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Decision Support for Mobile Crane Lifting Plan with Building Information Modelling (BIM)

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Abstract

Mobile cranes are one of the most commonly used equipment in construction, and an inappropriate choice of a mobile crane may cause a serious accident. The current practice relies on the engineers' experience in planning mobile crane operation, which is a tedious and potentially error-prone process. This paper makes use of recent developments in Building Information Modelling (BIM) to address the problem. It presents a comprehensive framework to model mobile crane safe lifting requirements from the 3D BIM model. Based on the requirements, it proposes a decision-support system for planning mobile crane operations. The result of this research facilitates engineers and a construction manager in construction site planning and improves construction site safety.

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Keywords: mobile crane lifting; code compliance; Building Informaton Modelling; decision support; application of BIM

1. Introduction

Mobile cranes have been extensively used as the heavy lifting equipment in construction industry in Singapore. It has also been identified as one of the key sources of incidents and accidents. According to the statistics from the Workplace Safety and Health Council Singapore [1], in 2014, 3 out of the 60 fatal incidents across different industries were related to crane lifting operation. In 2015, the number of crane related accident had risen to 5, which account for around 10% of the total number of fatal accidents across different industries. As Singapore is committed to work towards the vision of zero-accident in work place, it is imperative to improve the safety standard for crane operations. According to Ministry of Manpower of Singapore [2], lack of planning and supervision is one of the primary causes

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for crane-related accidents. As such, the Code of Practice on Safe Lifting Operations in Workplace [3] requires the contractor to establish a permit to work system for mobile crane lifting operation. In the permit to work system, the lifting engineer is required to complete a crane lifting plan form, which records the crane model, boom length and intended load for crane operations. The two main checks of the crane lifting plan are, firstly, the lifting capacity check and secondly, the lifting obstructions check. In current industrial practices, these checks are often carried out manually by the lifting engineers based on their experience. Thus, it is difficult for inexperienced engineers to complete these checks. Even for the more experienced engineers, checking the crane lifting plan for each lifting item is a tedious and potentially an error-prone process. Thus, despite the introduction of the crane lifting plan system, the workplace accidents related to crane lifting activities have not been drastically reduced.

The recent advances in Building Information Modelling (BIM) have provided new possibilities to address this problem. With the three dimensional BIM model, it is now possible to identify firstly, the crane position, loading point and unloading point in three-dimensional space and secondly, the spatial constraints in the lifting operation. With the identification of these key parameters, it is possible to automate the crane lifting plan, in particular the lifting capacity check and lifting obstruction check. This paper will start with a literature review on: the mobile crane lifting path planning; followed the use of Building Information Modelling (BIM) for code compliance check. This is followed by the framework for the proposed decision support system. A mobile crane information and parametric mobile crane lifting tasks are proposed and these are checked against the building information model for lifting constraints. The last part of this paper presents an outline for the decision support algorithm and a case study to illustrate the decision support system.

2. Literature Review

2.1. Mobile Crane Lifting Path Planning

Various scholars have studied the use of computer algorithms in mobile crane lifting path planning and checking safe lifting requirements. Tantisevi and Akinci [4] presented an approach for generating workspaces that encapsulates spaces occupied by mobile cranes moving during an operation and discussed an assessment of the effectiveness of the approach in identifying spatial conflicts between mobile cranes and building components. Zhang and Hammad [5] proposed a dynamic motion planning algorithm to ensure safety during the execution stage by quickly re-planning and avoiding collisions. Lin et al. [6] improved the bidirectional Rapidly exploring Random Trees (RRTs) using a sampling strategy and an expansion strategy to find an optimized path for crawler crane lifting. This algorithm has discretized the working space into different nodes. By checking that the nodes are within the safe working load of the crawler crane and is collision free with respect to the existing structure, this algorithm finds a safe lifting path for the lifting object.

The existing literature has formed a strong foundation for safe lifting path planning. However, for the collision check, the existing research tends to focus on the collision between the lifting object and the existing building structure. The collision between the crane structures and the building are often ignored in the research to simplify the problem. Lei's et alia research [7] had taken the collision between building structure and crane structure into consideration. They proposed a generic method for mobile crane lifting binary (yes-or-no) path for mobile crane path planning and checking. This method calculates the minimum and maximum crane lift radii based on capacity and industrial project the crane's configuration, which are then modified considering site constraints. A configuration space approach is used to simplify the work space. The modified radii and simplified work space are merged with the lifted module pick area for path checking. However, it assumes the entire building structure as a rectangular block and checks the feasible space against the block. Such an approach may only be applicable for building of regular shape, i.e. residential building. For building of irregular shape, especially for structures like chemical plants, such an approach would be an over-simplification, which may, unnecessarily eliminate many feasible spaces. This paper intends to take the exact shape and positions of each individual building component into consideration using the BIM model and the structure. This would be a more rigorous method for the feasibility check for collisions.

2.2. Building Information Modelling (BIM) and Code Compliance

Various researchers have pointed out the building information modelling has the potential to replace the various manual code compliance checks. Malsane et al. [8] proposed a Building Regulation-specific, semantically rich object model, appropriate for the requirements of automated compliance checking in Wales and England. Dimyadi et al. [9] have developed a set of guidelines to encode regulatory knowledge from New Zealand Building Code (NZBC) into computable representation. Shih et al. [10] explored the possibility of using BIM for fire safety requirement check based on Building Code of Australia (BCA). Ahmed and Chua [11] have applied intelligent automation to the most critical tedious manual check as well as checking that a design complies with regulatory codes. Nguyen et al. [12] have demonstrated how BIM is a firm basis for validating a design for safety at all stages of a building's life cycle. However, such research has exclusively focused on using BIM for design regulation compliance check. Very limited attempts have been made in utilizing BIM for construction safety requirement checks. Yeoh and Chua [13] have proposed a framework to represent construction requirement from the IFC model and Yeoh et al. [14] has proposed a framework for tower crane lifting plans. This paper explores the possibility of using BIM for code compliance check for construction safety in mobile crane activity.

3. Research Approach

The research approach in this paper builds on the existing research and makes use of the latest development in Building Information Modelling (BIM) software, particularly Autodesk Revit. It involves the interaction between the building information models (BIM), the mobile crane information model and a lifting task. A building information model includes all the existing structure on the construction site. A mobile crane information is proposed, which includes all the information for the crane operation. A lifting task specifies the user's objective in the lifting operation. From the building information model and the crane information model, lifting constraints are detected. From the parametric lifting task and the mobile crane information model, possible lifting plans are generated. The lifting plan is checked against the lifting constraints and decision support is provided to the user. The framework is shown in Fig. 1.

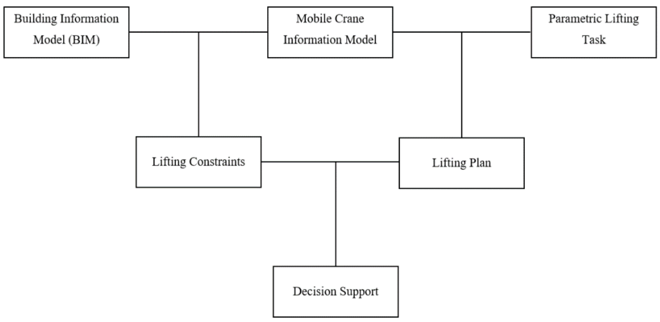

Fig. 1. Framework of the Research Approach.

3.1. Building Information Model

The building information model provides the environment for the crane lifting operation. A building information model used in this paper contains three important pieces of information. Firstly, it contains the geometric information of all the building components of construction. In the current industrial practice, usually the modeler models the final design of the building. In this case the user would need to specify the elements that have already been constructed in the building information model. This can be easily accomplished in conventional BIM software like Autodesk Revit. Secondly, is the geometric information of other construction equipment used on site. This is also important as the clashes between equipment may also result in a serious accident. The information provides the minimum data need for formulating a crane lifting plan. Thirdly, is the boundaries of the construction site.

3.2. Mobile Crane Information Model

From the input information, a mobile crane information model is generated. A mobile crane information model consists of all the necessary information for the crane operation. This information is categorized into the following: Mobile Crane Structure, Clearance Space, Lifting Capacity and Positional Parameter.

3.2.1. Mobile Crane Structure

The crane structure is the physical space occupied by the mobile crane itself. The fixed structure of the crane includes the winding drum and the outrigger. The shape of the fixed structure can be easily obtained from the mobile crane catalogue. On the other hand, boom, jib and robes can be extended to different lengths. Thus, they are considered as variable structures. The possible boom lengths, jib lengths and the associated robes length can be obtained from the load chart from the crane manufacturer.

3.2.2. Clearance Space

To avoid collision, there must be a clearance space between the mobile crane structure and the site constraints. The clearance space comes from two sources. If there is explicit code from the regulatory departments, the clearance space should follow the regulatory requirement. When such information is absent, the lifting engineer should define the minimum clearance spaces into the model.

3.2.3. Load Chart

One of the advantage of using a mobile crane is that the crane operator can adjust the boom length and boom angle according to the to the lifting task requirement. Usually the crane manufacturer provides the information in a crane load chart. For a particular type of crane, the possible boom lengths are usually fixed, while the boom angle can be adjusted by the crane operator according to the lifting radius, which is the horizontal distance between the crane location and the lifting hook. With a particular set of these variables, there is a specific maximum load capacity. A typical crane load chart for Liebherr LTF 1060-4.1 mobile crane is shown in Fig. 2 and Table 1 shows a typical load capacity at a defined position.

m	10,2 m		13,6 m	17 m	20,5 m	23,9 m	27,3 m	30,7 m	34,2 m	37,6 m	40 m	m
	*											
2,5	60											2,5
3	55,1	42,3	42,2	42,2	39,1	31,1	25					3
3,5	50,3	42,3	42,3	41,4	38,5	31,3	24,8					3,5
4	44,9	42	41,6	39,1	37,3	31,4	24,6	19,8				4
4,5	40,2	38,8	38,8	36	33,8	31,2	24,1	19,7				4,5
5	36,7	35,3	35,3	33,4	31,5	30,3	23,4	19,5	15,4			5
6	30,5	29,4	29,7	29,8	28,6	27,3	21,4	18,5	15,1	12,1	10,4	6
7	25,7	24,7	25	25,1	25,5	24,4	19,4	17,2	14,5	11,8	10,2	7
8			21,5	21,4	21,7	20,9	17,8	16	13,8	11,4	10	8
9			18,4	18,7	18,7	18	16,3	14,8	13,1	10,9	9,7	9
10			15,8	16,2	16,1	15,7	14,7	13,7	12,3	10,4	9,4	10
11			13,5	13,9	13,9	13,6	13,4	12,6	11,6	9,9	8,9	11
12				12,2	12,1	11,9	12,2	11,4	10,9	9,4	8,4	12
14				9,6	9,6	9,9	9,6	9,5	9,2	8,5	7,7	14
16					7,9	8,1	7,8	7,9	7,6	7,7	7	16
18						6,7	6,6	6,6	6,6	6,4	6,4	18
20						5,7	5,8	5,7	5,6	5,4	5,4	20
22							5	4,9	4,8	4,6	4,6	22
24							4,4	4,2	4,1	3,9	3,9	24
26								3,7	3,6	3,4	3,4	26
28								3,3	3,1	2,9	2,9	28
30									2,7	2,5	2,5	30
32										2,2	2,2	32
34										1,9	1,9	34
36											1,6	36

* nach hinten · over rear · en arrière · sul posteriore · hacia atrás · при выдвинутой назад стреле   t_199_00001_00_000 / 00101_00_000

Fig. 2. Load Chart Liebherr LTF 1060-4.1.

Source: [15].

Table 1. A typical lifting capacity.

Boom Length	Lifting Radius	Boom Angle	Lifting Capacity
15.2 m	6.2 m	66°	150.0 tons

3.2.4. Positional Parameter

In the proposed mobile crane information model, the feasibility of a crane lifting path would also depend on the position of the mobile crane. In this decision support system, the position of the mobile crane would be defined by the user. Table 2 summarizes the information input required for the mobile crane information model and the source of information.

Table 2. Information Input for Mobile Crane Information Model.

Parameter	Crane Structure	Clearance Space	Lifting Capacity	Positional Parameter
Information Source	Manufacturer	Regulations/User	Manufacturer & Lifting Task	User Defined

3.3. Parametric Lifting Task

In order to formulate a crane lifting plan, the first step is to have a clear definition of the lifting task. A lifting task is defined by the properties of the object being lifted, the material supply point and the unloading position. The key properties considered include the weight of the object and the shape of the object, which is simplified to be a rectangular shape bounding box. These properties are drawn from the three dimensional BIM model in conventional software like Autodesk Revit. The position of the object is simplified as the centroid of its bounding box in the completed building. This information can also be obtained from the three dimensional BIM model.

3.4. Lifting Constraints

From the interaction between the building information model and crane information model, a list of constraints can be detected against the lifting task. These include the boom length constraint, the spatial constraints, and the load capacity constraint. The boom length check ensures that the material supply point and the unloading position are within the reach of a specific lifting option. If the unloading position for a particular crane lifting task is above a specific boom length and boom angle combination, this lifting option would be identified as an infeasible lifting option. Three key spatial constraints are considered in this paper. Firstly, the existing building structure, secondly the other construction equipment on site and thirdly, the site boundaries. For safety operation, the crane structure should keep a minimum safety clearance with existing building structures. Load capacity check is the most important safety requirement check for the mobile crane operation. The object lifted should not exceed the lifting capacity of the crane at any point of the operation. The load capacity of the crane at a particular point is a function of the boom length and the radius. The load capacity is derived from the load chart provided by the crane manufacturer.

3.5. Lifting Plan

In construction, the lifting engineer needs to specify the following parameters in the lifting plan for the crane operator. Firstly, he needs to define the material supply point and the unloading point. In this decision support algorithm, the lifting engineer would have manually input the supply points and the unloading points when he defines the parametric lifting task. Secondly, he needs to specify the boom length of the mobile crane. The mobile crane information model would specify the different possible boom lengths and the program would test the feasibility of using different boom lengths. The engineer also needs to specify the boom angle during loading and unloading. These would be calculated by the program. The engineer also needs to specify the minimum boom angle when the crane boom is swinging from the loading position to the unloading position. This would also be one of the outputs from the decision support system, which is discussed in detail in the next section. The different requirements of the lifting plan and the sources of information are summarized in Table 3.

Table 3. Requirements of the lifting plan and information sources.

Requirements	Material Supply Point	Unloading Point	Boom Length	Boom Angle (Loading)	Boom Angle (Unloading)	Boom Angle (Swing)
Information Sources	Parametric Lifting Task	Parametric Lifting Task	Mobile Crane Information Model	Program Output	Program Output	Program Output

3.6. Decision Support

In the decision support system, the lifting plan is checked against the lifting constraints. Checks are carried out for three stages: (1) loading position; (2) swinging; (3) unloading position. At the loading and unloading positions, the decision support system carries out the boom length check, the load capacity constraint check and the lifting capacity check to determine the feasibility of the positions. For swinging, the decision support system calculates the minimum boom angle to avoid clashes with spatial constraints. The checks and outputs are summarized in Table 4.

Table 4. Checks and outputs for the decision support system.

Stages	Constraint	Output
Loading	Boom Length, Spatial, Lifting Capacity	Feasibility Check Result
Swinging	Spatial	Minimum Boom Angle
Unloading	Boom Length, Spatial, Lifting Capacity	Feasibility Check Result

4. Case Study

A hypothetical case study of an as-built BIM model is used to illustrate the decision support system. The user has defined a selected precast column on sixth floor as the lifting object and the supply position has been specified by the user. The unloading position is 24.0 meters above the ground and 22.8 meters away from the crane in plan view. The weight of the precast concrete column is 1.4 tons. The material supply point is 15.2 meters away from the crane position. Liebherr LTF 1060-4.1 with a counter weight of 10.2 tons is used in the project. The layout of the lifting task is shown in Fig. 3.

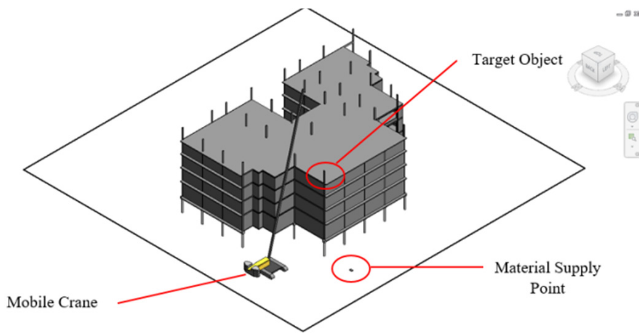

Fig. 3. Site layout for the case study.

The decision support system has eliminated boom lengths below 30.4 meters as infeasible options because they cannot reach the unloading position. For boom length of 34.2 meters and 37.6 meters, the boom lengths may clash with the existing object at the unloading position. If the boom is extended to 40 meters, the unloading point is within the reach of the mobile crane, without any clash with the existing structure. During swinging, a boom angle of at least 74.8° should be maintained to avoid any clash with the existing structure. The load is within the loading capacity of the crane. The output of a feasible crane lifting plan is summarized in Table 5.

Table 5. A feasible crane lifting plan for the case study.

Boom Length	Boom Angle (Loading)	Boom Angle (Unloading)	Boom Angle (Swing)
40.0 m	67.6°	55.2°	Minimum 74.8°

5. Conclusion

This paper proposes an approach for formulating crane lifting plan with the aid of the latest advancement in building information modelling (BIM). The approach used in this paper is more rigorous and accurate than the earlier research. This represents an advance in automating crane lifting planning. Also, this paper demonstrates the potential application of BIM in code compliance check for construction activities. There can be further research in this area to make full use of the latest BIM technology. However, the decision support system developed in this paper only considers the code compliance and safety checks. Other factors, such as time and cost, should also be taken into consideration in mobile crane lifting plan. Currently engineers rely on experience in estimating and optimizing these factors, which are not very rigorous and accurate. This can be an area for further research.

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