revealed the relationship between the constraints and criteria for crane selection. The seventh step elaborated on the differences in selection between tower and mobile cranes. In the eighth step, cluster analysis was used to propose the best practice in crane selection. Finally, in the ninth step, further research opportunities in the domain of crane selection were highlighted.

[Insert Figure 1]

3. LITERATURE IDENTIFICATION

To search for the relevant crane selection research in building construction, a systematic literature identification road map was proposed. The roadmap comprised 1) search strategy, (ii)2) inclusion and exclusion criteria, and 3) quality evaluation and data clustering.

3.1 Search strategy

This research adopted (“crane” AND “selection”) AND (“construction” OR “building”) as the search query to identify the relevant studies. To provide a large coverage of potential research, three digital databases were selected: 1) *Scopus*, the largest database offering indexing of research in the field of engineering and technology; 2) *WoS (Web of Science)*, a comprehensive citation database that includes 12,000 high impact journal sources and 160,000 conference proceedings; and 3) *ScienceDirect*, another famous platform for retrieving engineering related scientific and technical research articles.

3.2 Literature filtering

The literature filtering process took place over four iterations. In the first iteration, duplicate articles retrieved from the three search engines were removed. In the second iteration, all irrelevant studies were excluded by screening their titles and abstracts. In the third iteration, four inclusion criteria (*please see Figure 2*) were used to scrutinize the full research articles. Once an article satisfied the criteria, it was selected as part of the target studies. The final iteration involved backward snowballing (retrieval of other relevant articles by screening the references of a target study) and forward snowballing (retrieval of other relevant articles that cited a target study) were examined against the inclusion criteria [25]. Figure 2 shows the workflow of filtering the literature.

[Insert Figure 2]

The initial query retrieved 307 articles: 212 from Scopus, 73 from WoS, and 22 from ScienceDirect. During the first iteration, 47 out of 307 papers were excluded as duplicates. During the second iteration, 198 papers were removed after screening their titles and abstracts. Twenty papers were further ruled out by reviewing their full text in the third iteration. Finally, snowballing was applied to the remaining 42 articles, which yielded 31 additional relevant studies. In total, 73 articles were listed in the final set.

3.3 Quality evaluation and data clustering

The 73 articles identified from the literature filtering process were evaluated on their quality. Quality evaluation consisted of two dimensions "article property metric" and "article quality metric". Article property metric was measured by means of two reference questions (Q1 and Q2), while article quality metric was determined from four reference questions (Q3 through Q6). These questions (*please refer to Figure 3 for the description of the above-mentioned six questions*) were used to cluster the articles into three databases. The description of each database is as follows:

- Database 1: a group of identified review articles relevant to crane selection for building construction.

The articles in this database helped to identify the past research trends.

- Database 2: a group of journal articles that met all the quality evaluation constraints. The articles in this database facilitated further in-depth analysis, including research data and methods.
- Database 3: a group of the remaining studies on crane selection for building construction. Database 3, together with the studies in Database 2, contributed to the research attributes analysis e.g. the distribution investigation of research location and period.

As for the article property metric, Q1 directly screened the articles and placed the conference papers into Database 3. Whereas the journal articles that passed Q2 were to be placed in Database 1 that stored review articles, however, no single review journal article was found in this domain. The remaining journal articles were further securitized against Q3 through Q6 on article quality metrics. Journal articles that satisfied the four queries in this metric were entered into Database 2. Journal articles that didn't satisfy any of the four queries were placed into Database 3. The finalized articles in Database 1, Database 2, and Database 3 were 0, 36, and 37, respectively.

[Insert Figure 3]

4. SYSTEM BOUNDARY MODEL FOR CRANE SELECTION IN BUILDING CONSTRUCTION

4.1 System boundary theory

Von Bertalanffy [9] is regarded as the first to systematically develop the system theory. He identified a system as a set of elements standing in interaction, wherein boundaries distinguish a system from others. Bailey [26] mentioned that it is the boundary that separates a system from its environment and therefore, effectively defines the system. In a similar way, Checkland [11] defined system boundary as a distinction made by an observer to mark the difference between an entity (system) and its environment. Recently, system thinking has spread its wings in the construction industry for examining productivity [27] and the performance of zero-carbon buildings [14].

It should be noted that the identification and description of a system boundary is highly subjective, and rely largely on the experience of investigators, the purpose of research, and the availability of data [10,11]. For instance, in a system for life cycle carbon assessment of a construction project, Pan, et al. [28] regarded the climatic zone, building material, and prefabrication level as the system boundaries. On the other hand, in a system for construction collaboration, participants and contracts were taken as boundaries [29].

Furthermore, to make the boundary visible and measurable, Luhmann [30] described the boundary via two principal components: the boundary itself (distinction), and its metrics (indication). While a distinction defines the nature of the boundary, an indication describes the degree of its nature.

4.2 System boundary model for crane selection

In this research, a holistic system boundary model was developed to elaborate on the boundaries and indicators of crane selection research in building construction. In total, nine boundaries in three dimensions were developed (please refer to Figure 4). These dimensions were “research attributes”, “research objects”, and “research methods”. The nine boundaries comprised year (B1), location (B2), research source (B3), project height (B4), project typology (B5), crane type (B6), selection constraint (B7), selection criteria (B8), and selection method (B9).

[Insert Figure 4]

4.2.1 Research attribute dimension

The research attribute dimension delineated the basic features of the studies, including year (B1), location (B2), and research source (B3). Each of these features is described as follows:

1) Year boundary (B1) referred to the year of publication of a research study, such as 2020, 2019, and so on.

2) Location boundary (B2) illustrated the geographical location of a study. Its indicators were countries/regions, such as China, Hong Kong, Australia, etc.

3) Research source boundary (B3) indicated the research outlets, such as the Journal of Construction Engineering and Management, Automation in Construction, etc.

4.2.2 Research object dimension

The research object dimension comprised two boundaries, namely project height boundary (B4) and crane type boundary (B5), which are described below:

1) Project height boundary (B4) depicted the height of a building, which largely determined the required lifting height of a crane. Following the recommendations in [31], the indicators of B4 were high-rise (10 stories and above) and low-rise (9 stories and below) buildings.

2) Project typology boundary (B5) represented the project type, which could be classified as residential, commercial (e.g. office, shopping mall), public (e.g. school, hospital), and industrial (e.g. factory, warehouse) buildings.

3) Crane type boundary (B6) characterized the objects of the research. For example, the proposed methodology in a research article might be applicable for selecting an appropriate crane type (e.g. tower and mobile cranes), and determining an optimal crane model based on a predetermined crane type. Hence, the indicators of B6 were mobile crane, tower crane, crane type, and mixed. Mobile and tower cranes portrayed the research studies that provided the optimal mobile and tower crane models, respectively. On the other hand, crane type denoted the studies that determined the best crane type. Finally, the studies with multiple/integrated purposes were labelled as mixed.

4.2.3 Research method dimension

The research method dimension described the research methods adopted in the literature. This dimension consisted of three boundaries: selection constraint boundary (B7), selection criteria boundary (B8), and selection method boundary (B9). Each of these is further depicted in the following:

1) The selection constraint boundary (B7) reflected the constraints required for determining an optimal crane, such as the considerations of clients, lifting capacity constraint, and working radius constraint.

2) The selection criteria boundary (B8) implied the specific data items used for crane selection. The indicators here concerned the actual data derived from the real world, including crane lifting radius, crane rental cost, and others.

3) The selection method boundary (B9) showed the techniques adopted for the crane selection process, including simulation, AHP model, interview, and so on.

4.2.4 *An example on the utilization of boundaries*

Figure 5 presents the profiles of the system boundaries for some selected studies. For instance, research study [6], represented with red lines, was conducted in Canada (B2) in the year 2018 (B1) and was published in Automation in Construction (B3). This study focused on low-rise (B4) industrial construction (B5). Mobile crane model selection (B6) was the research question. The data items related to crane, project, and site were collected (B8). Simulation method (B9) was adopted to determine the best crane model under constraints, such as lifting coverage, lifting load, and collision-free maneuvering (B7).

[Insert Figure 5]

5. ANALYSIS OF RESULTS OF THE SYSTEM BOUNDARY MODEL

5.1 Distribution analysis of research attributes

Analysis of research attributes was based on the boundaries B1 to B3 and Databases 1 to 3. Seventy-three articles were used for the distribution analysis.

5.1.1 Distribution by the time period of publication (B1)

Distribution analysis was carried out to reveal the popularity and trend of crane selection research over the years. We utilized a 4-year period as the scale to measure the time distribution of studies to eliminate the influence of zero publication in some specific years (e.g. in 1986 and 1991). Figure 6 shows an overall increasing publication trend. This reflected that researchers have consistently concentrated on crane selection to improve construction performances in building projects. In total, 73 articles were found between 1984 and 2020. Notably, 21 research studies were published since 2016, which accounted for 28.8% of the total publications. This could be attributed to the recent boom in modular construction, whose schedule and productivity depend much on effective crane planning.

[Insert Figure 6]

5.1.2 Distribution by the location of research (B2)

Geospatial analysis indicated that the finalized 73 studies were conducted in 18 countries. Canada (24), United States (11), China (7), and Israel (6) were the major contributors. Other contributing countries included India (4), United Kingdom (3), South Korea (3), Iran (3), Germany (2), Czech Republic (2), Japan (1), Jordan (1), Slovakia (1), Egypt (1), Australia (1), Singapore (1), Saudi Arabia (1), and Poland (1). Figure 7 shows the geospatial distribution of the selected articles. These 18 countries were distributed across 5 continents including Asia, Europe, Australia, North America, and Africa. This distribution established that crane selection research had gained attention worldwide.

[Insert Figure 7]

5.1.3 Distribution by the research source (B3)

The selected studies were published in 23 journals and also in some conference proceedings (Table 1). “Journal of Construction Engineering and Management” published the highest number of articles i.e. 8.

"Automation in Construction", and "Construction Management and Economics" published 7 and 5 articles, respectively. Scholars may use this information when submitting their future research articles.

[Insert Table 1]

5.2 Relationship analysis of research objects

Existing studies showed that project type and height might affect crane selection [4,32,33]. This view was majorly appreciated as a rule of thumb. To further investigate this proposition, we studied the relationships between 1) project height boundary (B4) and crane type boundary (B6), and 2) project type boundary (B5) and crane type boundary (B6), through binary regression analysis using SPSS (v. 26.0) [34-36].

Twenty-five real cases (Table 2) of crane selection scenarios were extracted from Database 2 (*please see section 3.3*). Thirteen cases represented tower cranes and 12 represented mobile cranes. Besides, 15 cases focused on low-rise buildings, while 10 focused on high-rise buildings. Residential, commercial, public, and industrial buildings accounted for 4, 8, 2, and 11 cases, respectively. The P-value of the project height came out to be $0.015 < 0.05$ (Table 3), demonstrating its significant influence on crane type selection. On the other hand, all the P-values (Table 4) of building types came out to be larger than 0.05, depicting little influence of building types on crane selection.

[Insert Table 2]

[Insert Table 3]

[Insert Table 4]

Some studies argued that the building type contributed to crane type selection. On the contrary, our study presented a different but an interesting opinion. A larger-scale investigation, though, is needed to quantitatively investigate the correlations between "building type" and "crane type".

5.3 Systematic analysis of research methods

Systematic analysis was applied on the existing research methods, including crane selection constraints (B7), crane selection criteria (B8), and selection methods (B9). It was found that several terms depicting the same semantic meanings were used interchangeably in the literature (e.g. “crane size” vs “crane dimension” vs “crane geometry”). This study therefore, used a cyclic unification philosophy to unify such terms (Figure 8). As per the philosophy, the terms were re-adjusted and updated accordingly, once a new or inconsonant term having the same semantic meanings was found.

[Insert Figure 8]

5.3.1 Systematic analysis of crane selection constraints (B7)

Referring to the classifications in the literature [50-53], this study found three types of constraints for crane selection, namely “economic constraints”, “technical constraints”, and “environmental constraints” (Table 5).

[Insert Table 5]

5.3.1.1 Economic constraints

Economic constraints mainly occur due to the arrangements and allocations of resources that influence the progress, productivity, and cost of projects. This study found 8 economic constraints: project’s budget, assembly sequence, crane number, crane operation duration, crane management convenience, construction schedule, crane location, and resource availability constraints. For instance, proper [assembly sequence (constraint 2)] and larger [crane number (constraint 3)] might improve lifting efficiency. Thus, the duration of a construction project might be shortened, however, lower [project’s budget (constraint 1)] might not allow it [40,56].

5.3.1.2 Technical constraints

Technical constraints limit the technical feasibility and availability to use a crane, such as a restrictive site space or weak soil condition for crane installation. This category encompassed 9 constraints, divided into two branches, namely “capacity constraints” and “practical feasibility and operational constraints”. Capacity constraints include lifting capacity, site coverage, lifting height, and clearance requirement constraints. Whereas, practical feasibility and operational constraints consisted of foundation stability, functional area size, site accessibility, and site boundary constraints. For example, considering [foundation stability (constraint 13)] and [site boundary (constraint 16)], the selected crane might become incapable of entering and standing at some locations on site.

5.3.1.3 Environmental constraints

Environmental constraints were derived from crane operations that affect the surrounding environment such as [energy performance (constraint 18)] and [neighbor impact (constraint 19)]. [Special weather (constraint 17)] might restrict and impede the usage of certain crane types. For example, heavy wind might negatively impact crane stability and the winter season might extend the construction time beyond schedule. Therefore, both weather conditions might necessitate stable and faster crane models, respectively.

5.3.1.4 Prevalence of crane selection constraints in the literature

Figure 9 presents the above-mentioned 19 constraints as three dashed-circles, which are grouped with respect to their frequency of occurrence in the literature. For example, orange-colored [site coverage (constraint 10)] was placed in the high-frequency group. This constraint appeared exactly 25 times in the literature.

[Insert Figure 9]

Project’s budget (constraint 1) was the most popular constraint and it appeared 27 times in 36 studies. This is justifiable as cost control is always a prerequisite for any project’s success. Apart from constraint 1, which was an economic constraint, all the other constraints in “high” and “middle” frequency groups were technical constraints. This result demonstrated that considerable research attention was given to technical constraints. Specifically, capacity constraints were extensively investigated in the literature.

The “low” frequency group contained all the three environmental constraints, one technical constraint, and seven economic constraints. Three conclusions could be deduced on the constraints in the low-frequency group. Firstly, compared to other categories, environmental constraints were given less attention. Secondly, sometimes the consideration of low-level constraints might not be necessary for a particular project. For example, a project on a flat site had nothing to do with [foundation stability (constraint 13)], while a low-rise building project might not need to account for [crane number (constraint 3)]. Thirdly, some constraints were out of the research scope. For example, [assembly sequence (constraint 2)] would not be investigated if the research did not study specific crane lifting schedules.

5.3.2 Systematic analysis of crane selection criteria (B8)

Crane selection criteria represented the data items required for overcoming the constraints. A three-layer data tree was established to conduct a systematic analysis of the data items (Figure 10). The data tree illustrated the realization of the unification of all the data items extracted from studies in Database 2 (*please see section 3.3*). All the data items were placed in three branches, namely “project data”, “crane data”, and “user demands”. The project data branch had 6 second-layer data items and 32 third-layer items. The crane data branch had 5 second-layer and 27 third-layer items, and the user demands branch had 3 second-layer and 12 third-layer items. The description of second-layer data items of each of the three branches is given hereunder. Third-layer items were described with each second-layer data item.

[Insert Figure 10]

5.3.2.1 Project data

1) Company-level data referred to the requirements of a company that could affect the crane selection decision-making: a) previous experience (item 1.1.5) might raise concerns about handling unfamiliar crane types; b) commercial considerations (item 1.1.2), such as the collaboration with specific crane suppliers, might possibly restrict the choice to a limited crane pool.

2) Crane layout data considered the spatial characteristics of the site, including its boundary (item 1.2.1), space (item 1.2.3), elevation plan (item 1.2.4), and others.

3) Site condition data estimated the site accessibility (item 1.3.1) using gauges, such as preparation cost (item 1.3.2), site terrain (item 1.3.3), soil type (item 1.3.4), and allowable bearing pressure (item 1.3.5).

4) Project cost data accommodated the items of planned project costs, including construction budget (item 1.4.1) and storage cost (item 1.4.2).

5) Load data involved load information i.e. type, weight, size, location, and quantity of modules to be lifted.

6) Project schedule data signified the scheduled milestones, namely project completion time (item 1.6.1) and load lifting date (item 1.6.2). It also included other scheduling data, such as the sequence logic and the duration of lifting activities (items 1.6.3 and 1.6.4, respectively), and the shift and daily working hour arrangements of projects (items 1.6.5 and 1.6.6, respectively).

5.3.2.2 Crane data

1) Crane market information indicated the state of the cranes in the market, which reflected the three major concerns of the contractor: the availability of crane (item 2.1.1); the market location of crane (item 2.1.3); and the provision of sufficient technical support from the supplier (item 2.1.2).

2) Crane capacity referred to the required crane working radius, lifting height, load, and speed.

3) Crane cost measured the overall expenses for operating a crane, from the installation stage to demolishing.

4) Crane environmental parameter reflected the environmental effects, such as dust and noise caused by crane operations. The crane power (item 2.4.1) could be associated with energy consumption.

5) Crane feature contained other items apart from the above 4 categories. For instance, crane weight (item 2.5.1) was used to evaluate the ground pressure constraint. Crane location on-site (item 2.5.2) could be used

to check the coverage and clearance for crane operations, and operator's visibility (item 2.5.7) contributed to safety and productivity.

5.3.2.3 User demands

User demands were used to satisfy the users' considerations and expectations in crane selection. The considerations primarily focused on three aspects: safety, environment, and productivity.

1) Safety consideration accommodated some subjective elements, such as empirical judgment (item 3.1.3) to guarantee the safety of the crane model. Moreover, some objective conditions were also added to achieve safer choices. For example, a safety calculation margin (item 3.1.1) and minimum clearance value (item 3.1.2) were widely considered in the crane selection decision-making.

2) Environmental consideration comprised other environmental-related data items in the literature. The influences of these items were often multiple. The wind level (item 3.2.1), season factor (item 3.2.2), and visibility condition (item 3.2.4) were utilized to improve crane safety or/and productively performance. The carbon emission factor (item 3.2.3) corresponded to the environmental influence assessment.

3) Productivity consideration used subjective judgment (item 3.3.1) and an objective calculation margin (item 3.3.2) to evaluate different crane choices. Labor availability (item 3.3.3) checked whether the proposed crane could be appropriately handled.

5.3.2.4 Relationships between crane selection constraints and data items

Figure 11 establishes the relationships between crane selection constraints and data items. The colorful lines, in the figure, clearly visualized what data items were needed to fulfill the proposed constraints. For example, 6 data items were required to satisfy crane foundation stability (constraint 13). Ground condition should be first checked, which included site terrain (item 1.3.3) and soil type (item 1.3.4) [33,65,66]. In doing so, some crane models (item 2.5.9) that were not suitable for some specified ground conditions (e.g. slope and soft soil ground) could be ruled out. Further, the force applied on the ground, which was estimated from the weight of the crane and loads (items 2.5.1 and 1.5.2), should be less than the allowable bearing pressure (item 1.3.5) [3,48].

For the site coverage (constraint 10), the proposed crane location (item 2.5.2) and its working radius (item 2.2.1) estimated the cover capacity of the crane layout. If all the supply points (item 1.2.7) and demand points (e.g. item 1.5.4 load location, item 1.2.5 building location) could be covered then, constraint 10 was satisfied [6,20,32].

[Insert Figure 11]

5.3.3 Systematic analysis of selection methods (B9)

The analysis of the selection methods was on the basis of the literature classified in Database 2 *(please see section 3.3)*. A total of 8 methods were identified, and further classified into qualitative and quantitative techniques (Table 6). Qualitative techniques included interviews and case studies, whereas quantitative techniques included optimization, simulation, evaluation models, artificial intelligence, manual calculation, and augmented reality. Details of the techniques are as follows:

[Insert Table 6]

5.3.3.1 Interviews

Interview is one of the most common qualitative techniques utilized to learn from human experiences [68]. In a complex construction system, practical engineering experience significantly contributes to decision-making, and crane selection is no exception. Interviews could be unstructured, such as those adopted in [38], which investigated 27 soft factors for crane selection from the perspective of six project managers. Another kind could be structured interviews, where some specific questions are typically asked in order. For instance, Shapira and Schexnayder [4] investigated the practitioners' subjective opinions on the significance of 14 factors on crane selection.

5.3.3.2 Case studies

A case study involves a detailed examination of a particular case/project to extract relevant information. Case studies reflect the viewpoints of the real world and add credibility to research design. King and Schexnayder [47] explored the crane selection process of a real project which used a tower crane. They discussed the pros and cons of a tower crane over mobile crane from a life cycle perspective. Factors, such as site congestion and quiet working condition of a tower crane, influenced the company's decision to opt for a tower crane.

5.3.3.3 Optimization

Optimization is a generic approach to finding the best solution from all feasible solutions. Existing literature has often optimized crane selection in integration with other crane operations, such as crane location, supply point location, etc. Three types of optimization methods were employed 1) problem-specific heuristic methods, 2) metaheuristics, such as genetic algorithm; and 3) mathematical methods, such as linear and mixed-integer programming, and dynamic programming [69,70].

The problem-specific heuristic accounted for the largest portion in the optimization-based research (Table 6). Two potential reasons led to its popularity: the diversities of features amongst different projects and the various optimization objectives used. Each construction project system is distinctive in accordance with its specific characteristics, thereby presenting a different optimization problem. For example, Moselhi, et al. [44] used an algorithm to select a mobile crane for replacing the components of a residential building in Concordia University. The project's features were different from a new construction project. Similarly, optimization objectives also largely influenced the problem's uniqueness. For instance, Sohn, et al. [3] assessed crane types by considering only their cost, while [41] further took the overall construction period into account.

Unlike exact methods, metaheuristics do not guarantee a globally optimal solution for a problem. Instead, metaheuristics implement stochastic optimization to find good solutions for large-scale complex problems. In this regard, desirable outcomes can be achieved with less computational effort [71]. Some metaheuristics were used for optimizing the complex combinatorial (i.e. crane type and crane location) optimization problem, such as the genetic algorithm adopted in [32] and [46]. Regarding mathematical methods, a mixed-integer programming model and dynamic programming model have been used to determine optimal solutions for crane problems. Mixed-integer programming was applied to solve a crane problem with the integration of a large number of parameters (e.g. crane cost, jib length, etc.) [1,63]. The dynamic programming simplifies a complicated problem by breaking it down into simpler sub-problems. For example, Furusaka [55] solved a 3×10^{18} complex combinatorial crane optimization problem using dynamic programming.

5.3.3.4 Simulation

Simulation is an approximate imitation of the operations of a process. This reflection of reality helps designers to ensure the efficiency of designs before execution. For crane selection, simulation provides a systematic view of the interactions between the crane and its complex surroundings (e.g. the building, ground, loads, and environment). For example, clearance requirements [6,42], lifting capacity [37,40], and even the environment effects [60] could be systematically assessed in one simulation model.

Simulation enables the dynamic evaluation of crane performance throughout the full construction stage. Crane type influences the cost and effectiveness of site operations continuously from activity to activity, which demands dynamic considerations in crane planning. Existing studies deployed a variety of simulation means and platforms (e.g. Simphony in [60] and 3D CAD in [48]) to analyze and visualize crane options. Some recent research also attempted to incorporate time dimension into traditional 3D simulation models, thereby realizing the 4D visualization of crane performance on-site [37,40]. 4D models, through visual demonstration, further enhanced the decision-making ability of project stakeholders.

5.3.3.5 Evaluation model

Evaluation model refers to the quantitative techniques applied to evaluate the subjective data gathered from field and academic experts. For example, AHP (analytic hierarchy process) is a classical decision-making technique that uses interviewees' judgment on the pairwise significance of factors [72]. AHP allows the best crane selection considering project goals, sub-goals, and requirements. For instance, Dalalah, et al. [2] evaluated crane types on the basis of five sub-goals: building design, capacity, economy, safety, and site condition. Apart from AHP, the fuzzy theory was also used in crane selection literature [5].

5.3.3.6 Artificial intelligence (AI)

Artificial neural networks and expert systems are labeled as AI approaches, as they both demonstrate their machine-based intelligence to assist in crane selection. For the artificial neural networks, real cases of crane selection as learning examples are used as the building blocks to grasp and set up the correlations between inputs and outputs. Sawhney and Mund [33] developed an automated artificial neural network, which incorporated processing elements and rules for input variables, for the selection of optimal crane type. Expert systems, on the other hand, CRANES [15] and LOCRANE [16], formed their knowledge bases (i.e. crane selection rules) from experts' experiences to automatically realize the preferred crane model.

5.3.3.7 Manual calculation

Manual calculation includes all manual methods that are used to select cranes through the evaluation of cost and technical capacities (e.g. coverage, lifting load, etc.). The adoption of manual calculation could be attributed to the lack of advancement in computational technologies in the early years e.g. the study [56] in 1985 and [66] in 1987.

5.3.3.8 Augmented reality (AR)

Augmented reality (AR) enhances users' experience by adding computer-generated digital visualization onto the model. Jang and Yi [67] first investigated the AR usage for tower crane selection in 2013. They used Eclipse to establish the AR environment for a dynamic and 3D view of crane selection and layout.

6. DISCUSSION

6.1 Selection difference between tower and mobile cranes

Tower and mobile cranes are the two dominant crane types used in building construction. These cranes have significant differences in structures and features, leading to some variations in selection considerations and required data items. Table 7 summarizes the selection differences between tower and mobile cranes.

[Insert Table 7]

6.1.1 Discrepancies in evaluation focuses

Satisfying capacity constraints (i.e. coverage, lifting capacity, lifting height, etc.) is mandatory in a crane selection process. Capacity-related focus on tower and mobile crane selections show some disparities, especially in the lifting coverage and capacity considerations.

1) Coverage capacity: It is understandable that the coverage of the whole site is a necessary condition for delivering all lifting tasks. Therefore, designers usually calculate the coverage performance relative to the jib length and location of the proposed tower crane. For a mobile crane, however, the coverage constraint is not an issue because the covering capacity of any mobile crane is theoretically unlimited due to its mobility. It is well noted that the rail-mounted tower crane has limited movability. The coverage capacity of the rail-mounted tower crane is measured by the length of the crane jib and the rail together [32].
2) Lifting capacity: Regarding the lifting capacity, tower crane often uses the load chart provided by the manufacture, which is fair enough. Calculations of the load capacity for a mobile crane is more

complicated. As the crane configuration changes, its maximum lifting capacity also changes. Hence, existing research always have collected configuration data (e.g. the weight of slings, spreader, and hook block) of a mobile crane to calculate its lifting capacity.

3) Clearance evaluation: Clearance evaluation is another divergence. The clearance checking for the mobile crane is much more complex than that for a tower crane due to the flexible configurations of mobile cranes. Unlike a tower crane, which swings or rotates its jib within the horizontal or vertical plane, the movements of a mobile crane are the synergy of several crane elements (e.g. main boom, jib, etc.). Hence, the clearance required for a mobile crane should be addressed carefully considering every element.

6.1.2 Disparities in the considerations for ground condition

Ground condition considerations mainly differ in three items: ground space, ground bearing capacity, and ground slope.

1) Ground space: Apparently, the mobile crane requires enough space on-site during its movements. On the contrary, the tower crane only requires adequate operating space in the lifting process, thus it can be used on a constricted/congested site.
2) Ground bearing capacity: Since the mobile crane moves around the construction site, the ground capacity should be supportive enough. On the other hand, even if the ground is unsupportive, a tower crane can be used by strengthening and enhancing the foundation.
3) Ground slope: The last difference is the ground slope. While some mobile types (e.g. crawler crane) can move on a slightly sloped ground, a tower crane is a must for steep slopes [54].

6.1.3 Diversities in the integrated factors

Crane selection is often solved in integration with other crane-related problems. In this regard, the factors integrated with the selection of tower and mobile cranes are diverse. The tower crane selection problem is more likely to be solved in combination with the location factor because crane type and location determine the coverage capacity together. Comparatively, literature on mobile crane has modeled and simulated the crane selection problem as a part of the whole crane operating process. Since every single lifting task of a mobile crane corresponds to a unique crane "gesture", simulating all the operation processes can eliminate any potential scenario that may not satisfy the clearance requirements.

6.2 Best practice in crane selection

The best practice mainly involves three important considerations: 1) what constraints to consider? 2) what data items to gather? and 3) what kind of method to operate? The first two considerations are highly project-specific as different projects have particular requirements/restrictions. For instance, a project with a poor ground condition should treat the foundation stability constraint (constraint 13) as the main constraint. Figure 10 and 11 provide a useful reference for future studies to identify their constraints and data items. This leaves us with the last consideration i.e. what kind of method to operate?

Three primary types of studies with different research objectives have been identified from the literature: 1) determining an optimal tower crane model, 2) determining an optimal mobile crane model, and 3) determining an appropriate crane type. These three questions are labeled as a boundary (B6) (*please see point 3 in section 4.2.2*). The studies with "mixed" (the fourth indicator of B6) purposes can be seen as an integration of the above methods. To explore the best practice in crane selection, cluster analysis is developed to examine the relevance between research questions and preference for specific methodologies. This analysis is based on the features of the studies, specifically research object (B6) and selection method (B9) (*please refer to Figure 4 to recall boundaries*). For example, the study of Briskorn and Dienstknecht [1] has been coded as a tower/optimization/mathematical method because they adopt mixed-integer programming models to optimize the tower crane selection process. NVivo platform, which performs cluster analysis according to the similarities of coded feature, is used to conduct the clustering process. The 36 studies in Database 2 (*please see section 3.3*) are grouped into 4 clusters (Figure 12). The cells with the grey fill (on the right side) are the dominant methods for a specific research problem, and therefore, they are recommended as the preferred practice. From top to bottom (Figure 12), AI and evaluation models are the preferred practice for determining an appropriate crane type. Optimization is the preferred practice in determining an optimal tower crane type, and simulation and optimization are the preferred practices in determining an optimal mobile crane type.

[Insert Figure 12]

6.2.1 Best practice in mixed studies

Three studies are grouped in a mixed cluster (cluster 1 in Figure 12). Two of the studies combine the objectives of crane type and crane model selection [55,56], whereas the third study attempts to generalize the selection method for both tower crane and mobile crane models [58]. Although it is useful to achieve multiple goals via a single methodology from the academic point of view, certain impediments hamper the practicality of such methods. For instance, in comparing cranes of different types and models simultaneously (e.g. Mobile 1, 2, 3 & Tower 1, 2, 3), previous studies have used cost comparisons. However, the cost-oriented evaluations fail to comprehensively consider the pros and cons of the different crane types, which make the results less reliable. Hence, existing practices often decide the ideal crane type first, and optimize its model afterward. Also, developing one general selection method for both tower and mobile cranes is impractical due to the difference in the configurations and features of the two cranes (*please recall 6.1*). In a word, mixed research has not become mainstream theme and therefore, the best method for it doesn’t exist.

6.2.2 Best practice in crane selection type

Seven studies are grouped in the selection of crane type cluster (cluster 2 in Figure 12). Amongst the research techniques, AI and evaluation models appear to be the most popular ones, with each having three applications in the literature. Generally, AI and evaluation models stand for two diverse directions for crane type selection. AI method relies solely on objective data from past crane selection cases. Evaluation models, however, are built upon the experts’ subjective judgments on different crane types. Thus, it is concluded that AI technology can be the best practice in crane type selection for companies. Employing the data of their previous real construction projects, AI-based selection enables fast determination of the crane type. Moreover, as the database increases, the accuracy and reliability of AI systems rise. For special scenarios that are not similar to the past cases, an evaluation model can be used instead.

6.2.3 Best practice in tower crane model selection

Ten studies are grouped in the tower crane cluster (cluster 3 in Figure 12). Apart from the dominant optimization method that accounts for 50% of the studies, other techniques, e.g. AR and evaluation model, are also identified. The optimization method is employed frequently to solve the tower crane model selection problem due to the following reasons. Firstly, the best crane model is often equal to the most economic choice, which should be determined among numerous crane models. The manual calculation method can handle the comparison of limited cases, but the optimization algorithm has the superiority of dealing with a large pool of crane models. Secondly, tower crane planning is a complex problem involving many parameters, including crane number, crane location, and crane type. In this respect, the optimization method enables the 1) integration of parameters by setting different constraints for each factor, and 2) determination of the optimal solution among numerous combinations of the factors involved. This study considers optimization as the best method for solving tower crane selection problem not just due to its comparatively high maturity, but due to its capacity in evaluating the performance of crane types with an all-round perspective.

6.2.4 Best practice in mobile crane model selection

Mobile crane is the largest cluster with 16 studies (cluster 4 in Figure 12). Eight of these use problem-heuristic optimization methods, four apply simulation, and the last four adopt other techniques (i.e. interview and manual calculation). Clearance evaluation is considered as the core of mobile crane selection. Optimization models are typically developed to satisfy the space (i.e. clearance requirements) between the crane and its surroundings (e.g. buildings). As the configurations of crane types vary, a problem-heuristic rule is applied to 1) establish spatial relationships amongst different crane components, 2) evaluate the lifting height of the crane, and 3) further calibrate the safety clearance. This explains why all the optimization practices for mobile crane belong to problem-heuristic approaches. Another significant method is simulation, which can evaluate and visualize the performance of potential crane models over the full construction cycle in a vivid animation environment.

6.3 Crane selection research trends and opportunities

6.3.1 Research trends

The studies with their publication years and adopted research methods are marked in Figure 13. After investigating the development status quo of each category, some conclusions about the research trends are as follows.

[Insert Figure 13]

6.3.1.1 Mixed crane selection has not attracted enough research attention

The purple triangles, in Figure 13, imply that only 3 studies have solved a mixed crane selection problem and all are published in the early years (i.e. 1984, 1985, and 1995). After that, no such mixed study has been conducted. This shows the desire of early researchers to overcome the complicated crane type and model determination problem as a whole. However, as explained in *section 6.2*, this vision has not gained enough attention afterward due to the lack of its practicality. Thus, the trend in the mixed research stopped since 1996 and the later studies have focused on individual research questions.

6.3.1.2 Crane type selection research is quite mature

The brown squares, in Figure 13, illustrate the development of crane type research. Seven studies are published between 1990 and 2010, and no such study has been found thereafter. Our study concludes that the crane type selection has been thoroughly investigated. Several types of AI technologies and evaluation models have been successfully deployed for optimal crane type selection objectively and subjectively, respectively.

6.3.1.3 Mobile crane selection studies have shifted from labor-oriented methods to simulation

Mobile crane model selection studies, indicated by blue circles in Figure 13, show a continuous publication trend since the 1980s. In the early years, manual techniques are employed. Gradually, the focus shifts to optimization techniques in the 2000s. In recent years, researchers have focused on simulation. We deduce that an ongoing trend of simulation exists due to its benefits in clearance evaluation. Via simulation, all the potential collision scenarios of mobile crane operations can be modeled and identified in advance.

6.3.1.4 Trend of implementing optimization method in tower crane research is a recent discovery

The red rhombuses, in Figure 13, stand for tower crane model selection research. Optimization techniques account for over 50% of all studies on tower crane model selection. The Figure shows a steadily increasing trend in optimization study since 2013. This trend predicts a further increase in the exploration of optimization-based tower crane model selection.

6.3.2 Research opportunities

6.3.2.1 Advanced AI technologies for crane type selection

The benefits of AI-based crane type decision-making have been demonstrated by the development of neural network and expert system in the early studies. Deep learning and machine learning are two significant subsets of AI that have advanced the automation and precision of data analysis and decision-making. A standard neural network consists of many simple processors called neurons within a one-layer input and output system [73]. However, a deep learning-based neural network (i.e. deep neural network) can establish a multiple-layer structure. In doing so, the correct mathematical manipulation to turn input to output can be realized, whether the relationships are linear or non-linear [74]. Machine learning, on the other hand, has been extensively investigated for handling structured and unstructured big data, thus illustrating its efficiency and reliability. More machine learning techniques, such as decision trees, regression analysis, and Bayesian networks, can be employed to promote crane type selection.

6.3.2.2 Simulation of tower crane model selection

While simulation has been attempted to model the tower crane layout and operation [75,76], little research has been conducted by taking the tower crane selection into account. For tower crane planning problems, a predetermined crane model is often implemented. This is because including one more datum (i.e. crane type) results in an exponential increase in the overall computing load for crane planning problems. Yet, the crane type considerably influences the overall crane planning performance including lifting ability, lifting speed, and lifting cost. Therefore, it is essential to consider the selection of tower crane model in the integrated crane planning problem in the future.

Furthermore, the internal features of the crane models can be simulated as well. Take the machine breakdown percentage as an example, simulation approaches can model the potential productivity and economic losses due to such breakdowns in different scenarios.

6.3.2.3 A hybrid method for crane selection

Each methodology for crane selection has its limitations and advantages. Adopting a hybrid method, which refers to a combination of several methods, can overcome the drawbacks of using a single approach. For instance, optimization is suitable for finding the optimal solution but inappropriate to describe the details of the possible issues in a specific case. This drawback can be overcome through simulation.

A good practice in combining methods might be conducting the approaches in stages. For example, using an AHP evaluation model to determine the appropriate crane type and then a genetic algorithm may be applied to find the preferred crane model [32]. The stage-by-stage hybrid thinking is also appropriate for predicting and examining the crane performance using simulation. Despite the impracticality to simulate all crane models before the final decision, simulations for a small number of feasible cranes, generated by other methods, such as manual calculation or optimization, are practical and reasonable. This achieves the delicate balance between the computing resources and the performance of the final outputs.

6.3.2.4 Selection considerations should extend to a larger temporal, spatial and functional scope

As mentioned before, crane selection is a dynamic problem that interacts with other factors. From the perspective of the temporal dimension, the influence of the final crane option is continuous throughout the whole construction phase. It is, therefore, suggested to assess the overall performance (e.g. throughout the construction period) of the cranes during the selection process. Regarding the spatial aspect, crane operations have an influence on the surroundings, for example, noise, dust, and carbon emission. Soft considerations have been proposed in the existing literature but should be further investigated [38]. A third consideration is from the functional perspective, which stands for the unexpected factors that influence the performance of the crane option. The majority of the studies have selected cranes as per the significant cost and time objectives. However, unpredicted risks are also vital. For example, rainy weather may result in the loss of mobility of a mobile crane and an older crane tends to encounter failure during operations. Taking into accounting these nondeterministic and probabilistic situations would better reflect reality, enhance the resilience of the crane selection decision-making, and alleviate economic loss from the potential risks.

7. CONCLUSIONS

This research provided deep insights in characterizing and analyzing crane selection studies via a system boundary model. Three kinds of analyses, namely distribution, relationship, and systematic analyses, were deployed. Firstly, distribution analysis revealed an increasing trend and worldwide popularity of crane selection research. “Journal of Construction Engineering and Management”, “Automation in Construction” and “Construction Management and Economics” were the preferred journals for publishing crane selection studies. Secondly, relationship analysis indicated a strong correlation between building height and crane type determination via a binary logistic regression model. Thirdly, systematic analysis identified 19 constraints, 71 criteria, and 8 methods for crane selection. The 19 constraints were grouped into environmental, technical, and economic clusters. The 5 most popular constraints with higher appearance frequency were project budget, lifting capacity, site coverage, lifting height, and clearance requirement. Regarding the selection criteria, the 71 data items were grouped into three categories, namely crane data, project data, and user considerations. Besides, the relationships between the crane selection constraint and criteria were revealed and visualized. This study used qualitative and quantitative categories to accommodate the identified 8 methods. Qualitative methods included interviews and case studies, while the quantitative methods comprised manual calculation, augmented reality, optimization, simulation, evaluation model, and artificial intelligence.

Afterward, three key concerns on crane selection research were discussed. Firstly, in light of the identified research types in six boundaries, corresponding best practice was analyzed and deduced. For crane type selection, AI and evaluation models were found to be the preferred practices. Optimization was considered as the best practice in selecting a tower crane model. The best mobile crane option could be evaluated by the simulation and/or optimization method. Secondly, the selection differences between tower and mobile cranes were analyzed. Three issues were emphasized i.e. evaluation focuses, ground condition considerations, and integrated factors. Lastly, four research opportunities were identified: advanced AI technologies for crane type selection, simulation for tower crane model selection, a hybrid method for crane selection and extending the selection considerations to a larger temporal, spatial and functional scope.

The contributions of this study are two-fold. From an academic perspective, a novel system boundary review method was proposed for characterizing and analyzing the features of crane selection research. To a certain extent, compared to personal judgment, this method provided an objectively systematic, thorough, and consistent means for investigating the status quo for any research topic. From a practical perspective, this study comprehensively unified and summarised all the crane selection constraints, criteria, and methods. The industry planners can simplify and expedite the crane selection process using the gathered crane selection factors (e.g. selection constraints, criteria, and methods) identified in this study. The formation of the factor pool also facilitates planners to scrutinize all the potential attributes and determine the appropriate ones, so as to guarantee the credibility of the crane selection process. The proposed best practices in different types of crane selection problems provide credible solutions in the decision making of crane selection. This will be a reliable reference for planners in developing their crane selection models.

Three future research directions were proposed. Firstly, researchers can put efforts on the identified four research opportunities, such as implementing advanced AI technologies to determine the crane type. Secondly, the crane selection problem can be further integrated with other crane planning progress as crane location and crane operation problems. The third is concerned with the developed methodology. Future research can also implement the proposed system boundary model to other research topics such as construction site layout problem.

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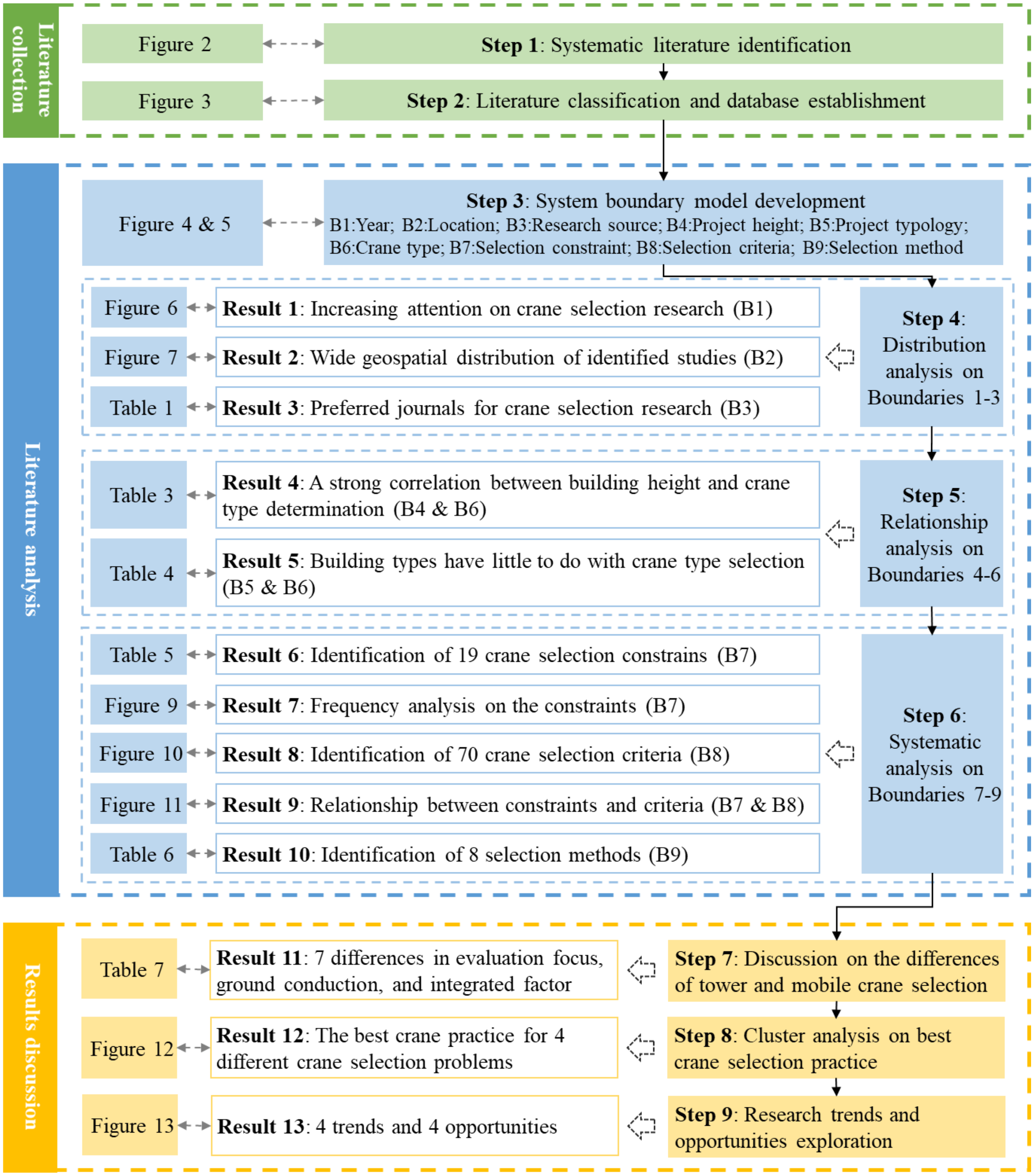


Figure 1 The overall review methodology

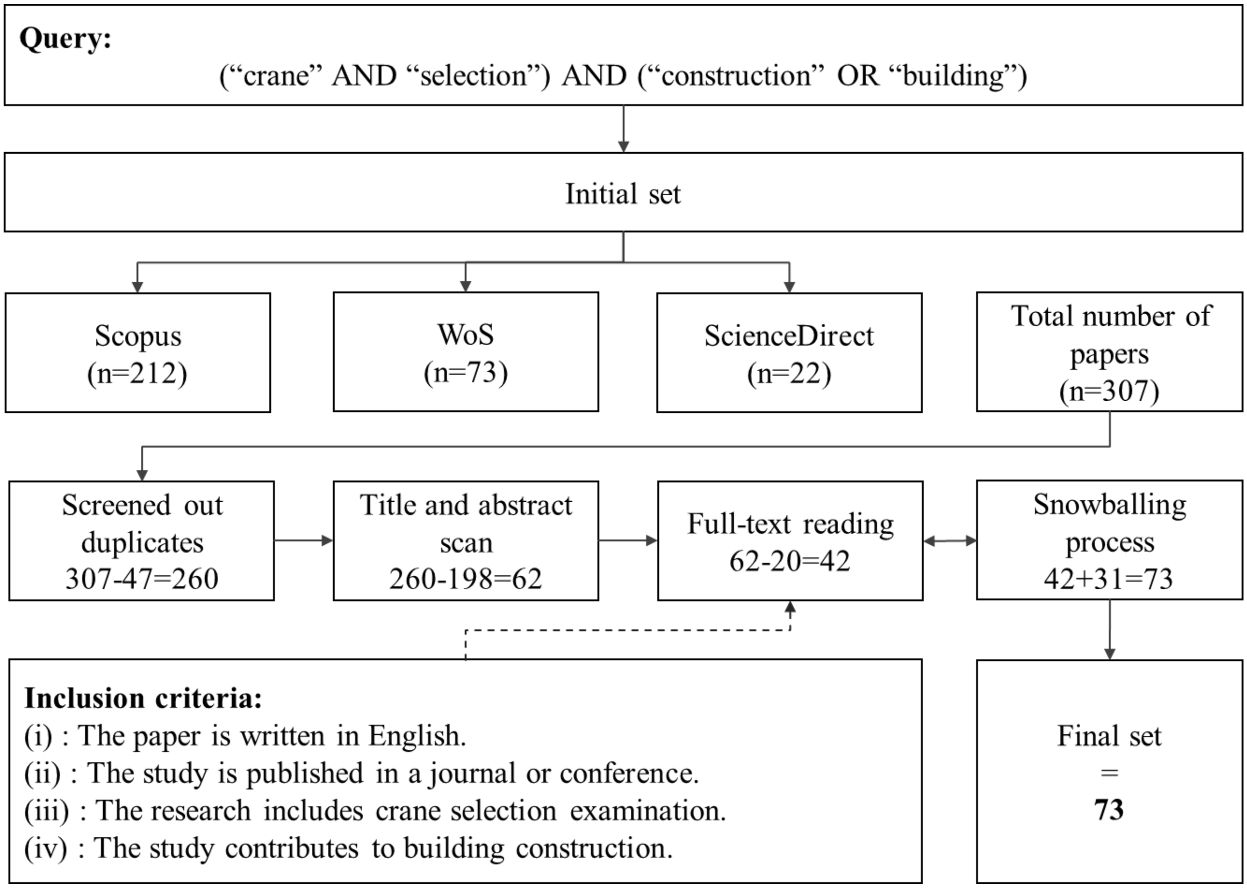
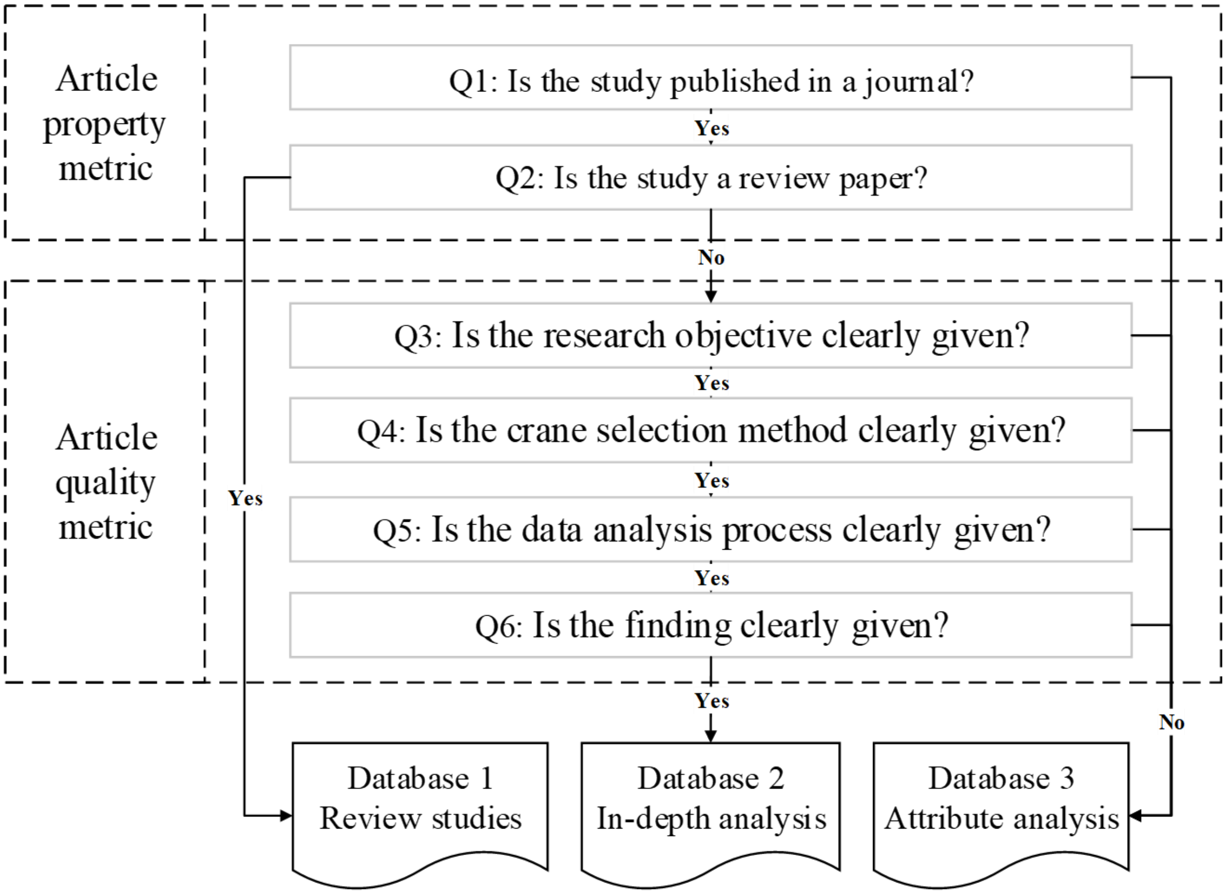


Figure 2 The flowchart of study selection, including search query and filtering process



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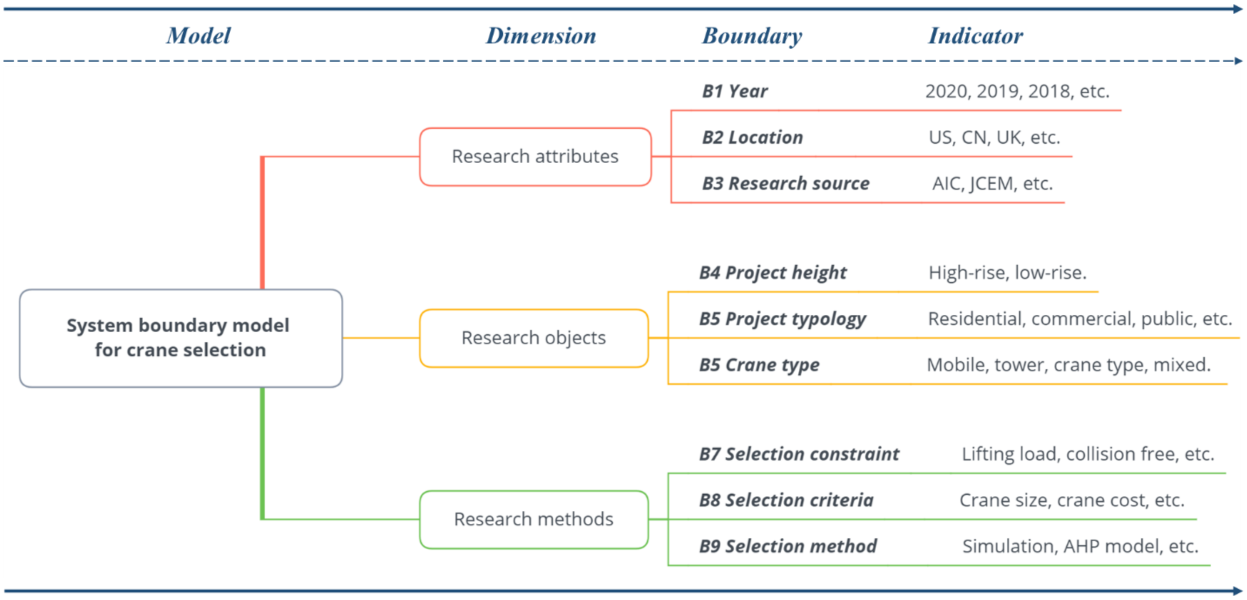

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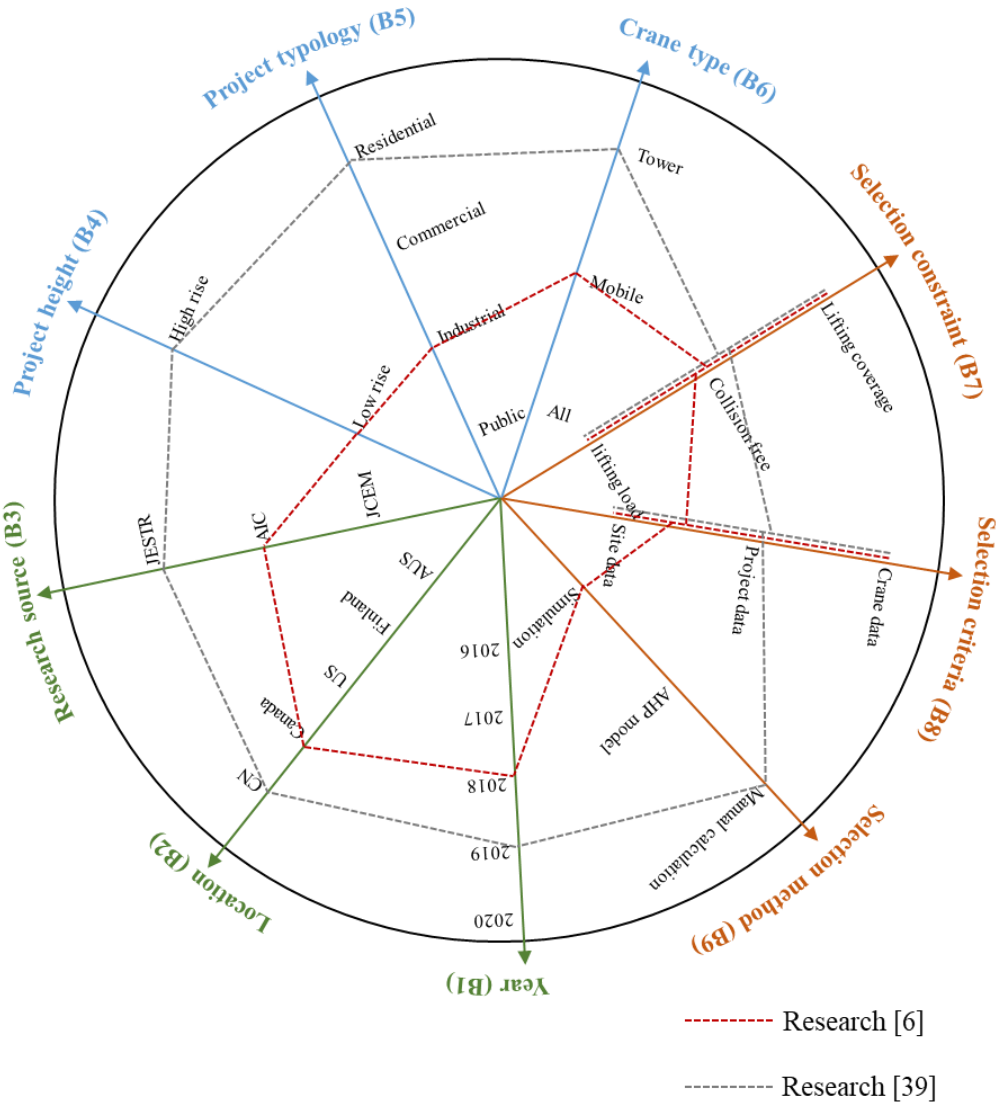

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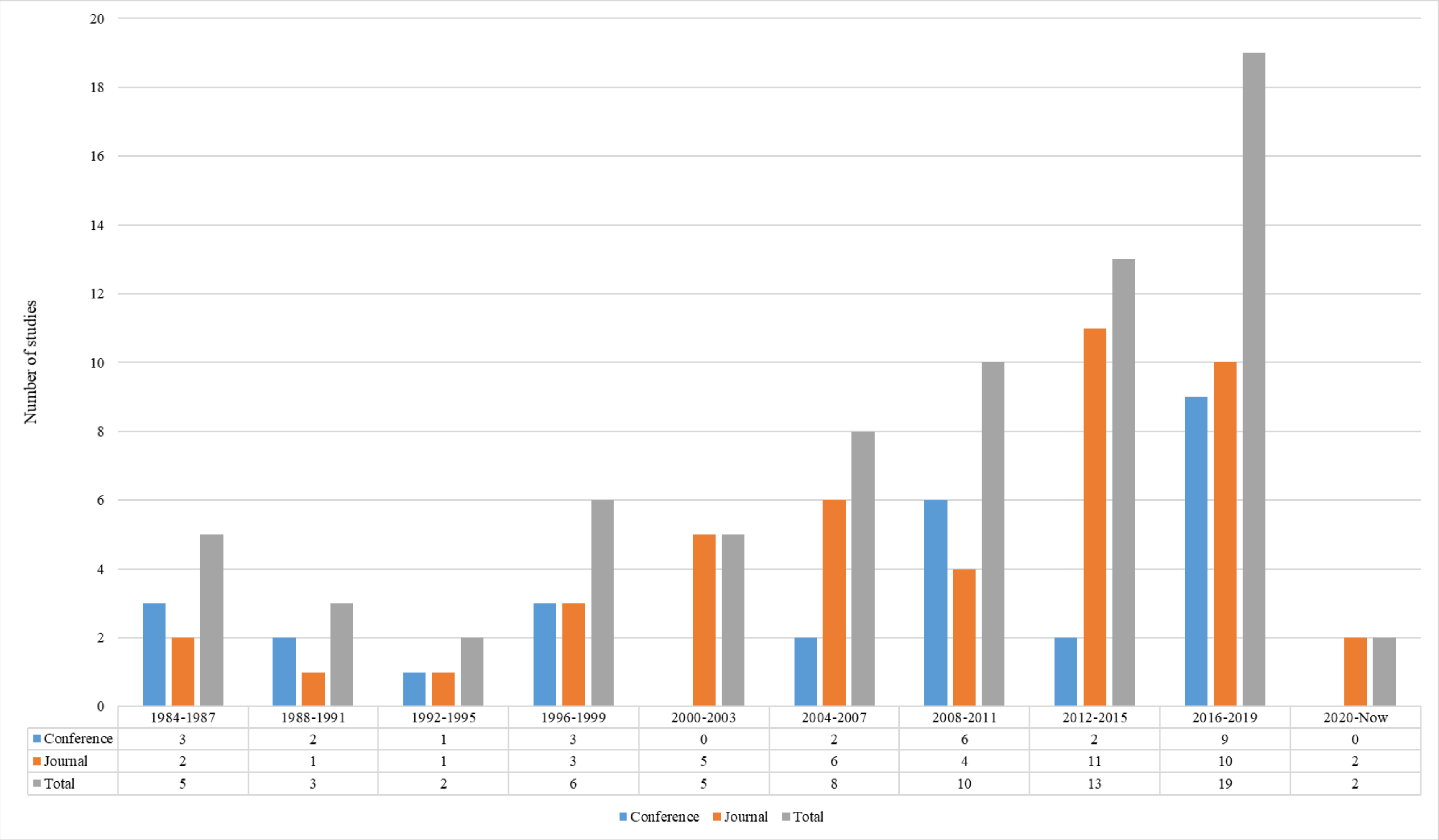

	1984-1987	1988-1991	1992-1995	1996-1999	2000-2003	2004-2007	2008-2011	2012-2015	2016-2019	2020-Now
Conference	3	2	1	3	0	2	6	2	9	0
Journal	2	1	1	3	5	6	4	11	10	2
Total	5	3	2	6	5	8	10	13	19	2

Figure 6 Publications’ trend on crane selection for building construction

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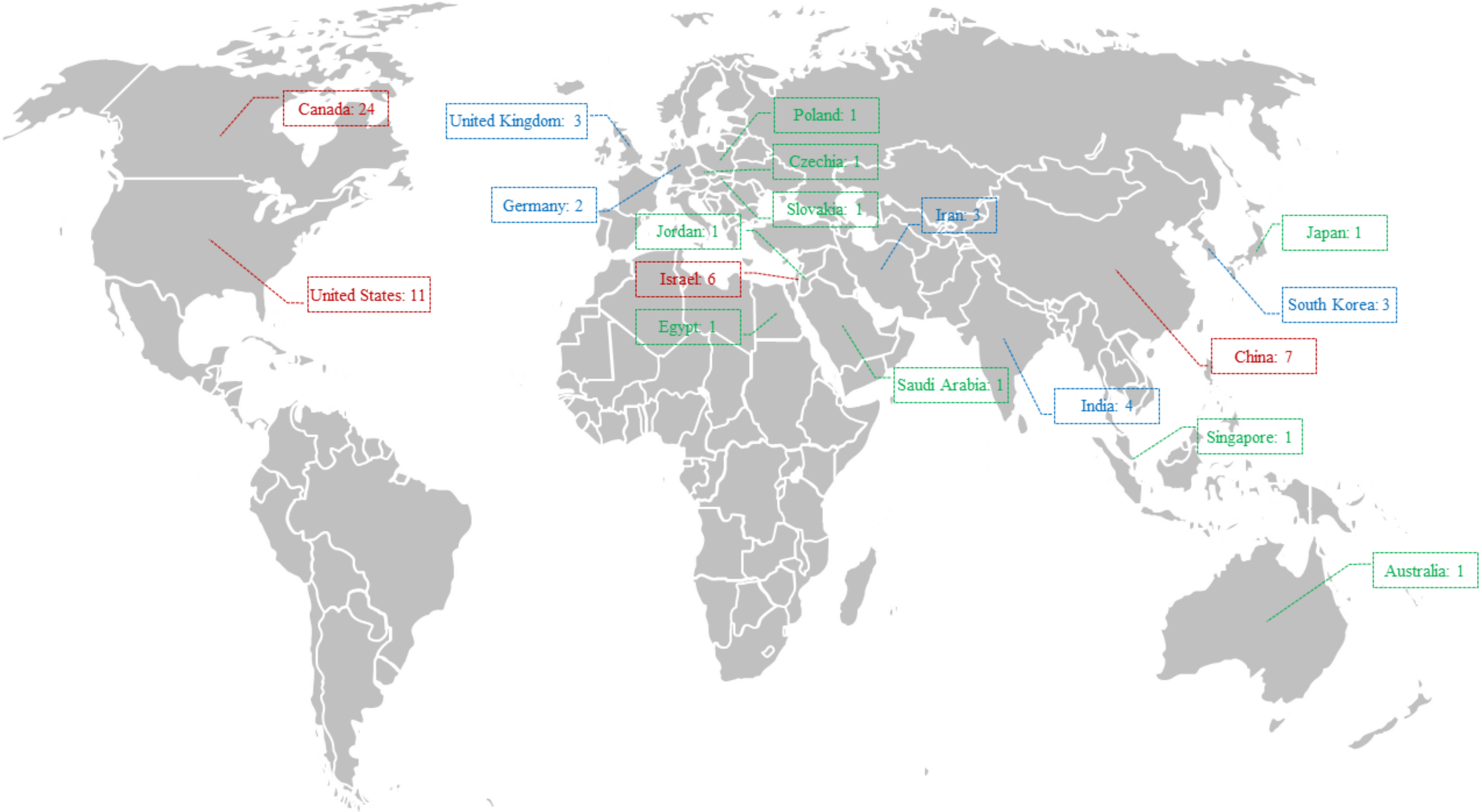

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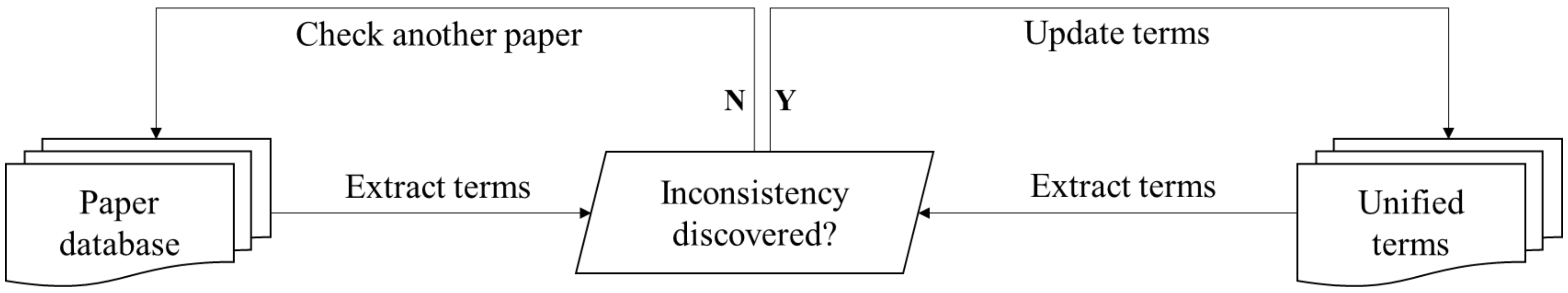
949 Figure 7 Geospatial distribution of crane selection research



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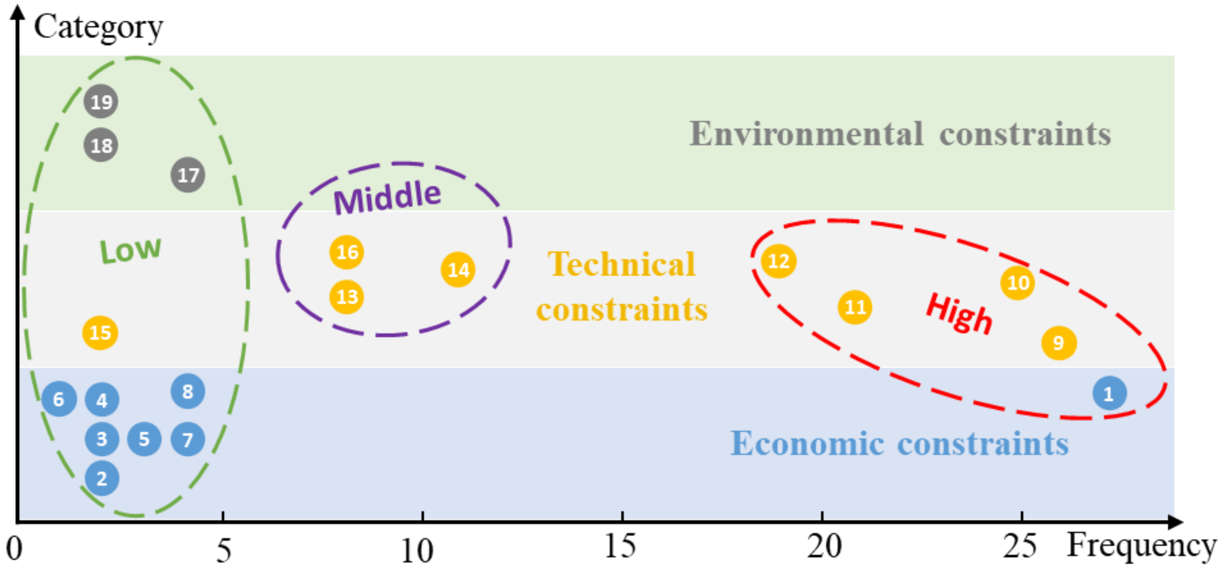

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953 Figure 9 The quantitative grouping results of crane selection constraints

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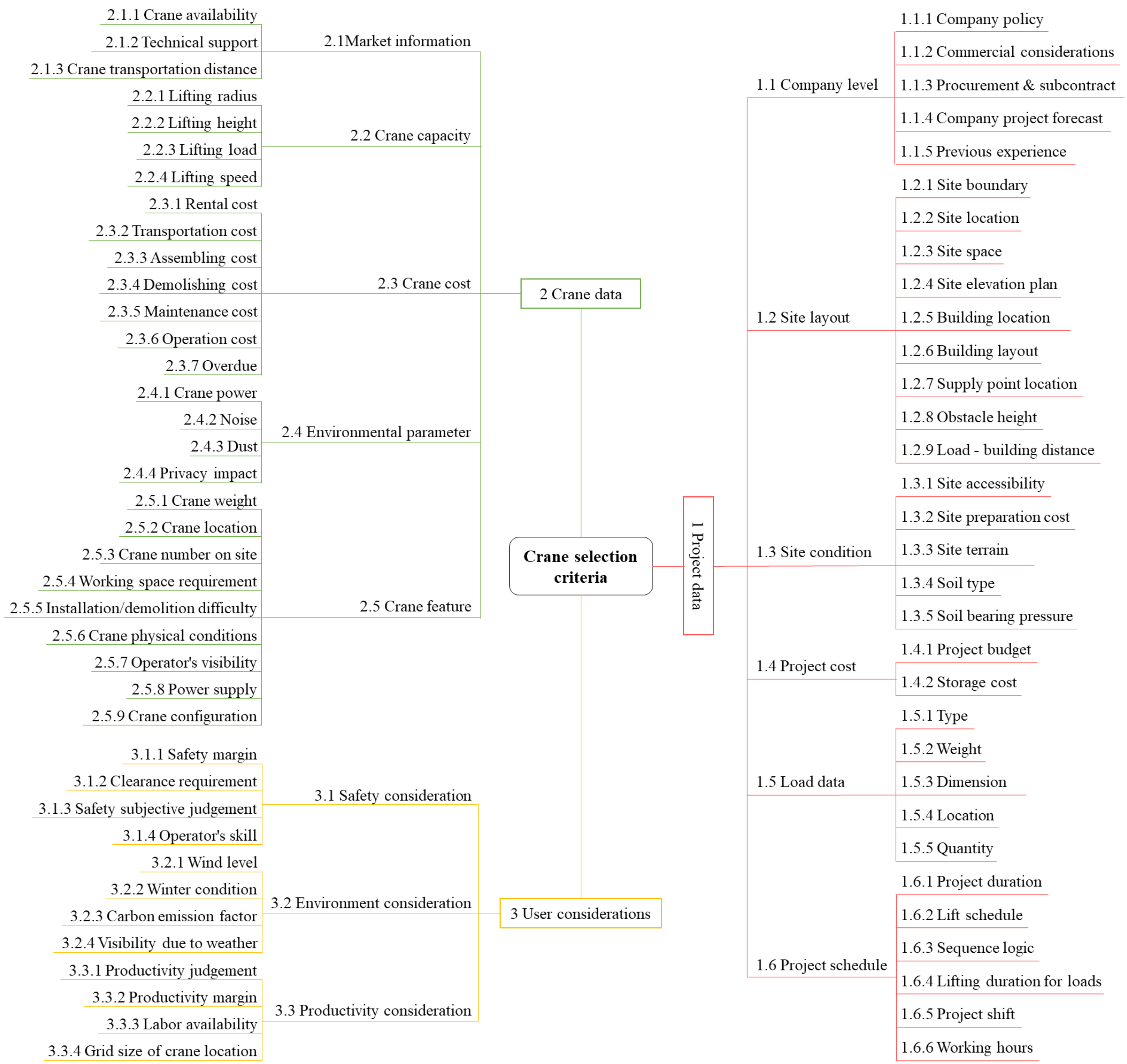

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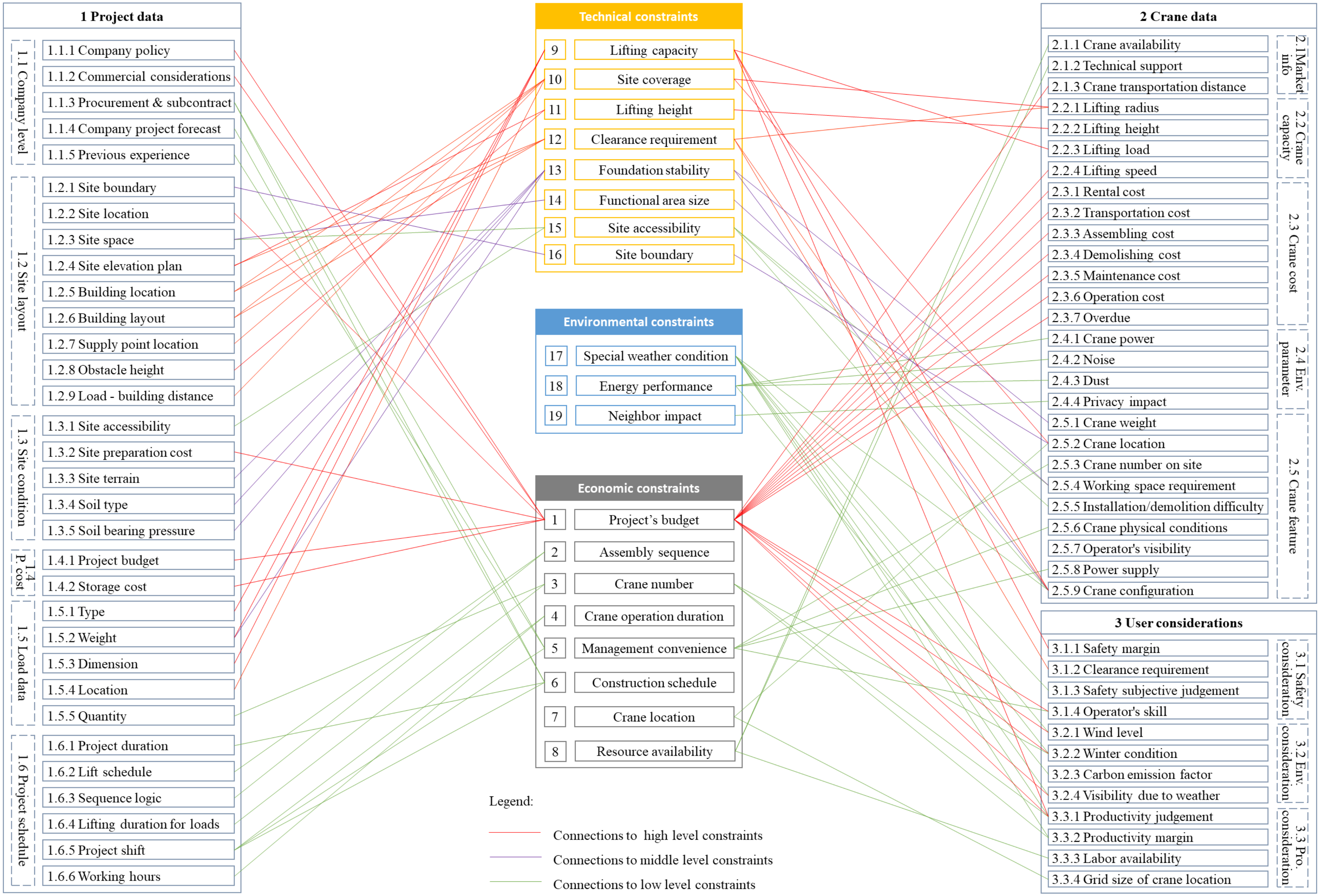

Figure 11 Relationships between crane selection constraints and criteria

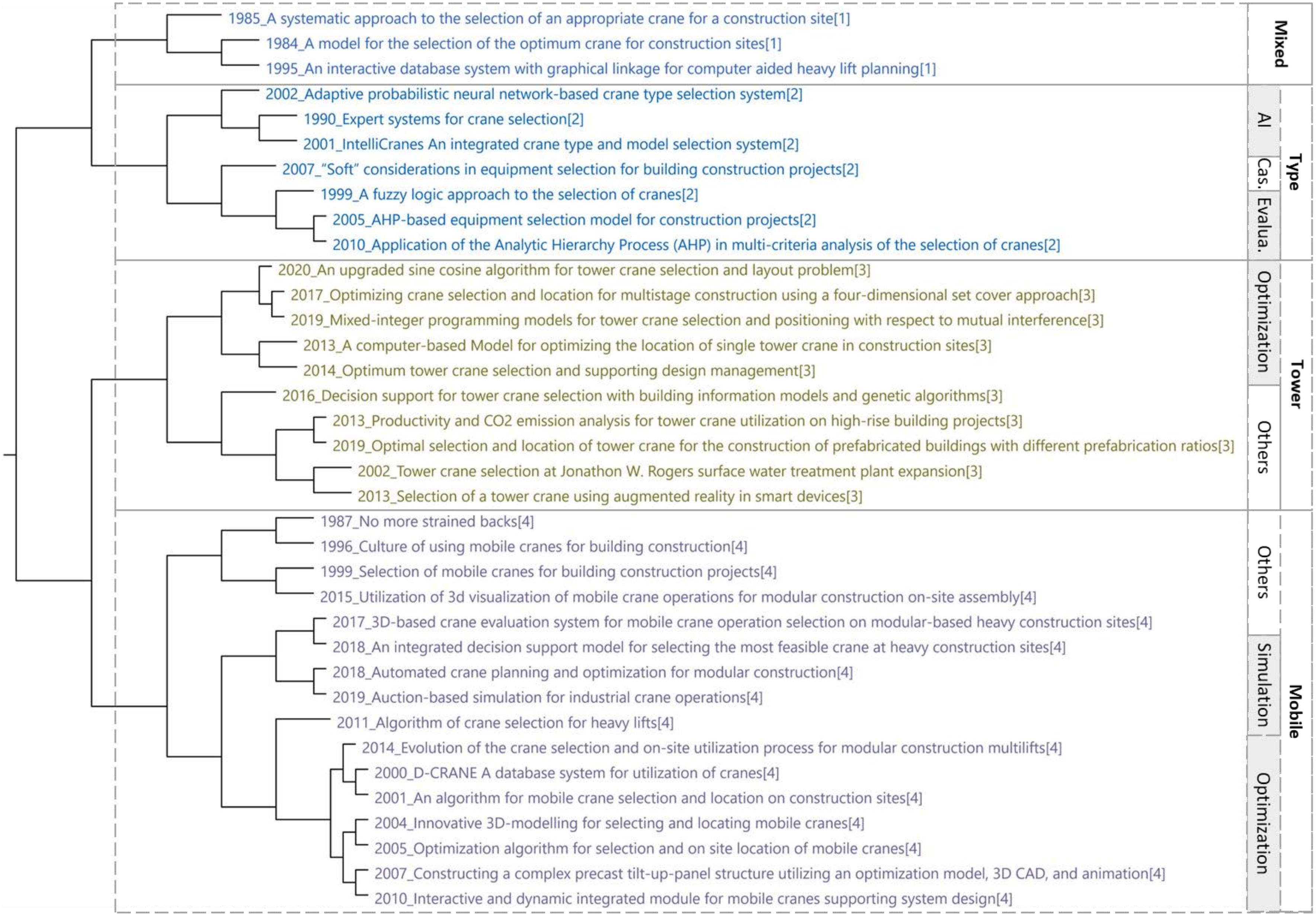

Figure 12 Cluster analysis to explore the best selection method for crane selection problem (*cas. = case studies; evalua. = evaluation methods)

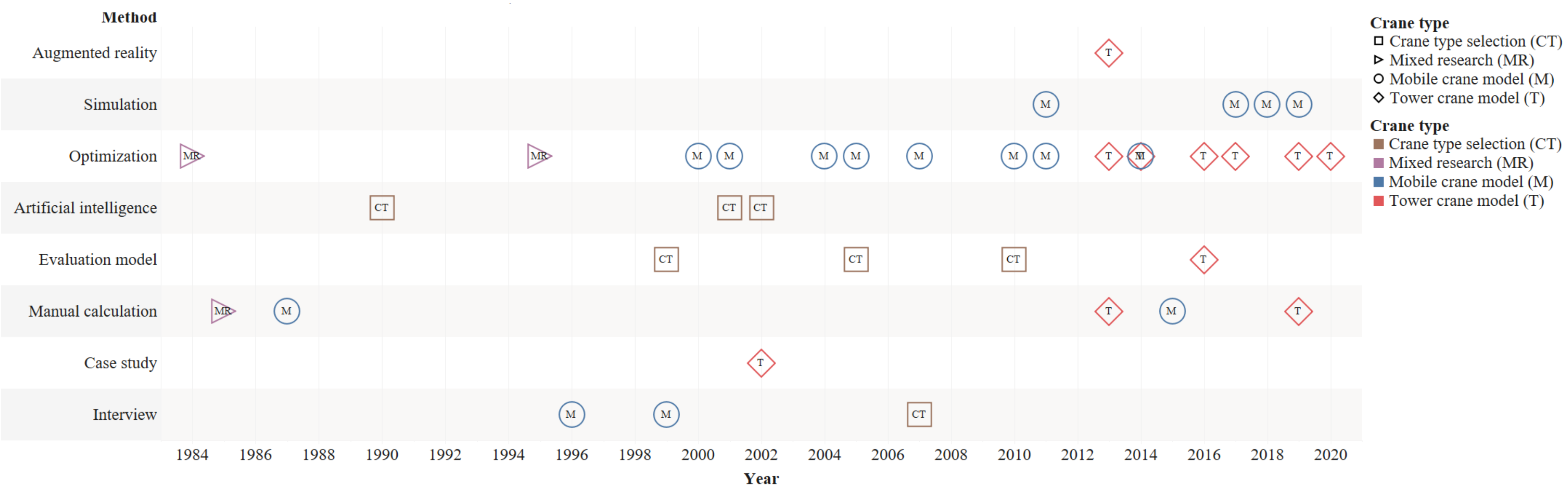

Figure 13 Temporal distribution of crane selection research

List of Tables

Table 1 Distribution of research sources

Name of research sources	Number of articles
Journal of Construction Engineering and Management	8
Automation in Construction	7
Construction Management and Economics	5
Advanced Materials Research	1
Buildings	1
Canadian Journal of Civil Engineering	1
Civil Engineering	1
Construction Innovation	1
Engineering, Construction and Architectural Management	1
European Journal of Operational Research	1
International Journal of Advanced Robotic Systems	1
International Journal of Civil, Structural, Construction and Architectural Engineering	1
International Journal of Engineering Management and Economics	1
International Review of Applied Sciences and Engineering	1
Jordan Journal of Mechanical & Industrial Engineering	1
Journal of Computing in Civil Engineering	1
Journal of Engineering Science and Technology Review	1
Journal of Image Processing & Pattern Recognition Progress	1
Journal of Management in Engineering	1
Journal of Structural Engineering (Madras)	1
Omega (United Kingdom)	1
Periodica Polytechnica Civil Engineering	1
Practice Periodical on Structural Design and Construction	1
Conference	33

Table 2 Research objects information (B4-B6) of identified cases in Database 2

ID	**Project height B4**	**Project type B5**	**Crane type B6**	**Ref.**		**ID**	**Project height B4**	**Project type B5**	**Crane type B6**	**Ref.**
1	Low	Industrial	Mobile	[37]		14	High	Commercial	Tower	[38]
2	High	Residential	Tower	[39]		15	High	Commercial	Tower	[38]
3	Low	Industrial	Mobile	[6]		16	High	Commercial	Tower	[38]
4	Low	Industrial	Mobile	[40]		17	High	Commercial	Tower	[38]
5	Low	Industrial	Mobile	[40]		18	Low	Residential	Mobile	[41]
6	Low	Industrial	Mobile	[42]		19	Low	Industrial	Mobile	[43]
7	Low	Commercial	Tower	[32]		20	Low	Public	Mobile	[44]
8	Low	Residential	Mobile	[45]		21	Low	Commercial	Tower	[33]
9	High	Residential	Tower	[46]		22	Low	Industrial	Tower	[47]
10	High	Industrial	Mobile	[48]		23	Low	Industrial	Mobile	[20]
11	Low	Industrial	Mobile	[49]		24	High	Industrial	Mobile	[7]
12	High	Commercial	Tower	[38]		25	Low	Public	Tower	[5]
13	High	Commercial	Tower	[38]						

Table 3 SPSS analysis of the relationship between B4 and B6

Variables	B	S.E.	Wald	df	Sig.	Exp(B)	95% C.I.for EXP(B)	
							Lower	Upper
Height_B4(1)	2.398	.983	5.953	1	.015	11.000	1.603	75.502
Constant	-1.012	.584	3.002	1	.083	.364		

Table 4 SPSS analysis of the relationship between B5 and B6

Variables	B	S.E.	Wald	df	Sig.	Exp(B)	95% C.I.for EXP(B)	
							Lower	Upper
Building_B5			3.001	3	.391			
Building_B5(1)	21.203	14210.361	.000	1	.999	1615474842.851	.000	.
Building_B5(2)	-2.303	1.449	2.525	1	.112	.100	.006	1.712
Building_B5(3)	.000	1.732	.000	1	1.000	1.000	.034	29.807
Constant	.000	1.000	.000	1	1.000	1.000		

Table 5 A list of constraints for crane selection in existing studies

Categories	**ID**	**Constraints**	**Specifications**	**Sources**	**Number of Sources**
Economic constraints	1	Project's budget constraint	The determined crane type should be within the allocated budget and should contribute to an economic crane plan.	[1] [2] [17] [5] [6] [7] [20] [32] [37] [38] [40] [41] [43] [44] [47] [48] [54] [55] [56] [57] [58] [59] [60] [61] [3] [62] [63]	27
	2	Assembly sequence constraint	The lifting of loads and modules should be in order.	[37] [40]	2
	3	Crane number constraint	The determined crane number should have the capacity to handle the workloads throughout the project.	[55] [56]	2
	4	Crane operation duration constraint	There would be a maximum working duration of crane per day.	[46] [60]	2
	5	Crane management convenience constraint	The company should have knowledge, experience, and skills to manage and operate the selected crane.	[5] [38] [58]	3
	6	Construction schedule constraint	The selected crane should achieve the schedule requirements of project.	[38]	1
	7	Crane location constraint	Each potential location can accommodate at most one crane.	[55] [56] [58] [63]	4
	8	Resource availability constraint	The determined resources (e.g., crane and its operators) should be available in the market during construction.	[37] [40] [56] [58] [3]	5
Technical constraints	9	Lifting capacity constraint	The weight of the load/module should be less than the lifting capacity of the crane.	[1] [6] [7] [20] [32] [33] [37] [39] [40] [41] [42] [43] [44] [45] [46] [47] [48] [55] [56] [58] [60] [3] [63] [64] [65] [66]	26
	10	Site coverage constraint	The crane layout can reach every demand points.	[1] [6] [7] [20] [32] [33] [37] [39] [40] [41] [43] [44] [45] [46] [47]	25

				[48] [55] [56] [58] [60] [3] [63] [64] [65] [66]	
	11	Lifting height constraint	The feasible crane lifting height should be larger than the maximum project height.	[1] [6] [7] [33] [37] [40] [42] [44] [45] [46] [47] [48] [55] [56] [58] [60] [3] [63] [64] [65] [66]	21
	12	Clearance requirement constraint	A minimum clearance requirement should be met to avoid collisions during crane operations.	[1] [6] [7] [20] [33] [37] [40] [41] [42] [43] [44] [45] [48] [56] [58] [63] [64] [65] [66]	19
	13	Foundation stability constraint	The ground pressure should be calculated to guarantee safety and stability of crane from its installation to operation. The slope condition should be also checked.	[33] [45] [48] [56] [58] [3] [65] [66]	8
	14	Functional area size constraint	There would be a minimum spatial requirement for performing some activities (e.g., crane installation and demolishing).	[20] [32] [33] [37] [40] [41] [43] [44] [56] [63] [64]	11
	15	Site accessibility constraint	The selected crane could access the assigned areas and locations.	[33] [65]	2
	16	Site boundary constraint	The crane locations should be always within the site.	[1] [6] [40] [42] [46] [55] [56] [65]	8
Environmental constraints	17	Special weather condition constraint	The selected crane should consider the influence of special weather conditions such as winter season, wind, and fog.	[6] [38] [47] [66]	4
	18	Energy performance constraint	The crane with less energy consumption should be appreciated.	[6] [60]	2
	19	Neighbor impact constraint	The selected crane should have acceptable/minimal impact (e.g., dust, noise, privacy) on its surrounding environment.	[6] [38]	2

Table 6 Selection methods adopted in existing studies

Category	**Methods**		**Sources**
Qualitative techniques	Interview		[4] [38] [54]
	Case study		[47]
Quantitative techniques	Optimization	Problem-specific heuristic	[7] [20] [41] [43] [44] [48] [58] [61] [3] [64]
		Metaheuristics	[32] [46]
		Mathematical methods	[1] [55] [63]
	Simulation	3D simulation	[6] [42] [48]
		4D simulation	[37] [40]
	Evaluation model	AHP model	[2] [32] [59]
		Fuzzy theory	[5]
	Artificial intelligence	Artificial neural networks	[33] [65]
		Expert system	[57] [65]
	Manual calculation		[39] [45] [56] [60] [66]
	Augmented reality		[67]

Table 7 Selection difference between tower and mobile cranes

Different items		**Tower cranes**	**Mobile cranes**
Evaluation focuses	Lifting capacity	Easy to consider the constraint	Complicated to consider
	Lifting coverage	Easy to consider	N/A
	Clearance requirement	Easy to consider	Complicated to consider
Ground condition Considerations	Ground space	Needs adequate operation space	Needs adequate move and operation space
	Ground bearing capacity	Can operate where ground conditions are poor	Requires good ground conditions
	Ground slope	Feasible on steep slopes	Feasible on slight slopes
Integrated factors	Crane location	Being integrated	Being integrated
	Crane operation	N/A	Being integrated