A FRAMEWORK FOR CRANE SELECTION IN LARGE-SCALE INDUSTRIAL CONSTRUCTION PROJECTS

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ABSTRACT

Selecting the best possible cranes and identifying spatial conflict-free locations on sites can result in productivity and safety improvements for large-scale industrial construction projects. In the current practice, experienced lift engineers select cranes based on the heaviest lift and/or the largest lifting radius of the identified crane. This practice is relatively time-consuming, and optimization of the crane's use and location is also difficult. There are many factors which need to be considered during the crane selection process, a reality which further complicates the process. This paper presents a framework which aims at developing a decision support system to enhance the crane selection process and collision-free path planning for large-scale construction projects. This paper utilizes an innovative crane selection matrix in order to establish a process for optimized crane selection for construction projects. The study considers more than 40 different factors in order to reduce time and improve safety for crane operations. Following finalization of crane type (mobile crane versus tower crane), a visualization model to simulate crane operation and identify collision-free crane operation paths is proposed. This process can assist project managers to plan the lifting process more effectively and efficiently. A case study-based approach was utilized to demonstrate the proposed methodology. The methodology was tested in the planning and construction process for boiler house structures in Mannheim, Germany. The project entailed numerous challenges: one of the major tasks was to lift a 102-ton load on the top of the boiler structure through crane collaboration; space limitations on site also presented several challenges related to crane selection, location, and operation processes. Based on the project constraints, the proposed crane selection framework, and the visualization models, two tower cranes were selected and successfully implemented in the case study.

KEYWORDS

Optimum crane selection, Crane selection matrix, Visualization, Heavy structure

INTRODUCTION

In industrial construction projects, the utilization of cranes often relates to the project budget and scheduling control. Inappropriate planning of crane operations can lead to cost overruns and schedule delays. In particular, the selection of crane types and locations plays a crucial role in the entire crane lift planning. To this end, analysis results are usually generated at the beginning stage of the project which will consequently have an impact on the entire construction process. In order to determine the suitable crane type and reasonable positions, many factors are taken into consideration, such that the analysis is conducted considering the heaviest lift or the largest lifting radius as the priority in the analysis. A fuzzy logic approach has been proposed by Hanna and Lotfallah (1999) to select the best crane type. Two types of factors, dynamic and static, are considered in order to select the crane type among mobile, tower, and derrick cranes. An algorithm has been proposed by Al-Hussein, Alkass, and Moselhi (2001) for selecting and locating mobile cranes on construction sites with the most suitable crane configurations and corresponding lift settings. Sawhney and Mund (2002) presented the features of a prototype crane selection tool, so-called IntelliCranes. The presented system considered three types of crane types and several crane-selecting parameters (such as type of crane use, duration, construction height, etc.). However, it did not check for potential collisions of the selected crane with its surrounding environment, which implies that the selected crane may not have feasible lifting paths in practice. Wu, Lin, Wang, Wang, and Gao (2011) proposed an algorithm for selecting mobile cranes, considering the lifting capacity and the geometry of the

crane, among other factors. Although incorporated with the 3D visualization model, the proposed system is limited to the selection of mobile crane types, and cannot be applied more generally for other types of cranes. An optimization model has been proposed for selecting the tower crane and material supply locations for high-rise building sites using mixed-integer linear programming (Huang, Wong, & Tam, 2011). Other crane and location selection-related works include Kang and Miranda (2006); Safouhi, Mouattamid, Hermann, and Hendi (2011); and Olearczyk, Al-Hussein, Bouferguène, and Telyas (2012). Meanwhile, apart from the crane type and location selections, practitioners have been developing useful tools or algorithms to assist with crane lift planning from other perspectives: crane path planning (Sivakumar, Varghese, & Babu, 2003; Chang, Hung, & Kang, 2012; Lei, Taghaddos, Hermann, & Al-Hussein, 2013); crane lift sequencing (Hermann, Hendi, Olearczyk, & Al-Hussein, 2010; Taghaddos, AbouRizk, Mohamed, & Hermann, 2012); and the environmental impact of on-site crane operations (Hasan, Bouferguène, Al-Hussein, Gillis, & Telyas, 2013). In this paper, a newly developed decision support system is proposed for crane selection and collision-free path planning for industrial construction projects. The crane selection is based on an innovative crane selection matrix that accounts for more than 40 factors concerning construction efficiency and safety. Both mobile cranes and tower cranes are taken into account in analyzing the best crane selection option, based upon which a visualization model is utilized to simulate crane operations and plan feasible lift paths. The proposed methodology has been tested and validated through implementation in a boiler house structure located in Mannheim, Germany, which features congested operational space and massive loads. Figure 1 presents the proposed methodology, which consists of two main components: (1) crane selection; and (2) collision-free path planning. The inputs include: (1) crane selection categories, factors, and sub-factors; (2) questionnaire feedback to determine the weighting of the categories and factors; (3) crane information, such as crane type and capacity; and (4) site obstructions which are used to develop the 3D visualization. The methodology is also subject to the following criteria: (1) available crane type; (2) site information such as space limited, location and accessibility; (3) weather conditions; and (4) the neighbourhood surrounding the construction site.
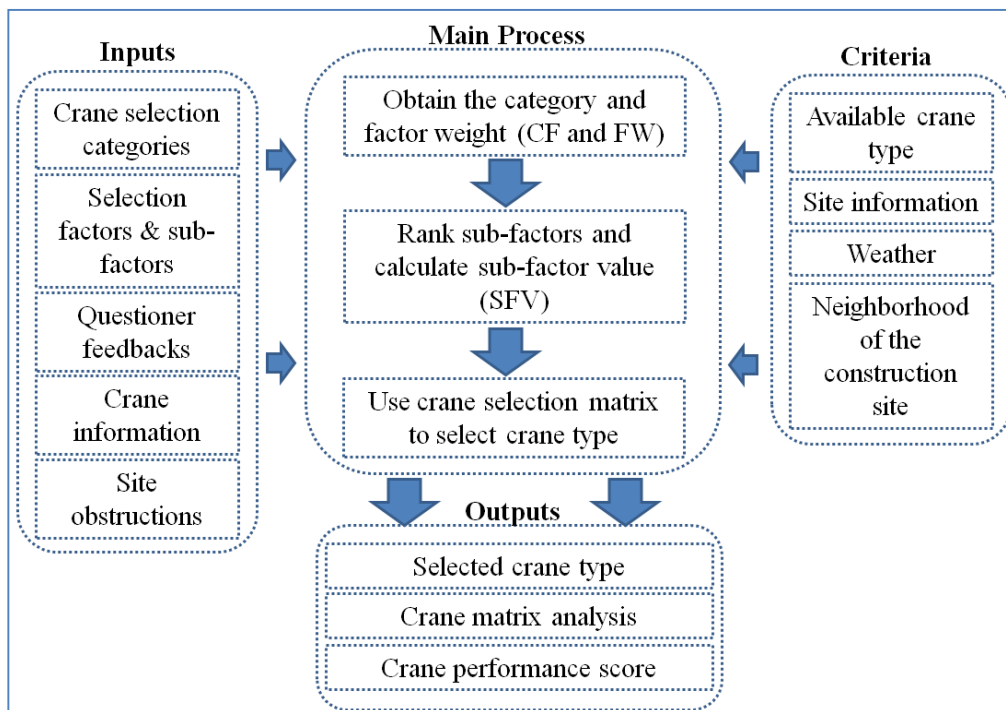

Figure 1 – Proposed methodology

FACTOR SELECTION AND RANKING

In industrial projects, selecting a suitable crane is an important task in the initial stages of construction project planning since it has a major impact on project cost and scheduling related to project productivity. Previous research has been conducted regarding crane selection based on such critical factors as the crane capacity and project type. However, previous studies have not taken into account an exhaustive list of factors affecting crane selection but decide it based on the lifting engineer's experience. In this paper, a comprehensive list of factors is provided, based upon which a decision support matrix is used to select the optimal crane type which is a mobile crane versus tower crane. The matrix considers three main categories: (1) equipment and cost; (2) location and site; and (3) environmental impact. The "equipment and cost category" has to do primarily with the cost aspect of crane utilization, such as rental and installation expenses; the "location and site category" considers weather conditions, crane availability, spatial constraints, etc.; and the "environmental impact category" targets the energy consumption and pollution generated by the selected crane type. Various factors and sub-factors are considered for each category; (note that due to space limitations, not all sub-factors are listed in Table 1).

Table 1 – Categories and factors

Main Categories	Factors
Equipment and cost category	Cost (sub-factors: rental, transportation, installation expenses, etc.)
	Installation & Disassembly (sub-factors: time/difficulties in installation, etc.)
	Maintenance & Depreciations (sub-factors: average breakdown cycle, etc.)
	Additional Safety Features/Technology (sub-factors: operator's skill, etc.)
Location and site category	Weather (sub-factors: sub-factors: daily wind conditions, etc.)
	Availability (sub-factors: crane availability, etc.)
	Space (space requirement for installation, etc.)
	Support System (sub-factors: depreciation of support system, etc.)
	Transportation (sub-factors: transportation of the crane, etc.)
Environmental impact category	Energy (sub-factors: type of crane power, etc.)
	Health (sub-factors: Noise & dust)
	CO_2 emission (sub-factors: CO_2 emission at operation, etc.)
	Neighbor impact (sub-factor: privacy)

Both the categories and the factors are ranked based on questionnaire feedback. Figure 2 gives an example of category and factor ranking, while the percentages in Figure 2 indicate the importance of each category or factor for the given project. Each sub-factor is ranked by the project managers or engineers for each crane type being analyzed, according to four levels: (1) best option (weight=5); (2) good option (weight=4); (3) acceptable (weight=2.5); (4) somehow satisfy (weight=1); and (5) not satisfy (weight =0). Each level describes how suitable the analyzing crane type is for the project for that particular sub-factor. An example of sub-factor ranking is provided in Figure 3 for one specific crane. Based on the weights and ranking, the crane types are entered into the decision support matrix for selection analysis, which will be introduced in the following section.

Figure 2 – Questionnaires for category and factor ranking

Crane Ranking

Project Type: Boiler Structure, Germany
Location: Mannheim
Heaviest Load: 102 ton

Crane Type: Rough Terrain Cranes
Model No: LTM 1100 4.1
Capacity: 120 Ton

Categories	Factors	Not Satisfy	Some how Satisfy	Accept-able	Good Option	Best Option
	Cost					
	Rental expenses				0	
	Transportation expenses				0	
	Installation expenses				0	
	Disassembly expenses				0	
	Expenses for support system				0	
	Crane operator wages				0	
	Installation & Disassembly					
	Time / difficulties in installation				0	
	Time / difficulties in disassembly				0	
	Difficulties in changing configuration			0		
Equipment and Cost	**Maintenance & Depreciations**					
	Average breakdown cycle			0		
	Average repair time			0		
	Backup power system		0			
	Availability of Parts				0	
	Complexity in maintenance				0	
	Maintenance for ____ (old)				0	
					0	

Figure 3 – Sub-factor ranking

CRANE SELECTION MATRIX MECHANISM

The crane selection matrix mechanisms calculate the sub-factor values for each type of crane type, and then calculate total scores for each crane type which are used to select the best crane. The relationship between sub-factors and crane type, and the count numbers for each sub-factor, are given in Equations (1) and (2), respectively. The Sub-Factor Value (SFV) is calculated satisfying Equation (3). After all the SFVs are calculated, the Crane Evaluation Score (CES) is calculated for each crane based on all the sub-factors, the Category Weight (CW), and the Factor Weight (FW), satisfying Equation (4). A screenshot from MS Excel is provided to illustrate CES calculation (Figure 4).

$$M_{SFV} = \begin{bmatrix} SFV_1^1 & \cdots & SFV_1^j \\ \vdots & \ddots & \vdots \\ SFV_i^1 & \cdots & SFV_i^j \end{bmatrix} \tag{1}$$

$$M_{CNV} = \begin{bmatrix} CN_1^1 & \cdots & CN_1^4 \\ \vdots & \ddots & \vdots \\ CN_i^1 & \cdots & CN_i^4 \end{bmatrix} \tag{2}$$

$$SFV_i^j = \frac{\sum(CN_i^z \times CNW_i^z)}{5 \times \sum CN_i^z \ (i=1 \ to \ number \ of \ sub-factor \ under \ the \ same \ factor)} \tag{3}$$

$$CES_j = \sum(CW_x \times \sum(\frac{\sum_{i=1}^{l} SFV_i^j}{l} \times FW_y)) \tag{4}$$

Where: M_{SFV} =sub-factor value matrix; SFV_i^j is the sub-factor value for sub-factor i and crane type j; M_{CNV} is the count number value matrix; CN_i^z is the count number for sub-factor i and level z (four level: (1) best option; (2) good option; (3) acceptable; (4) somehow satisfy; and (5) not satisfy); CNW_i^z is the count number weight for sub-factor i and level z (weight for each level: (1) best option (weight=5); (2) good option (weight=4); (3) acceptable (weight=2.5); (4) somehow satisfy (weight=1); and (5) not satisfy (weight =0)); CES_j is the crane evaluation score for crane j; CW_x is the category weight for category x; FW_y is the factor weight for factor y and factor y has a total of l sub-factors.
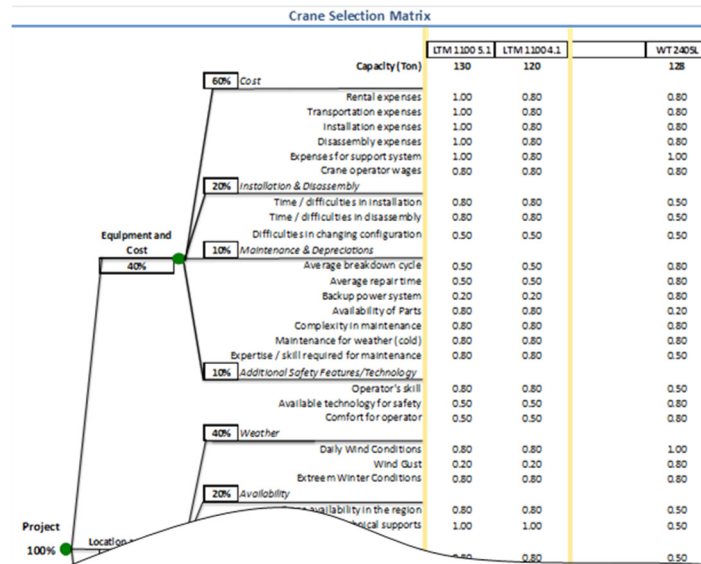
Figure 4 – Crane selection matrix

CASE STUDY

A case study-based approach has been utilized to demonstrate the proposed methodology. The methodology was tested in the planning and construction process for boiler house structures in Mannheim, Germany. The structures each consisted of five storeys (235 m x 290 m x 115 m) which each storey had a different structure and height. There were some constraints involved in crane selection: (1) the greatest weight to be installed on top of the boiler structure in a single load was 102 tons (front and back bridge structures); (2) there were some site space limitations for crane location since the structures were to be assembled on-site; (3) the selected crane needed a sufficient radius to load and install structures at their final positions on the boiler structures. The assembly and storage areas were located in front of the structures, as shown in Figure 5a.

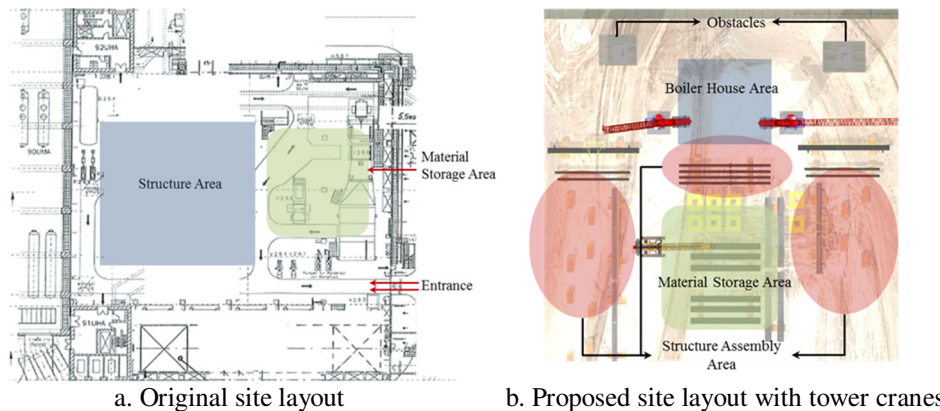a. Original site layout   b. Proposed site layout with tower cranes

Figure 5 – Site layout of boiler structures in Mannheim

According to the procedures outlined in the methodology and given the project information, the crane selection criteria were designed based on the nature of the case study. The most important factors in this case were: (1) installation and disassembly in the equipment section and (2) space requirements for installation and movement in the site section, since the construction site offered limited space for crane location and operation. Therefore, the limitations in terms of on-site utilization and the availability of crane and technical support were highly ranked factors. After evaluating the crane selection criteria, the crane

score was calculated to determine feasible cranes, which were a WT 2405L (128-ton) tower crane and an LTM 1100 (120-ton) mobile crane. The respective crane scores (Table 2) were 72% for the WT 2405L and 67% for the LTM 1100. The WT2405L was thus determined to be the best type for this certain project since it required less site space for crane location, installation, and disassembly than the mobile crane.

Table 2 – Feasible crane score

Crane Score				Crane Score		
Cost	0.867			Cost	0.800	
Installation & Disassembly	0.500			Installation & Disassembly	0.700	
Maintenance & Depreciations	0.800			Maintenance & Depreciations	0.629	
Safety	0.700			Safety	0.600	
Weather	0.867			Weather	0.800	
Availability	0.800			Availability	0.900	
Space	0.933	72%		Space	0.600	67%
Support System	0.650			Support System	0.800	
Transportation	0.800			Transportation	0.800	
Energy	0.700			Energy	0.425	
Health	1.000			Health	0.500	
CO2	0.600			CO2	0.400	
Neighboor	0.200			Neighboor	0.800	

A. WT 2405L   B. LTM 1100

The selected tower crane in this paper, WT 2405L, has the following specifications: (1) the capacity is 128 tons; (2) the maximum radius is 42 m and the minimum radius is 20 m; (3) the selected crane features a 42-m jib, which can move up and down to lift and/or load lifted objects, providing similar functionality to a mobile crane; (4) the counterweight moves up and down according to the jib movements; and (5) the maximum free-standing height is 75 m, with the standard tower elements on the foundation. Therefore, the tower crane requires two bracing structures for stable lifting operations, but at different respective heights. In this case, the left tower crane required the bracing structures to be at 45.125 m and 87.125 m, and the right tower crane required them to be at 48.325 m and 90.325 m.

Based on the selected tower crane and project information, the visualization was implemented to design the proposed site layout (Figure 5b) and crane operations in order to identify constraints and eliminate feasible errors to ensure high productivity. The middle, right, and left sides of the front site area served as the structure assembly area where the leg and bridge structures were assembled by two tower cranes; one mobile crane assisted in delivering components of structures into the maximum radius area of tower cranes. The material storage area was located in the middle between the left and right assembly areas in order to supply material easily. Two obstacles were also discovered when tower cranes were rotated to load and place structures in position, which particularly affected the back side of the structures. The towers were located 7.9 m from front-center of the structure and 7 m from the side-centers. The sequences of tower crane operations illustrated in Figure 6a can be outlined as follows: (1) tower cranes on the two sides assemble the respective bridge structures; (2) a mobile crane assembles the leg structures and delivers them to within the maximum radius of the tower cranes; (3) the tower cranes lift the leg structures and place them in their respective positions if they are ready to be placed, even though the bridge structure is not assembled yet; and (4) the bridge structures are installed if they are ready.

a. Crane operation from 1st to 5th floors

b. Crane collaboration
Figure 6 – The sequences of crane operations

Based on these sequences, the boiler structures were built from the 1st to the 5th floor. However, there were two challenges identified during the visualization. It was determined that a feasible collision between the crane and obstacles may occur when the cranes were carrying the bridge structures for the back, left, and right sides into position. To prevent these errors, either the crane should be rotated to the front side (where there is no obstacle) or the jib should be raised to provide sufficient clearance. As shown in Figure 6b, the other challenge was that two tower cranes were required to collaborate in order to lift and install front and back bridge structures, which were 102 tons, on to the top floor. In practice a major collision could have occurred at this stage in the assembly process, and this underscores the value of visualization as a proactive tool to assist crane operators in reducing operational errors. Based on these outputs from the proposed methodology, the use of two tower cranes was selected for a quick and safe assembly process, and was successfully implemented in practice as illustrated in Figure 7.

Figure 7- Crane operation in practice

CONCLUSIONS

In current practice, crane selection is carried out by lift engineers who draw on their experience to determine the heaviest lift and/or the largest lifting radius for identified cranes. This practice is relatively time-consuming, and optimization of the crane's use and location is also difficult. Therefore, a framework as a decision support system to select the best possible cranes and identify spatial conflict-free locations on site is necessary to facilitate productivity and safety improvements for large-scale industrial construction projects. There are many factors, such as environmental, site, and equipment factors, which need to be considered during the crane selection process, a reality which further complicates the process. This paper utilizes an innovative crane selection matrix with more than 40 factors in order to establish a process for optimized crane selection in large-scale industrial construction projects. A visualization model to simulate crane operations and identify collision-free crane operation paths is proposed to validate the crane selection. In the case study, the selected crane, WT2405L, was identified and the visualization was built to plan the lifting process effectively and efficiently by identifying and removing potential errors. The visualization entailed (1) lifting a 102-ton load onto the top of the boiler structure using two cranes in collaboration and (2) presenting on-site space limitations related to crane selection, location, and operation. Based on the

project constraints, the proposed crane selection framework, and the visualization models, two tower cranes were selected and successfully implemented in the case study.

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