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SIMULATION OF MOBILE CRANE OPERATIONS IN 3D SPACE

SangHyeok Han

Construction Engineering and Management
University of Alberta
Edmonton, AB, T6G-2W2,CANADA

Shafiul Hasan

Construction Engineering and Management
University of Alberta
Edmonton, AB, T6G-2W2,CANADA

Mohamed Al-Hussein

Department of Civil and Env. Engineering
University of Alberta
Edmonton, AB, T6G-2W2,CANADA

Kamil Umut Gökçe

Department of Civil and Env. Engineering
University of Alberta
Edmonton, AB, T6G-2W2,CANADA

Ahmed Bouferguene

Campus Saint-Jean
University of Alberta
Edmonton, AB, T6C-4G9,CANADA

ABSTRACT

A 3D model allows users to visualize the construction process during a given period of the schedule. This paper presents a methodology to aid practitioners in preparing lift studies with crane selection, positioning, and lift optimization using a 3D space. The 3D visualization helps to identify collision free paths and optimize lifting activities based on optimal crane paths with cycle time and speed of each crane activity from simulation models in Simphony. The proposed methodology provides to help lifting engineering and project manager select the best possible crane. A case study-based approach is utilized to illustrate the proposed methodology. The case study involves construction of a four story, sixty-eight unit building for older adults in Westlock, AB, Canada. The 3D visualization model was provided for the construction team more than two months before the scheduled day of lifting, which assisted the contractor in selecting the optimum crane and successfully completing all lifts (thirty modules, 25 tons each) in just two working days.

1 INTRODUCTION

Modular building is widely becoming more popular than traditional, on-site construction for new buildings, especially houses and apartments, since it meets owners' and builders' requirements for an environmentally-friendly construction process, and reduced construction time and waste at cost-competitive prices (MBI 2008). Although the manufacturing process is complex because of physical and space constraints, previous research (Senghore 2001; Sabharwal 2004; Jeong 2003; Hammad 2003; Yu et al. 2008; Han et al. 2012) has studied how to increase productivity and optimize material control through improving an existing production line or developing a new production line by using lean, simulation, and visualization methods. Crane operation is critical to implementing projects in the manufacturing industry be-

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cause it strongly influences successful project completion for modules' installation without potential site errors such as spatial collision which could lead to reduce productivity by increasing cost and time.

Crane application has improved the construction industry's efficiency dramatically in recent decades, making prefabrication and on-site installation possible. Efficient crane use also improves work productivity and quality with cost and time savings. After modules are manufactured in a factory, they are delivered to construction sites for assembly. In respect to construction assembly operations on-site, cranes play crucial roles in the North American construction industry, especially mobile cranes due to their high capacity (Shapira, Lucko, and Schexnayder 2007). A number of factors such as delivery material information and site constraints influence crane operation including crane type, number, selection, and location. Due to the complexity of crane operation, computer applications have been developed to assist practitioners in selecting, locating, and using cranes. These applications use various algorithms which are based on crane types, namely mobile or tower cranes. This paper focuses on the mobile crane, which the type that most commonly installs modules on-site in the manufacturing industry. Automated computer applications, developed by programming languages, have implemented mobile crane selection and on-site location using algorithms (Di Wu et al. 2011; Al-Hussein et al. 2005A). Various methods have developed automated crane path planning for mobile crane lifts, including collision detection, in both 2D and 3D (Chi and Kang 2010; Sivakumar, Varghese, and Babu 2003; Reddy and Varghese 2002; Lin and Haas 1996).

Although private companies and researchers develop computer applications to select and locate cranes, and plan crane paths, validation and verification is required to reduce risks, costs, and time before implementing on the actual site. Previous research has proven that computer simulation is an efficient and cost-effective validation tool to experiment with potential plans (Al-Hussein et al. 2005B). However, simulation is an abstraction of the real-world which may be confusing for a number of users. 3D visualization has been combined with simulation to provide practitioners with detailed project information to ease understanding of the construction process (Al-Hussein et al. 2005B; Kang and Miranda 2006; Abourizk and Mather 2000). Since communication is a key to succeed projects, 3D visualization streamlines information exchange between users from diverse fields to identify space conflicts, site layout, construction sequences, workspace requirements and schedule errors in order to save time, and reduce costs and risks before actual implementation (Koo and Fischer 2000; Manrique et al. 2007; Olearczyk et al. 2009; Tantisevi and Akinci 2007; Tantisevi and Akinci 2009; Moselhi et al. 2004). However, 3D visualization has only been applied as a supporting tool for validating and verifying new methodologies and algorithms; it does not actively develop new methodologies and algorithms.

This paper focuses on using 3D visualization as an active tool to analyze and simulate crane selection, location, and operation in order to install modules on-site. This tool is also used to optimize sequential crane lifting patterns. A case study-based approach is utilized to illustrate the proposed methodology. The case study was implemented in which thirty modules, each weighing 25 tons, were installed in order to build a four-story, 68 unit building for older adults in Westlock, AB, Canada.

2 METHODOLOGY

The traditional document-based project delivery method is archaic, error-prone, litigation-prone, high-risk, and reliant upon very inefficient, hard to predict construction processes that result in owners taking over projects with little information on how to operate and maintain their buildings (Neeley, 2010). 2D drawing base approach has major limitations in identifying possible spatial conflicts related to dynamic crane operations (Tantisevi and Akinci 2008). It is essential with the technology available today to improve the project delivery process. 3D visualization is helpful in the verification and validation of crane operations and can be a useful tool to improve the productivity of crane operation. Koo et al. (2000) have determined that 3D visualization allows project participants to be more creative in providing and testing solutions through viewing the simulated time-lapse representations of the corresponding construction sequences. The proposed methodology in this paper, as presented in Figure 1, consists of two processes: simulation and visualization modeling and reaction calculation. Prior to implementing the proposed method, input data such as building and module information from project managers, crane geometry from crane manufacturers, and load rigging databases from Hasan et al. (2010) must be collected. The crane geometry database contains not only crane configuration specifications, but also the resulting 3D crane models. These 3D models allow users to implement simulation/animation easily and quickly for various crane operation alternatives in 3D space. The simulation and visualization modeling consists of six steps: 1) Select a crane and its configurations; 2) Identify the possible crane paths; 3) Simulate the crane operation, 4) Develop 3D animation; 5) Identify clearance and spatial conflicts; and 6) Select the optimized path. Based on the crane operation activities in the 3D animation, the ground reaction calculation is implemented in order to design the support foundation using steel plates or timber for the safety environment on-site. As a result, the lifting schedule, reaction influence chart, 3D animation, site layout, and collision free path of the crane operation are generated.

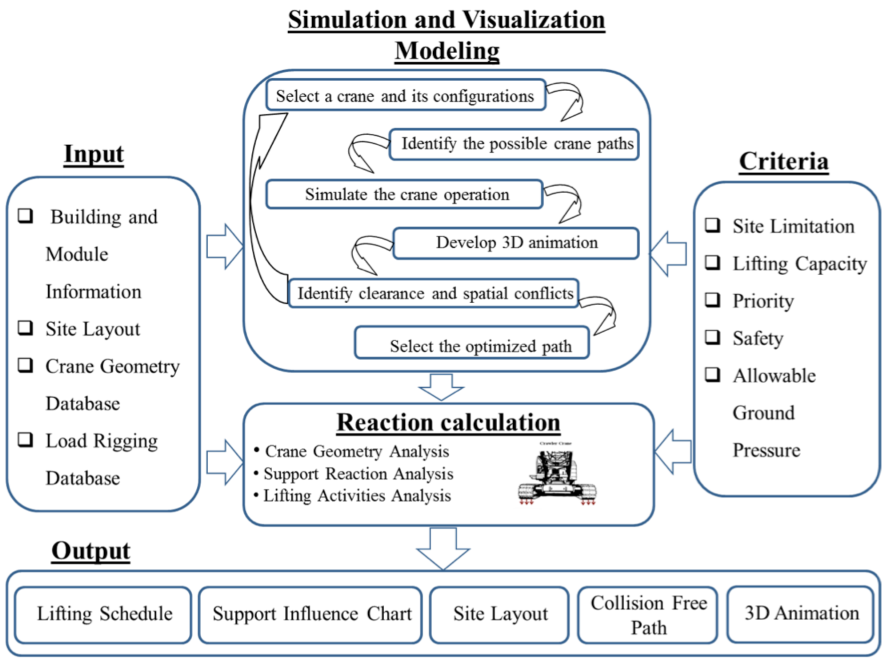

Figure 1: System structure of the proposed methodology

2.1 Simulation and Visualization Modeling

2.1.1 Crane Selection

Algorithms used to select mobile cranes have been developed in computer applications (Al-Hussein 2005A; Hasan et al. 2010; Di Wu et al. 2011). Mobile crane selection usually consists of four steps: lifting capacity, working radius, lifting height, and clearance calculations. Since this paper focuses on determining the feasibility of simulating crane operations in 3D space, the algorithm used to select mobile cranes is not illustrated. However, algorithms developed by Hasan et al. (2010) have been used to implement the mobile crane selection.

2.1.2 Crane Paths Identifications

Before determining the crane location on-site, some data must be collected, including building information, module information, site layout, and most notably, site limitations. A number of 3D programs, such as AutoCAD, ArchiCad, and 3D Studio Max (3DS), provide various user-friendly perspective views using 2D and 3D coordinates in which kinematics functions as a fundamental mechanism in the 3D environments. This paper presents the proposed methodology in 3DS as a visualization modeling tool. The crane location calculation is implemented in the 2D coordinate in 3DS. Five steps are required to determine the crane location:

1. Draw a line by the default value (2ft) or user defined from a building outline and generate random points (Pn) on the line.
2. Determine distances (Dn), illustrated in Figure 2, from the centers of each module installed on the building to each point on the line.
3. Select a maximum distance for the distances (Dn).
4. Repeat steps 1 to 3 until determining all maximum distances for points on the line.
5. Select a minimum distance between the maximum distances.

The crane location may be various points which are not only minimum distances, but also minimum crane operation paths. Based on the crane location, the different crane paths with each distance of crane activities are identified manually.

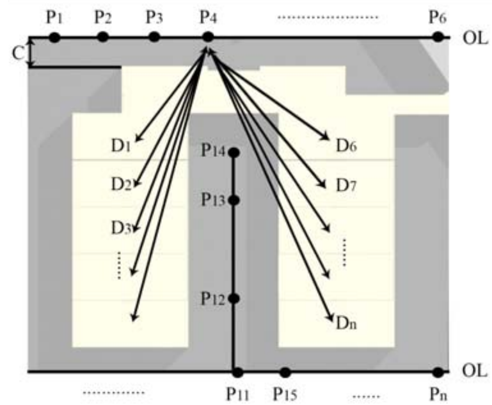

Figure 2: The distances from each point to center of each module

2.1.3 Simulation of Crane Operations

Before the crane location is finalized by the minimum distance between the maximum distances, site limitation, lift capacity and priority of modules installation as criteria factors should be considered. The minimum distance could indicate minimum crane operation activities related to cost and time savings. Crane operation can be broken down into separate activities and simulation of the crane activities depends on: (1) source location; (2) destination location; (3) weight and size; (4) priority setting; (5) possible location of crane; (6) boom/jib length; (7) rotating speed; and (8) reach. To simulate the lifting operation, travel speeds for hoisting, radial, and luffing jib vertical movement also need to be considered. Based on these movements and crane paths, the simulation models have been developed using Simphony.NET3.5 (Hazzar and AbouRizk, 1999) as shown in Figure 3 to find the shortest time-based crane operation. From the simulation models, cycle time and speed of each crane activity are generated for developing real-time crane operation in 3DS.

2.1.4 3D Animation

As a supporting tool, 3D visualization (Al-Hussein 2005B; Han et al. 2012) helps decision makers fully understand projects and validate simulation results through dynamic graphical depictions of construction operations in 3DS. These graphical depictions reflect real world operation in order to improve cooperation and communication between construction project team members with various fields of expertise. This paper describes 3D visualization to identify and solve potential errors regarding workspace requirements/limitations, crane operation sequences, spatial conflicts, and crane selection and location prior to real-world implementation. Based on the various crane path alternatives and time data from simulation models, the 3D visualization is developed to determine the optimal crane operation with the safety environment provided by calculating ground reaction and clearance between crane configurations and a building/delivery material.

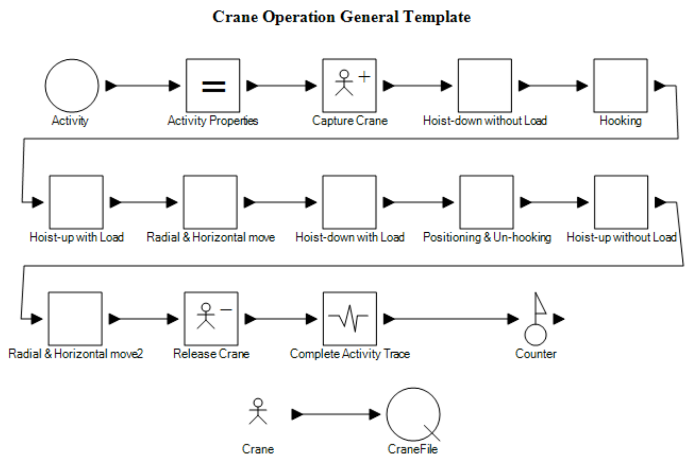

Figure 3: Simulation Model from Simphony.NET3.5

Users should know fundamental mechanism, Inverse Kinematics (IK) as science of motion, to build animation in 3DS. The IK can create IK chains which contain a hierarchical structure (i.e. the child objects are linked to the parent objects). As a result, when parent objects move, the child objects follow the parent's motion. For example, the mobile crane with luffing jib consists of five components: superstructure, boom , luffing jib, hook block, and module. The hook block is involved in the sling, spread bar, and hook. Due to their free mobility on-site, mobile cranes are widely used for construction projects. Since the superstructure is movable in 3D space, the mobile crane with luffing jib as an IK chain is linked as follows: superstructure ----> boom ----> luffing jib---->hook<---- module. The linkage between hook and module could be changed by user defined. Figure 43 shows the linkage between the mobile crane and luffing jib. The IK algorithm developed by Kang (2005) describes the mobile crane's components' positions and degrees.

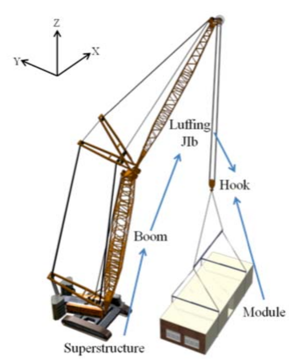

Figure 4: Linkage of Crawler Crane Configurations

2.1.5 Clearances - Conflicts Identification

After developing the visualization model it is easy to identify different clearances and spatial conflicts of crane operations if any in 3D space. Three clearances must need to be checked: 1) the clearance between the lifted load and the boom or jib, 2) the clearance between the lifted load and the existing facilities, and

3) the clearance between the crane and the existing facilities. Construction sites in a large project developed dynamically and reach congestion quickly. Planning the crane path with identifying conflicts is critical. The spatial conflicts can be identified using the 3D animation where the 2D drawings of the site and time dependent obstructions will be transformed in the 3D space.

2.1.6 Optimum Path Selection

The 3D animation need to be developed for possible every paths from the simulation model and for all path the clearance and conflicts need to be checked. If the selected crane fails do any lift due to safety purpose then another suitable crane need to be selected and need to follow the same procedure. This methodology will allow for identification of the shortest path as well as the selection of optimum crane.

2.2 Support Reaction Calculation

Although the type of mobile cranes vary due to different types of booms (telescoping or lattice) and undercarriages (on wheeled or crawler-tracked) used, in this paper, mobile cranes have been divided into two categories, truck crane and crawler crane, which are illustrated in Figure 5. The crane support reactions are a function of the respective weights of the lift and crane components and their moments around the crane's centre of rotation. Based on vertical and horizontal movements of the boom, these moments are classified into two categories: one acting around the crane's sides and the other acting on the crane's rear or front. Based on crane operation activities, such as lifting or swinging, in the 3D visualization, the reaction of the truck crane's four outriggers, as illustrated in Figure 5, is composed of two fronts (P.Front1, P.Front2) and two rears (P.Rear1, P.Rear2); or crawler crane track pressures under track 1 (P.Front1, P.Rear1) and track 2 (P.Front2, P.Rear2). An automated supporting reaction system developed by Hasan et al. (2010) calculates the reaction of each outrigger.

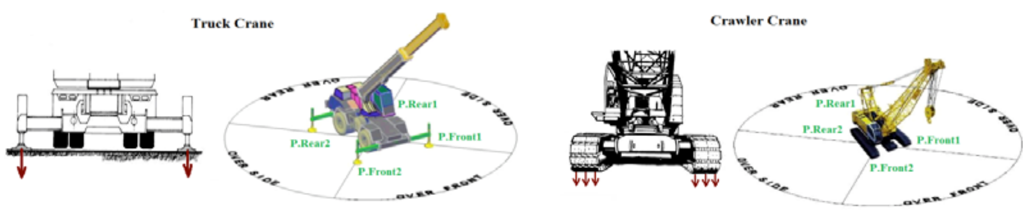

Figure 5: The type of mobile cranes for support reactions.

The system also provides a support influence chart (Hasan et al. 2010), as shown in Figure 6, which is significantly more comprehensible for contractors or crane operators than the manufacturer's crane load chart in controlling crane swing direction and changing boom positions for particular crane operations. Negative reactions indicate that tension force has developed on the corresponding support which may cause crane tipping. Thus, to maintain crane stability, a project manager must be aware that all support reactions should be positive in order to schedule crane operations safely and successfully.

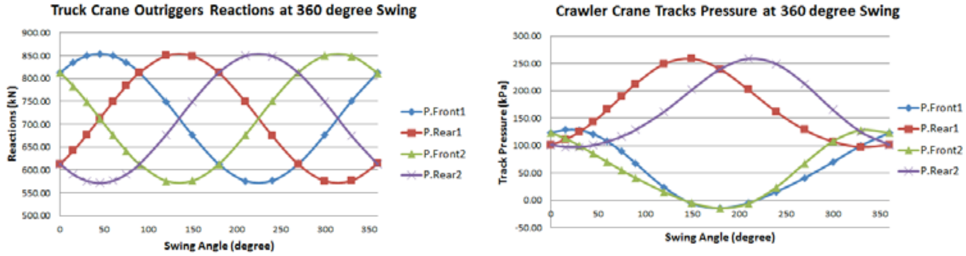

Figure 6: Reaction influence chart

3 A CASE STUDY

The case study involved construction of a four story, 68 unit building for older adults called Pembina Lodge located at 10247-104 street, Westlock, Alberta, Canada. The earthwork of the project started on July, 2011. Thirty modules were required to construct the top three floors and the main floor was constructed on-site. The module dimensions were 22 ft (6.7m) X 56 ft (17m) X 11 ft (3.4m) and the weight was 24.95 ton. The site shown in Figure 7 had some constraints, most notably mature trees and power line, which influenced the crane's location when installing modules. The owner wanted to keep the mature trees on-site and the power line limited crane accessibility, only allowing movement along route 1 or route 3 to reach the site.

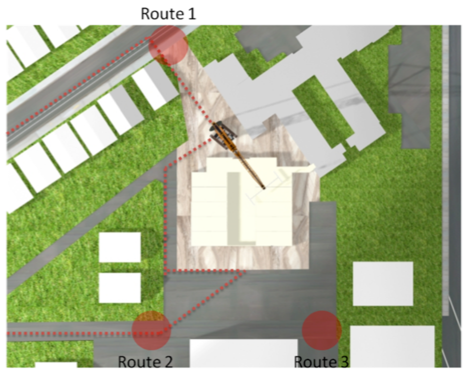

Figure 7: Site Layout with feasible entrances

According to the proposed methodology, there possible cranes were selected and three possible paths were identified from the crane operations simulations. Table 1 summarizes the three different scenarios with different crane types.

Table 1: The Scenarios with Crane Information

	Crane Type	Required Capacity	Working Radius	Clearance errors
Scenario 1	Liebherr LIM 1800 crawler crane	32 Ton	46 m	None
Scenario 2	Liebherr LR 1300 crawler crane	30 Ton	28.3 m	None
Scenario 3	Liebherr LR 1160 crawler crane	28 Ton	19.6 m	None

Scenario 1, described in Figure 8, had a required radius of 39 m with a 32 ton capacity requirement. The liebherr LIM 1800 crawler crane was selected to satisfy the requirements. This scenario included two crane locations possible, one at the front side of the building, and the other at the back. In order to improve crane and trucks accessibility, the back location was selected and the crane can install all modules from that location. Based on this analysis, 3D visualization in 3DS was built and simulated to identify site errors and clearances between crane configurations and the building or crane configurations and modules during lifting operations. The module installation sequences were also simulated in 3D visualization. There were no errors found in 3D visualization.

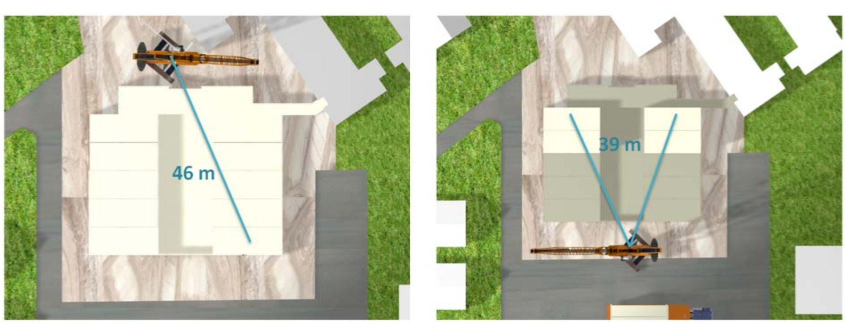

Figure 8: Simulation of Liebherr LTM 1800

Scenario 2, illustrated in Figure 9, had a required radius of 28.3 m and capacity of 30 tons. The liebherr LR 1300 crawler crane was selected. The crane operation activities for this crane were followed : 1) install the front two building units from the right side of the building to the left side, 2) move the crane to the back side of the building through route 1 and 2, 3) install the remaining three building units on the back side. Based on these scenarios, 3D visualization in 3DS was built and simulated to identify clearances and crane operation sequences in order to install modules. No site errors, including clearance problems, were found.

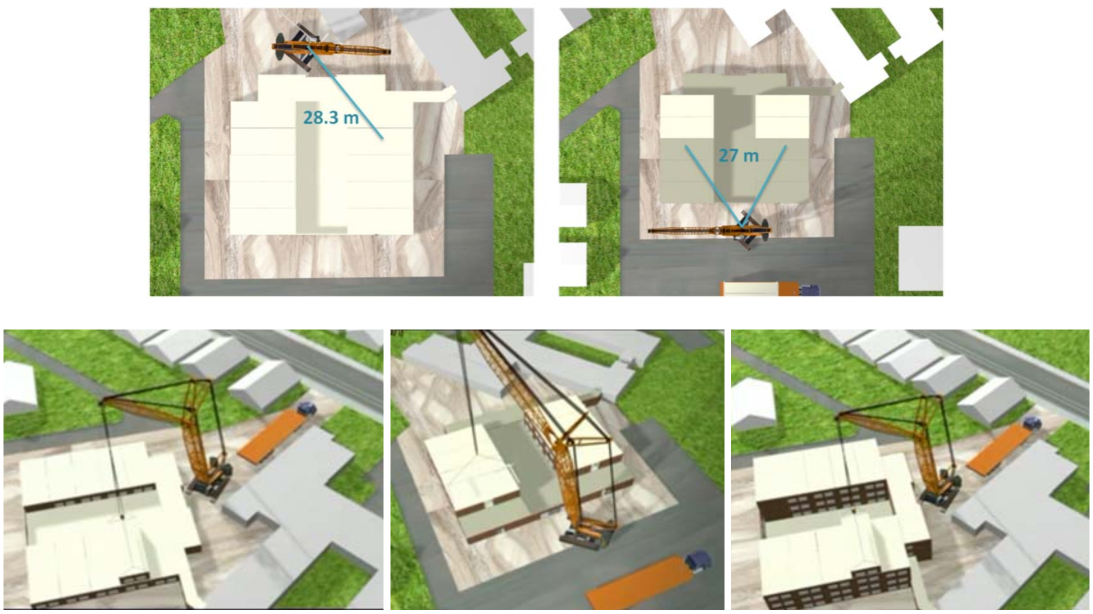

Figure 9: Simulation of Liebherr LR 1300

Scenario 3, as shown in Figure 10, had a required radius of 19.6 m and capacity of 28 tons. According to the crane selection calculation (Hasan et al. 2010) in order to satisfy requirements, the liebherr LR 1160 crawler crane was selected. The crane operation activities were followed: 1) lift module, 2) move crane to the proper location between two legs of the building, 3) install module on the correct building location and 4) move the crane back to the lifting location. The core point of the crane operation in this scenario was that the crane was moving forward and backward between two legs of the building to reach optimal locations for module installation. This operation could result in spatial collisions between crane configurations and the building. Therefore, clearance identification was the most critical analysis. The 3D visualization identified clearances, feasible errors, and modules installation sequences before the plans were implemented in the real world. No errors were found in the visualization.

Figure 10: Simulation of Liebherr LR1160

Based on these three scenarios, the company selected scenario 3 due to cost and time savings during crane operation. According to the visualization of scenario 3, the reaction influence chart for crane operations was generated as shown in Figure 11. Using the influence chart, researchers identified that the 360 degree swing operation of the Liebherr LR1160 was safe and that the maximum ground pressure to lift a 25 ton module is 217 kPa when the crane swings 150 degrees from the front (see Figure 12).

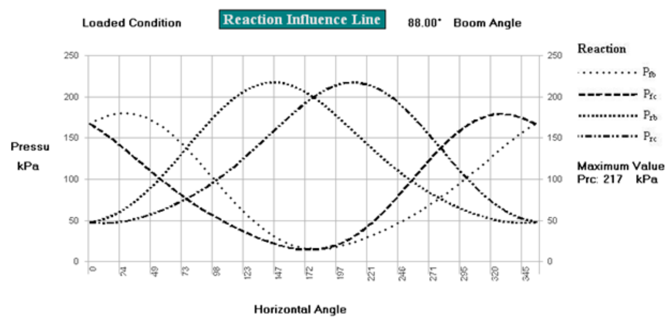

Figure 11: Reaction influence chart for scenario 3

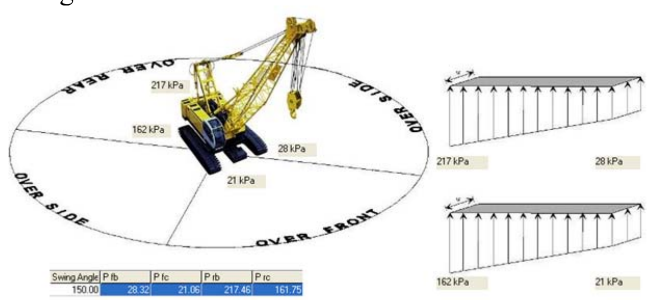

Figure 12: Crawler track pressure diagram at 150 degree swing for scenario 3

All the lifts were very critical as the clearances between the crane tail and the proposed building was less than half of a meter as shown in Figure 13. The visualization model had been share with the crane operator and all member of the construction team. By the help of the developed visualization model the crane operator was able to do all critical lifts successfully. Compared to the proposed visualization, the actual lifting followed a similar sequence, and similar clearances between the crane and the constructed main floor were also observed (see Figure 13). Figure 14 illustrates the actual lifting sequences using the Liebherr LR1160 crawler crane. The significance of the visualization model was in improving construction (lifting) operation efficiency while maintaining workers' safety. The difference between visualization and real was the module installation sequence in the building. Unlike actual construction, 3D visualization did not consider human activities during module installation. The modules were completed in only two working days.

(a) (b)

Figure 13. Crane Clearances: (a) from Visualization Model, (b) from Construction Site

Figure 14. Actual Lifting Sequence Photos

4 CONCLUSION

The dynamic graphical description of 3D visualization is an effective for validating or supporting new methodology and plans to help productivity and cost analysis, resource management, and site layout assessments to prevent costly on-site errors before real world implementation. The proposed methodology suggests that 3D visualization could be used as an active and simulation tool for construction management, especially crane operation. It could assist lift engineers in scheduling crane operations more efficiently and in identifying and preventing potential crane accidents. To verify and validate the proposed methodology, the case study demonstrated the effectiveness and efficiency of proposed crane operation scenarios which were simulated in 3D visualization. A company then selected scenario 3 which allowed them to install modules on-site in only two days. This scenario helped design crane operation activities and prevent potential spatial collisions through identifying clearances between crane configurations and the building when the crane was operating between legs of the building. Furthermore, 3D visualization assisted a lifting engineer and project manager in eliminating scheduling uncertainties during crane operation without sacrificing safety, quality, cost, and time associated with lift planning and execution. Detailed project information in 3D visualization improved communication between a crane company and manufacturing company during the period of the project. According to crane operation activities in the 3D visualization, the supporting reaction influence chart was generated to determine the safe and maximum ground pressure required to lift a 25 ton module. The case study demonstrated that human resources must be considered when building the same crane operation sequences in 3D visualization and the real-world.

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AUTHOR BIOGRAPHIES

SANGHYEOK HAN is a graduate student (Ph.D. Student) in the Department of Civil and Environmental Engineering, University of Alberta. His research interests include engineered crane lift studies, IFC-based Information Modeling, process improvement studies utilizing lean, post lean simulation and post simulation visualization in manufacturing industry. His email address is sanghyeo@ualberta.ca.

SHAFIUL HASAN is a graduate student (Ph.D. Candidate) in the Department of Civil and Environmental Engineering, University of Alberta. He completed his M.Sc. degree in Construction Engineering and Management from University of Alberta in 2008. His research interests include engineered lift studies, rigging equipment and special construction designs, software development and user interfaces. His email address is mdshafiv@ualberta.ca.

MOHAMED AL-HUSSEIN is a Professor in the Department of Civil and Environmental Engineering, University of Alberta and a NSERC Industrial Research Char in the Industrialization of Building Construction. He has extensive research experience in construction project management, including resource, facility, equipment and procurement management, as well as project cost control and claims analysis. His expertise is in computer modeling with regards to operation process modeling and data modeling in construction. He has a proven record of contributing to the industrialization (manufacturing) of building construction. His email address is malhussein@ualberta.ca.

KAMIL UMUT GÖKçE is a visiting professor in the Department of Civil and Environmental Engineering, University of Alberta. His main fields of interests are Building Information Modeling, Energy Efficient Building Operation, Product and Process Modeling, Facility Management, Collaborative Design, Software engineering, and Wireless Network Technologies. Among his research career at TU Dresden, UCC, University of Alberta and ITU for more than 9 years, he has worked at private sector for five years and managed/involved important construction projects. He is currently active in BuildingSmart, ECTP and E2BA. His email address is gokce@ualberta.ca.

AHMED BOUFERGUENE is an associate professor in the campus Saint-Jean at the University of Alberta. He is working on first-principles calculations/modeling in heterogeneous catalysis to understand how modifications of the surface can influence the selectivity of a chemical reaction. He is also involved in efficient algorithms for the evaluation of multicenter integrals over Slater Type Orbitals (STOs) for the elaboration of software. His interesting topics focus on developing computational methodologies in quantum chemistry. His email address is ahmed.bouferguene@ualberta.ca.