Near-Real-Time Optimization of Overlapping Tower Crane Operations: A Model and Case Study

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Abstract: Construction projects require effective planning and management of site equipment. Tower cranes are heavily employed on large-scale construction projects, thus incurring additional costs and delays if used inefficiently. This research aims to optimize crane operations on high-rise buildings by considering the overlap space between cranes. Look-ahead planning (LAP) is employed to perform daily operations' planning and provide a reliable, constraint-free daily schedule of crane operations. A simulation model performing metaheuristic optimization is developed to optimize in near real time the allocation of cranes to tasks on the LAP schedule while calculating crane movements in a three-dimensional environment and checking for collisions. The LAP simulation model is tested on a case study project, and results show that having overlaps and coupling LAP with optimization can better reduce duration and balance the work demand. This study provides practitioners with a daily planning and optimization process and tool to enhance crane operations. **DOI: 10.1061/(ASCE)CP.1943-5487.0000666.** © *2017 American Society of Civil Engineers.*

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Introduction

Tower cranes are indispensable for construction operations on high-rise buildings. They are among the most critical equipment because they are involved in the majority of site operations and are heavily utilized by other resources to enhance productivity and reduce execution times of activities. Selection of the type, location, and number of cranes is dependent on factors such as project space and congestion, laydown areas, surrounding traffic, safety concerns, characteristics of loads to be lifted, and crane coverage, as well as the level of site demand. Therefore, planning of tower crane logistics is instrumental in efficient production of labor crews and other equipment.

The management of tower cranes focuses on nonwasteful operations so that high-demand areas are supplied without incurring excessive delays. On sites with high demand, several cranes are set up to meet the demand of operations and perform them in a safe manner. Tower crane locations are selected to satisfy the required coverage and operate without any collisions (Zhang et al. 1999). Moreover, if cranes cannot meet the demand of labor crews or other equipment promptly, production levels are reduced, resulting in schedule delays. Research on tower crane operations has targeted aspects such as the selection of optimal locations of single and multiple cranes (Zhang et al. 1999; Tam and Tong 2003; Alkriz and Mangin 2005; Tam et al. 2001), the detection of collisions through motion planning (Kang and Miranda 2008; AlBahnassi and Hammad 2012; Chang et al. 2012; Tantisevi and Akinci 2007), and optimizing a crane's service sequence (Zavichi 2013; Zavichi and Behzadan 2011; Al Hattab et al. 2014).

The early planning stages of crane logistics involve decisions about the number, type and location of cranes, safety planning for crane movements, and efforts to maximize the coverage area. When multiple cranes are employed, further planning is required to increase crane utilization, prevent collisions between cranes, and decide on the required overlapping area to ensure all activities can be executed in an effective and safe manner. While safety considerations impose constraints on crane location and overlap, having an adequate area of overlap gives more flexibility in crane assignment to activities so that demand can be proficiently met and properly distributed in order to reduce the overall duration. Research in this area does not sufficiently address optimization of the overlapping area of cranes in high-rise building projects and the optimal allocation of cranes for on-site activities.

The motivation behind this paper stems from the need to explore the potential benefits of the overlapping space between multiple cranes and the optimal allocation of cranes to tasks falling within and outside the overlap area. Previous studies optimize the location of multiple cranes to balance the work demand by considering the coverage areas of cranes; however, they do not address the demand (number of tasks) when optimizing based on the coverage areas. Therefore, this study targets the work demand within the coverage areas, assuming a preset close to optimal location of cranes, thus bridging the gap in the existing body of research in this area. Activities that fall within the common work zone need to be carefully planned to ensure safe performance and proper crane allocation. This paper addresses the optimal allocation sequence of two overlapping tower cranes (assuming their locations to be optimally predefined) to the tasks falling in their common zone and outside while maintaining collision-free motion paths. To achieve this, a simulation-optimization (SO) model using look-ahead planning (LAP) and building information modeling (BIM) is employed to find the optimal allocation of two overlapping tower cranes. By optimizing the allocation process, the total schedule of crane tasks can be reduced and the work demand and crane coverage requirements can be better distributed and balanced. This helps to prevent

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crane idleness or demand capacity overload resulting in potential breakdowns and extra costs. The developed SO model also detects potential collisions during crane performance. The study contributes toward providing practitioners, such as engineers, planners, crane operators, and supervisors, with a near-real-time operations' planning and optimization tool that can be used daily to enhance the operations of tower cranes and capitalize on the existing overlap zone. Look-ahead planning is based on an initially predefined optimal location of tower cranes and site logistics, then it utilizes newly acquired and updated information to perform near-real-time optimization of day-to-day activities and not global schedule optimization. In relation to this premise, the proposed optimization method is not in lieu of existing programming methods that have generated global optimum solutions, rather it complements these optimal solutions toward generating near-real-time schedule optimization when getting closer to execution on site.

This study primarily considers the existing overlap zone of two tower cranes by coupling look-ahead planning and a simulation and optimization engine in order to fulfil the following objectives:

1. Optimize the distribution of available work demand, balance the capacities of overlapping cranes, and match the demand with crane coverage requirements;
2. Optimize the allocation of overlapping tower cranes to construction operations;
3. Establish an algorithm for detecting collisions with the presence of overlapping operations;
4. Assess the potential benefits of overlapping cranes on reducing durations and improving crane utilization work demand; and
5. Provide a near-real-time (everyday) planning and optimization method for overlapping crane operations.

Previous Research on Tower Cranes

Previous studies have investigated tower cranes for enhancing their overall performance, safety, and productivity because they are the hub of site activities and critical to the continuous flow of work.

Crane Motion Travel Time

Leung and Tam (1999) employed multiple linear regression models to predict supply and return hoisting times that are critical for coordinating and scheduling hoisting operations. In their study, Tam et al. (2002) developed linear regression models and nonlinear neural network models for predicting hoisting times of a tower crane. Fung et al. (2008) adopted a genetic algorithm approach to optimize the vertical hoisting and storage layout on a high-rise tower building in order to reduce total transportation costs. Similarly, Tam and Tong (2003) developed a combined genetic algorithm-artificial neural network model to predict the tower crane hoisting time and determine tower crane and supply locations. Artificial neural networks and multiple regression analysis were used to model the hoisting time of cranes (Leung et al. 2001). On the other hand, Zhang et al. (1996) employed a mathematical model based on the supply, demand, and crane location Cartesian coordinates for calculating motion durations.

Crane Location and Site Layout

Zhang et al. (1996, 1999) developed stochastic simulation models in order to optimize the location of a single crane and similarly the location of multiple tower cranes based on the work schedule demand. Alkriz and Mangin (2005) used genetic algorithms to determine the optimal position for cranes and facilities. Tam et al. (2001) also used genetic algorithms for optimizing the locations of cranes and key storage areas considering the complex relationship between them while minimizing transportation time. Moreover, a combination of artificial neural networks and genetic algorithms was used to select optimal locations of cranes and supply points for high-rise construction (Tam and Tong 2003). An interesting study by Huang et al. (2011) utilized mixed-integer linear programming to search for a global optimum solution for selecting the optimal tower crane and material supply positions in order to minimize total operating cost. Other studies used genetic algorithms, geographic information system (GIS) and BIM, and computerized models to search for optimal locations (Tantisevi and Akinci 2007; Irizarry and Karan 2012).

Crane Lifting Operations

Frameworks, algorithms for planning trajectories, and methodologies such as the incremental coordination method and probabilistic road map method have been developed for motion planning of multiple cranes and synchronizing their operations to avoid collisions (Kang and Miranda 2008; AlBahnassi and Hammad 2012; Chang et al. 2012; Olearczyk et al. 2014; Tantisevi and Akinci 2007).

Others have focused on modeling the operations of tower cranes by integrating three-dimensional (3D) visualization and Special Purpose Simulation (Al-Hussein et al. 2006). Laser scanning and tracking technologies were used to model crane operator visibility to identify obstacles and enhance visibility to increase the safety of operations (Cheng and Teizer 2014). Incorporating automation, robotic crane operations are being explored and developed to enhance crane lifting operations and safety (Kang and Miranda 2006).

Researchers have utilized nondeterministic polynomial optimization to solve the problem of crane service sequence scheduling to search for the best sequence of supplying demand points based on total travel time (Zavichi 2013; Zavichi and Behzadan 2011).

While Kang and Miranda (2009) developed a mathematical model to support the simulation and visualization of crane activities, Kamat and Martinez (2001) presented a general-purpose 3D visualization system that enables spatially and chronologically accurate visualization of operations. Hasan et al. (2010) presented an integrated system dynamics model and lean concepts to simulate crane operations and reduce resource requirements. Marx et al. (2010) developed a constraint-based simulation model to evaluate execution sequences and check for spatial conflicts using the Monte Carlo optimization concept.

The safety of crane operations is highly important on job sites. Hammad and Zhang (2011) proposed real-time simulation of construction activities considering spatiotemporal resolution to improve productivity and safety of operations. Li and Liu (2012) developed a data-driven remote monitoring and alarming system for cranes by using 3D simulation to avoid accidents and increase efficiency of project management. Also, Lai and Kang (2009) utilized virtual construction simulation as an algorithm for detecting collisions.

Table 1 summarizes some previous research studies on tower cranes and highlights methods and issues targeted in this paper. This research assesses the advantages of overlapping crane operations while providing a flexible look-ahead schedule of site work demand within and outside crane overlap zones while maintaining collision-free motion paths.

Look-Ahead Planning

The last planner system (LPS) was developed to support conventional planning and scheduling practices by improving collaborative planning, enhancing workflow, improving the definition of activities, and increasing the realism of planned processes (Hamzeh et al. 2015b). The LPS outlines four major planning steps: (1) master scheduling that delineates the project milestones; (2) phase pull scheduling that defines the flow of packages or

Table 1. Summary of Some Previous Studies on Tower Cranes

Problems studied	Methods adopted	References
Hoisting time prediction	Linear regression models and nonlinear neural networks	Leung and Tam (1999) and Tam et al. (2002)
Vertical hoisting time and storage layout optimization	Genetic algorithms	Fung et al. (2008)
Hoisting time modeling	Artificial neural networks and multiple regression	Leung et al. (2001)
Single- and multiple-crane location optimization	Stochastic simulation models	Zhang et al. (1996, 1999)
Cranes and facilities position optimization	Genetic algorithms	Tam et al. (2001) and Alkriz and Mangin (2005)
Optimal crane and supply point location selection	Artificial neural networks and genetic algorithms	Tam and Tong (2003)
Global optimum solution for crane and material supply location	Mixed-integer linear programming	Huang et al. (2011)
Optimal crane location selection	Genetic algorithms and computerized optimization models	Tantisevi and Akinci (2007)
	GIS and BIM	Irizarry and Karan (2012)
Motion planning and synchronization for collision avoidance	Incremental coordination method and probabilistic road map method	Kang and Miranda (2008), AlBahnassi and Hammad (2012), Chang et al. (2012), Olearczyk et al. (2014), and Tantisevi and Akinci (2007)
Crane operations modeling	3D visualization and special purpose simulation	Al-Hussein et al. (2006)
Operator visibility	Laser scanning and tracking	Cheng and Teizer (2014)
Lifting operation and safety	Robotic crane operation	Kang and Miranda (2006)
Crane service sequence scheduling optimization	Nondeterministic polynomial optimization	Zavichi (2013) and Zavichi and Behzadan (2011)
Visualization of operations	Mathematical models, simulation and 3D visualization, system dynamics models, Monte Carlo optimization	Kang and Miranda (2009), Kamat and Martinez (2001), Hasan et al. (2010), and Marx et al. (2010)
Safety and productivity enhancement	Real-time simulation using spatiotemporal resolution; 3D virtual construction and remote simulation	Hammad and Zhang (2011), Li and Liu (2012), and Lai and Kang (2009)
Near-real-time overlapping crane allocation to tasks (travel time and load and area)	Look-ahead planning and discrete event simulation and optimization	This study

phases among different disciplines; (3) LAP that further divides tasks into executable operations a few weeks ahead of their execution, ensuring they are well studied for execution and that all prerequisites have been satisfied; and (4) weekly work commitment planning that coordinates the operations that supervisors and work teams commit to accomplish within the specified time (Ballard 2000).

Look-ahead planning involves the breakdown of activities on the master or phase schedule into operations, definition of operations, and planning of their execution methods, as well as identification and removal of constraints. Look-ahead planning, based on informed decision making, increases the likelihood of operations being performed as planned, thus improving the reliability of construction operations, reducing variation, and enhancing workflow and task handoffs among different teams. Look-ahead planning also involves the anticipation of tasks that will be executed 2 or 3 weeks later, making those tasks ready by removing time constraints for task execution (Hamzeh et al. 2015a).

The contribution of this research is the introduction of a new method that can be used daily to efficiently and safely allocate overlapping cranes on high-rise buildings to tasks that fall in their common work zone. In order to reduce crane schedule durations and balance the demand, this study targets the demand (number of tasks per working zone) and matches it with the coverage requirements of each crane, a matter that previous optimization processes (finding optimal crane locations, construction sequences, and safety planning) did not consider as part of their objectives. The novelty of this work lies in highlighting the potential benefits of overlapping space between cranes and harnessing the power of LAP and simulation to optimize clash-free crane operations, as well as providing a practical and near-real-time planning tool that can be used daily by planners and crane operators to plan construction tasks and optimize the allocation sequence of cranes.

The literature is rich in works and leading efforts to improve performance of cranes and overall site productivity. Yet, research is still narrow when it comes to utilizing the overlapping work zones for cranes and utilizing look-ahead planning to optimize the allocation of cranes. The following are some gaps in tower crane studies and practical applications:

- The planning techniques involve a single stage at the beginning of operations and logistics planning. With the lack of detailed information and limited knowledge at the start of the project, choices regarding crane positions, work demand, and resource requirements are usually selected without consideration of the inherent uncertainties in construction tasks. These choices are not usually updated and new acquired information or uncertainties are not incorporated into day-to-day operations. Also, the absence of near-real-time operations' planning results in suboptimal utilization and performance of cranes and a mismatch between an actual crane's work demand and available crane coverage.
- The traditional way of reducing the overlap of cranes to avoid the occurrence of clashes compromises flexibility in matching demand and crane coverage requirements and creates unfavorable rigid motion paths. There is limited research on how to accommodate safety concerns in the presence of cranes' overlaps.
- Unreliable planning and sequencing of crane schedules based on push systems and preset schedules can lead to suboptimal performance of cranes. Crane lift planners usually operate cranes without a well-defined schedule, thus not guaranteeing an optimal execution sequence. Without considering prerequisites that need to be satisfied prior to crane lifting, delays and safety issues

might arise, resulting in longer durations and inefficient utilization.

- The potential flexibility from having an overlapping space between cranes has not been explored in earlier studies. The impacts of the overlap area on total schedule duration, crane utilization rates, and safety considerations have not been fully explored. Satisfying site work demand inside and outside overlapping areas, properly assigning cranes to such demand, and determining the size of the overlap area that best serves the mentioned impacts have not been yet covered.
- Different zones in the work area have varying work demand and only one crane reach might not be sufficient for covering the tasks. Moreover, studies base supply and demand matching on total work demand present with respect to crane coverage area (working radius). However, current studies do not consider the number of tasks present in a specific area (work demand per area), which is important for positioning cranes.

Research Methodology and Model Framework

The research methodology followed to achieve the defined objectives is shown in Fig. 1 and involves the following steps: (1) performing LAP and preparing well-defined, constraint-free crane tasks; (2) calculating task durations; (3) creating a simulation model for the optimization process; and (4) investigating and removing clashes within the overlap zone. Each of these steps is discussed in detail in the following sections.

Performing Look-Ahead Planning and Defining Crane Activities

To manage day-to-day site operations, tasks on the master schedule should be broken down to the level of operations. Look-ahead planning is used to provide unconstrained and well-defined tasks within a reasonable window of control and flexibility to achieve the desired project goals. The LAP process accommodates changes and integrates newly acquired information as operations progress closer to their execution. Everyday planning decreases uncertainty and increases knowledge and information regarding operations to be performed.

Look-ahead planning can be used to better plan the operations of tower cranes by anticipating in advance what tasks need to be performed during a given week, then detailing them down to operations during a day, and removing any constraints. Look-ahead planning not only addresses the scheduling aspects and removal of constraints, it also looks into operations by planning the most convenient and optimal approach for crane selection and demand assignments.

The first step in the optimization procedure is preparing a daily schedule of detailed crane tasks based on which cranes will be optimally assigned. Fig. 2 presents a general framework for defining crane tasks through LAP. The LAP process starts by the phase breakdown, which involves breaking down each phase in the master schedule into weekly work processes (under the weekly work plans). As the project progresses closer to execution, the process breakdown step occurs at the beginning of each week. In this

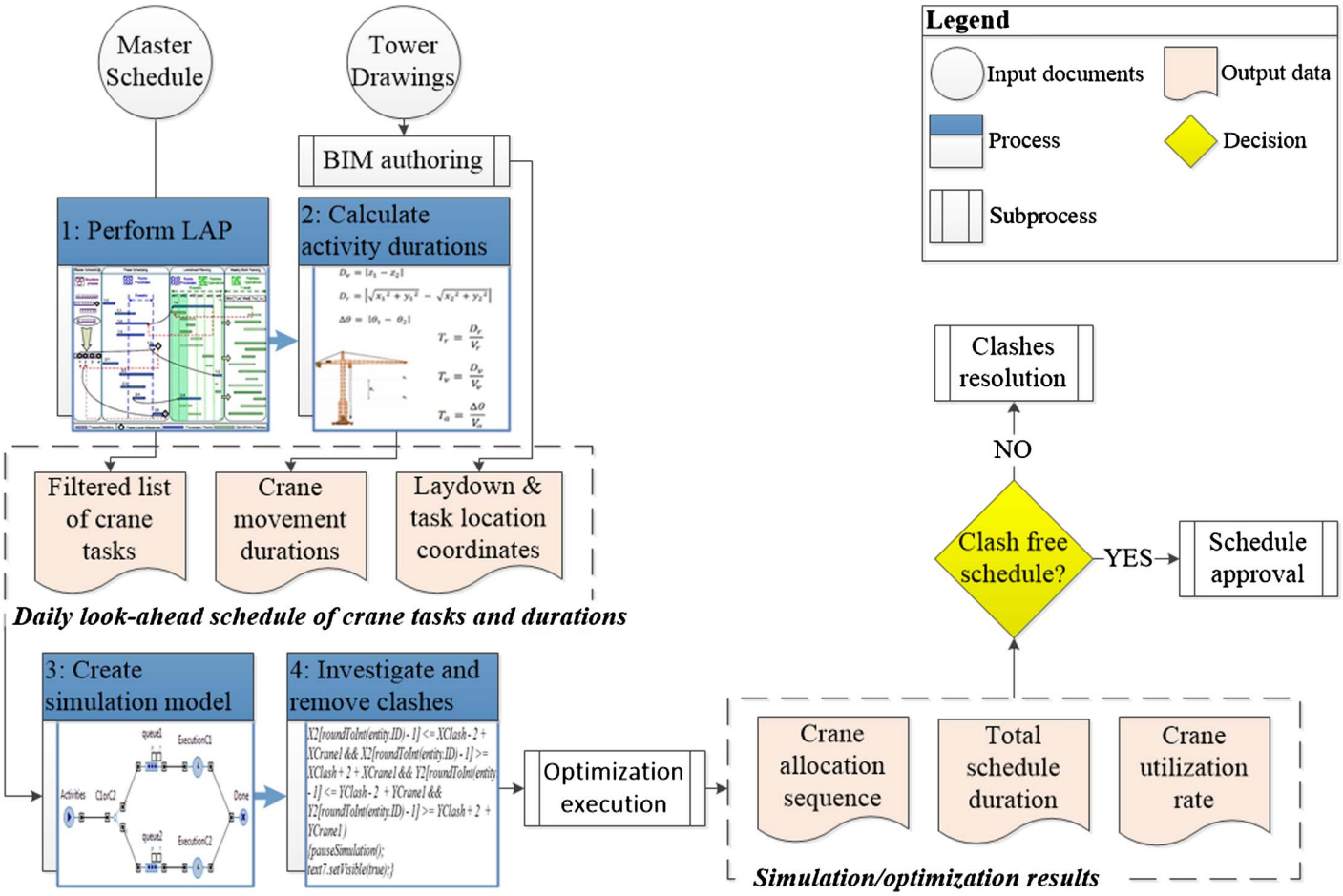

Fig. 1. Research method and model framework

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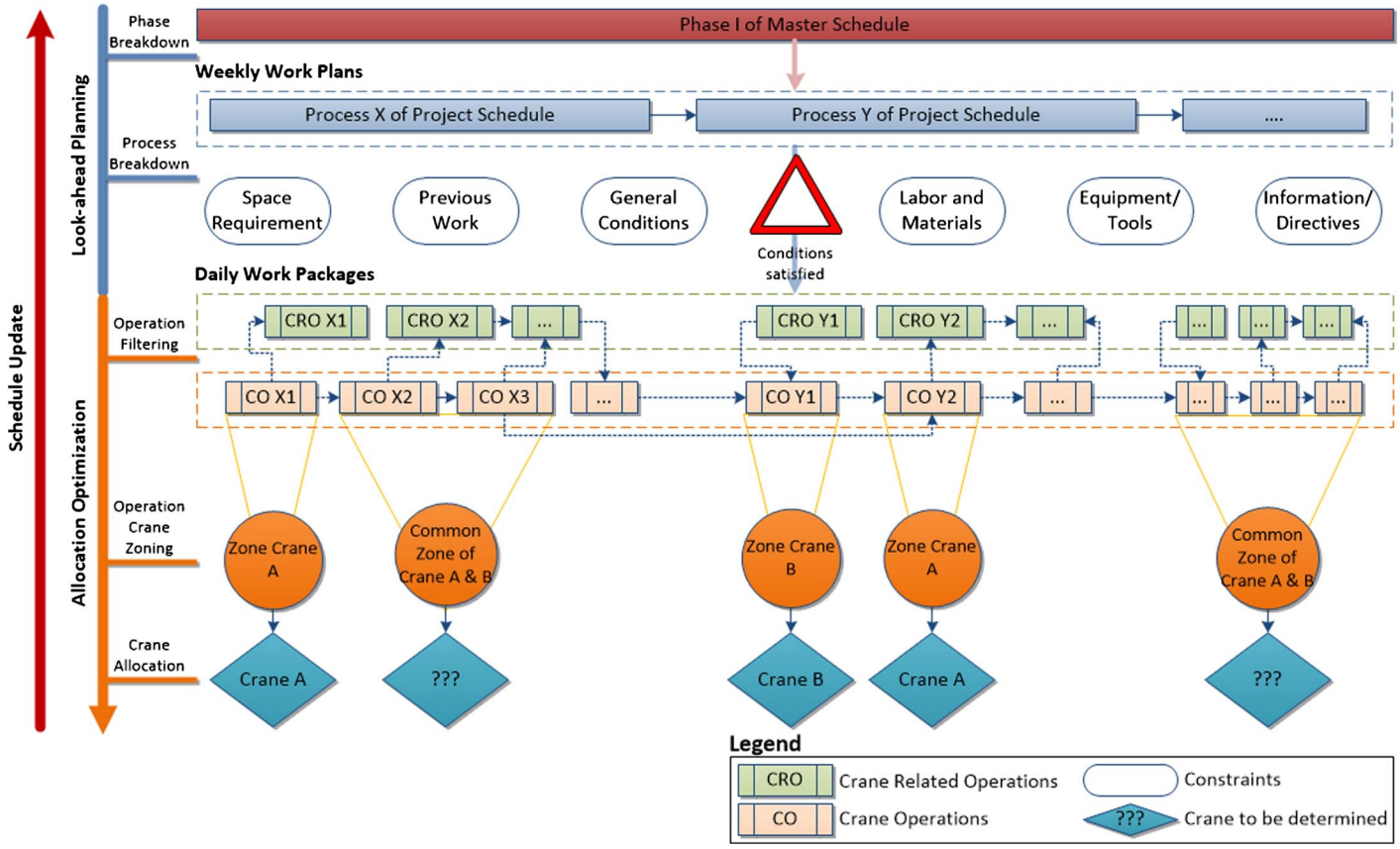

Fig. 2. Framework for look-ahead planning and crane operations definition

step, each weekly work process is subdivided into daily work operations and tasks (under the daily work packages). Process breakdown ensures that all conditions are satisfied prior to the execution of the daily work operations, namely, space requirements are fulfilled, previous work or predecessor activities are completed, general site conditions are favorable, labor and materials are available, equipment and tools are maintained and available for use, and any information, directives, and permits are prepared and present. For example, Phase I of the master schedule can be broken down into several weekly work processes (e.g., Process *X*, Process *Y*). Prerequisites for the execution of Process *X* are checked, and when satisfied, Process *X* is then broken down at the beginning of the week into daily operations (e.g., CRO X1, CRO X2) as the example shown in Fig. 3 illustrates. After preparing a daily schedule, a further filtering step, defined as operation filtering in Fig. 2, is required to define operations pertaining only to crane movements (separating crane-specific operations from other related tasks that assist in the crane operations). These crane tasks are detailed on a daily schedule that the site engineer or superintendent prepares for the next day based on the work progress and expected site demand. Each of these crane tasks then goes through the operation crane zoning step. In this step, each crane operation is manually assigned by the planner to a crane zone based on its location on the project and the resulting list of crane operations with their respective crane zone is manually entered into a Microsoft *Excel* sheet. Proceeding with the previous example, if there are two cranes A and B, and crane operation CO X1, the planner checks if crane operation CO X1 falls in the zone where only Crane A can reach, and then assigns it to the Crane A zone. Otherwise, it can be assigned to Crane B or to the overlapping zone if it falls in the common area. In the case a crane operation falls in the overlapping zone, the crane allocation step is applied in order to select the optimal crane choice. In this step, the SO model is applied to the daily schedule and automatically assigns the crane task to the suitable crane. The model

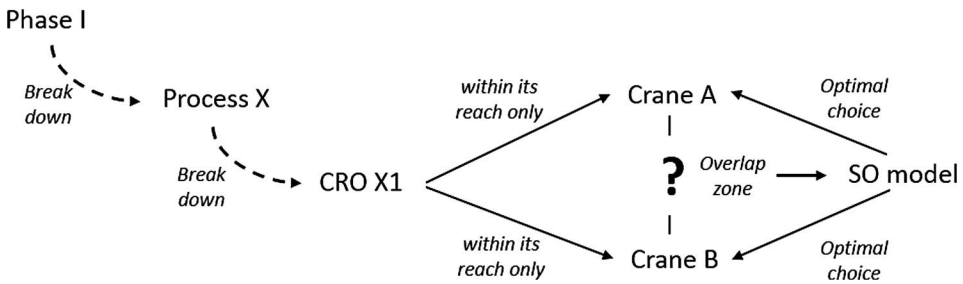

Fig. 3. LAP example

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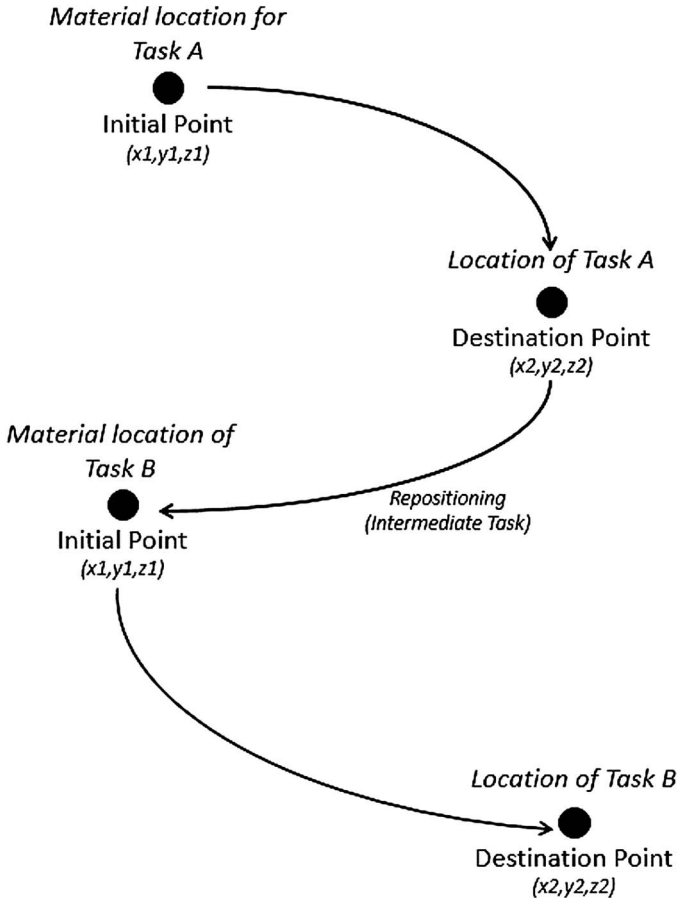

Fig. 4. Crane movement coordinates example

optimizes the overall allocations of cranes tasks falling in the joint work zone of the cranes to reduce the total daily crane duration, balance crane work demand, and maintain collision-free motion paths. The schedule is then updated with the optimal crane allocation sequence.

Calculating Durations of Crane Tasks

After defining tower crane tasks, the durations of these tasks are then mathematically calculated. Equations are geometrically derived based on the location coordinates of the task's starting and ending points including the distance to material laydown areas. These equations are based on the work of Zhang et al. (1996, 1999), which were developed to calculate the travel distance between the supply and demand points.

Each task duration consists of two parts: (1) sequence and coordinate independent duration (material loading and unloading by labor), which is measured by site observations and averaged; and (2) sequence and coordinate dependent duration, which is the duration of crane movement from the initial position to the destination position. For example, if Task A is to be performed, the material location in the laydown area serves as the initial coordinates ($x1$, $y1$, $z1$) of the movement required to perform Task A. Then, the location coordinates of Task A (where the material needs to be unloaded) serve as the destination coordinates of Task A ($x2$, $y2$, $z2$). The repositioning (intermediate) task between two consecutive tasks (e.g., Task A followed by Task B) follows a similar logic, whereby the destination location of Task A serves as the initial coordinates of the intermediate task, and the material location of Task B serves as the destination location of this intermediate task. The example is illustrated in Fig. 4. Assuming the crane center coordinates are (0, 0, 0), mathematical equations are used to calculate all durations with respect to the center.

The duration of each crane task is measured by calculating the distance traveled by the crane hook for each movement and multiplying it by the corresponding crane speed. To that end and for simplicity, the equations are based on a polar coordinate system. Eqs. (1)–(4) are derived to calculate the distances and angles of each crane task movement based on geometric and trigonometric equations. The definitions of the parameters used in Eqs. (1)–(9) are listed in the Notation and are schematically represented in Fig. 5 in reference to tower crane geometry. The heights of the cranes are adjusted and erected with the progress of floor construction. However, the calculations account for the change in height of the crane by calculating distances and durations with respect to sling elevation irrespective of the crane's jib elevation (specifically

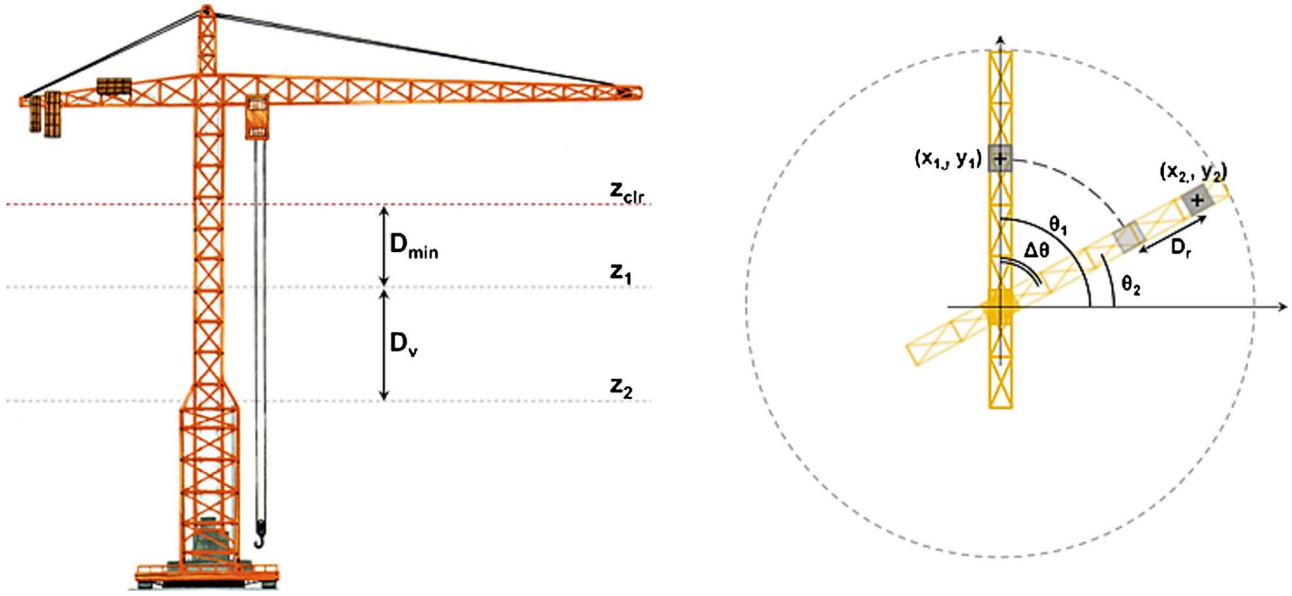

Fig. 5. Vertical, angular, and radial parameters of a tower crane

by including the z_{clr} parameter and initial and final movement point elevations).

Eq. (1) calculates the vertical distance (D_v) that needs to be traveled during the hoisting movement between two locations. It is equal to the absolute difference in elevation coordinates between the initial movement elevation (z_1) and final movement elevation (z_2). Eq. (2) calculates the radial distance (D_r) that needs to be traveled by the crane hook during the slewing movement. It is equivalent to the linear distance in the XY-plane between the initial crane location (x_1, y_1) and destination crane location (x_2, y_2). Eq. (3) measures θ_i, which is the angle formed by the crane's jib in the XY-plane with the X-axis. It can be calculated using the XY-coordinates of the hook's position along the jib. The angle's equation varies according to the hook's position, measured through the trigonometric quadrant in which the hook is located. Eq. (4) calculates the angular amount ($\Delta\theta$) by which the jib needs to be rotated from one location to another, and it is measured by the difference between the angle formed at the initial point in the XY-plane (θ_1) and the angle formed in the XY-plane at the destination point (θ_2)

$$D_v = |z_1 - z_2| \tag{1}$$

$$D_r = |\sqrt{x_1^2 + y_1^2} - \sqrt{x_2^2 + y_2^2}| \tag{2}$$

$$\theta_i = \begin{cases} \theta_i = \arctan\left(\dfrac{y_i}{x_i}\right) + \text{sgn}(y_i)[1 - \text{sgn}(x_i)]\left(\dfrac{\pi}{2}\right), x \neq 0 \\ \dfrac{\pi}{2} \text{ if } x_i = 0 \text{ and } y_i > 0 \\ -\dfrac{\pi}{2} \text{ if } x_i = 0 \text{ and } y_i < 0 \end{cases} \tag{3}$$

$$\Delta\theta = |\theta_1 - \theta_2| \tag{4}$$

The time required for each movement is obtained by applying Eqs. (5)–(9). The distance or angle is divided by the corresponding speed, which may vary depending on the type of tower crane used. Eq. (5) calculates T_r, the time needed for trolleying movement to be completed. It is measured by dividing the radial distance (D_r) between initial and destination crane locations by the trolleying radial velocity (V_r). Eq. (6) measures T_v, the hoisting time to lift the load vertically by dividing the vertical distance (D_v) in addition to the clearance distance by the hoisting velocity (V_v). Similarly, Eq. (7) calculates the time needed for slewing the jib (T_a) between the initial and destination locations by dividing the angular rotation amount ($\Delta\theta$) by the crane's slewing velocity (V_a). The three velocities (T_r, T_v, and T_a) are obtained from the crane's specification charts of velocity versus carried load

$$T_r = \frac{D_r}{V_r} \tag{5}$$

$$T_v = \frac{D_v + 2 \times D_{\text{clr}}}{V_v} \tag{6}$$

$$T_a = \frac{\Delta\theta}{V_a} \tag{7}$$

Parameter α is used in Eq. (8) to consider the time overlap between the radial and angular movements. Parameter α reflects the degree of simultaneity in moving the hook in both radial and angular directions as developed by Zhang et al. (1996, 1999). Eq. (8) accounts for this simultaneity between the two horizontal movements in the XY-plane, which are slewing and trolleying. The horizontal travel time (T_h) is considered to be equal to the longest duration of the two in addition to the shortest duration, the latter multiplied by the α factor to be specified on a case-by-case basis.

Parameter β is used to account for the operator's skill in simultaneous movement of the hook in horizontal and vertical planes. Travel time can be longer due to working site conditions such as weather conditions, obstacles, and different safety issues. Parameter k is used to account for such working site conditions and is included in Eq. (9), which was developed by Huang et al. (2011). Total travel time, which is the combination of horizontal and vertical movement times, can be calculated using Eq. (9) (Huang et al. 2011). Eq. (9) accounts for the simultaneity between the horizontal movement duration (T_h) and the vertical movement duration (T_v). The longer of the two durations is taken and the shortest duration is added to it after being multiplied by the β factor that will also be specified on a case-by-case basis. Following this step, the sum is multiplied by a factor k greater than or equal to 1 to account for wastes and contingency. Factor T_L accounts for the durations for labor loading and unloading obtained by site measurements then added to the total crane duration (T)

$$T_h = \max(T_r, T_a) + \alpha \times \min(T_r, T_a) \tag{8}$$

$$T = k \times [\max(T_h, T_v) + \beta \times \min(T_h, T_v)] + T_L \tag{9}$$

While it might be a burdensome and error-prone approach to manually calculate coordinates based on a set of two-dimensional (2D) drawings, automating the process using 3D building information modeling provides a fast and error-free schedule of all task coordinates. The user specifies on the BIM model the locations of the tasks and laydown areas, and then, through the integrated databases and automation procedures of BIM, a schedule can be simply and automatically retrieved and lists all tasks and material locations with their respective X, Y, and level or floor (Z) coordinates. Using a BIM model ensures an error-free schedule and allows for easy updates to the project.

Creating the Simulation Model for Optimization

A discrete-event simulation (DES) model is created to perform the crane allocation optimization process and detect any collisions between the cranes and the loads. Simulation is adopted in this research to solve the problem of allocating multiple cranes to a daily set of tasks that can sometimes exceed 100. Therefore, to account for all possible combinations and to mimic the real project setup, simulation is selected where traditional analytical methods are too complex and time-consuming to apply.

Although the optimization problem cannot be completely solved in analytical terms, the mathematical constructs summarizing the problem are presented and discussed in Fig. 6 for a better understanding of the optimization process through the simulation model. The objective of the optimization problem is to minimize the total crane activities' duration, where the duration can be expressed as shown in Eq. (10)

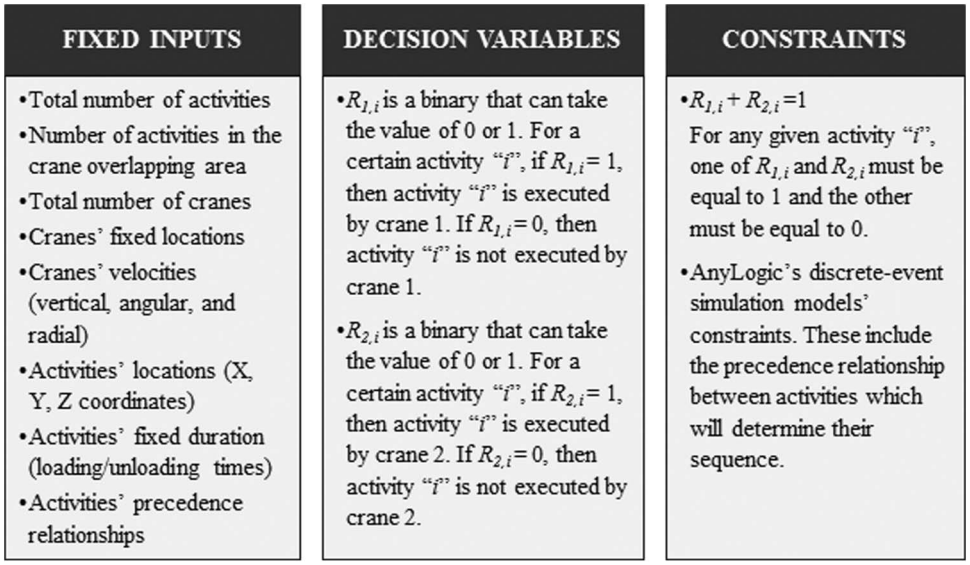

Fig. 6. Formulation of the mathematical optimization problem

$$\max\left\{\left[\sum_{i=1}^{n_1}(\mathrm{AFD}_{1,i}+\mathrm{AVD}_{1,i})+\sum_{i=1}^{s}R_{1,i}\times(\mathrm{AFDO}_i+\mathrm{AVDO}_i)+\mathrm{IV}_1\right],\left[\sum_{i=1}^{n_2}(\mathrm{AFD}_{2,i}+\mathrm{AVD}_{2,i})+\sum_{i=1}^{s}R_{2,i}\times(\mathrm{AFDO}_i+\mathrm{AVDO}_i)+\mathrm{IV}_2\right]\right\} \tag{10}$$

Some of the duration components are fixed while others are variable and depend on the decision variables. Therefore, the objective function can be simplified in a way to include only those terms affected by the decision variables. Because the objective is to minimize the total crane activities' duration, the objective function can be formulated as shown in Eq. (11)

$$\min\left\{\max\left[\left(\sum_{i=1}^{n_1}\mathrm{AVD}_{1,i}+\sum_{i=1}^{s}R_{1,i}\times\mathrm{AVDO}_i+\mathrm{IV}_1\right),\left(\sum_{i=1}^{n_2}\mathrm{AVD}_{2,i}+\sum_{i=1}^{s}R_{2,i}\times\mathrm{AVDO}_i+\mathrm{IV}_2\right)\right]\right\} \tag{11}$$

The explanation and definition of the parameters used in Eqs. (10) and (11) are listed in the Notation.

The OptQuest Engine combines Tabu search, scatter search, integer programming, and neural networks into a single, composite search algorithm (OptTek Systems 2011). Metaheuristics help guide the selection of partial search algorithms to provide a near-optimal solution for an optimization problem, thus using less effort than other computational or heuristic methods (Blum and Roli 2003). The procedures combined in the metaheuristic approach such as tabu search are used to prevent getting stuck in suboptimal or confined regions by using a memory structure (Glover 1989). This means that when a solution is tested and turns out to be suboptimal, it is marked as tabu and is not visited again during the solution search procedure. This optimizes the searching process and explores wider possibilities to find the near-optimal solution. The specific problem at hand can be considered as a combinatorial problem where it has a finite, yet very large, set of solutions (Lawler et al. 1985). The random search algorithm of the optimization engine is used because the parameters being varied in search of a near-optimal solution are of discrete nature and thus do not require the gradient of the problem to be optimized. Moreover, random search algorithms ensure convergence in probability and provide a relatively good solution quickly and easily. This method can also be applied on a broad class of global optimization problems without requiring gradient and Hessian information (Solis and Wets 1981). The simulation and optimization process is performed in the *AnyLogic7* software environment. To validate the model, degenerate tests are carried out to test how the outputs vary based on value of input and internal parameters. Face validation is then performed by consulting with experts in the field of simulation and crane operations in order to validate the logic of the model's concept and behavior as well as the rationality of the model's input and output (Sargent 2011).

Table 2 is a sample template of a Microsoft *Excel* sheet that the planner, engineer, crane operator, or supervisor can simply fill in at the beginning of the work day (or at the end of the preceding day). This file stores the parameters needed for the simulation model. The user enters the identification (ID) (designated ID for a task), list of daily crane tasks obtained by LAP, and crane task definition procedures outlined previously. The cranes used, listed in the "Res." Column in Table 2, are given a value of 0 if the task falls in the joint work zone and needs to be assigned based on the optimization model, a value of 1 if it will be performed by Crane 1, and a value of 2 if it will be performed by Crane 2. The user specifies the relationships between tasks under the "Constrained," "SS," and "FS" columns. The X, Y, and Z columns pertain to the crane task coordinates in reference to the center point of the respective crane and are obtained through *Revit* or the desired BIM software. For example, consider Task 1 to be load steel from Laydown Area 1 to Zone 5 on Floor 10, which can be conducted by either Crane 1 or 2. Thus, a resource value of 0 is assigned. Because the crane resource is not yet assigned to this task, Task 1 will have two sets of initial coordinates accounting for the two crane options (from Crane 1 or from Crane 2 to location of steel in Laydown Area 1). The calculation of Task 1's duration will be performed in an iterative manner, starting with an initial assumed duration value based on one of the coordinate sets. The optimization results then

Table 2. Sample Data Input Sheet for Simulation Model

Identifier	Res.	Duration (min)	Constrained	SS	FS	X_1	Y_1	Z_1	X_2	Y_2	Z_2
1	0	3.80	False	—	—	−22.62	11.84	0.40	22.89	12.28	0.40
2	0	1.80	True	—	1	7.42	−22.32	60.24	−5.07	24.62	60.24
3	2	6.00	True	2	—	—	—	—	9.79	−13.84	0.40
4	2	4.00	True	—	3	—	—	—	−25.43	4.90	32.02
5	1	6.00	True	2	—	−7.02	10.83	0.40	—	—	—

Note: FS = finish-to-start; Res. = crane resource; SS = start-to-start.

give the specific duration based on the selected crane resource and the respective coordinate set. Then, Task 2, unload steel at Zone 5 on Floor 10, which depends on the completion of Task 1, will have a constrained value of true (having a finish-to-start dependency with Task 1) and so on with Task 3 The total duration of crane tasks and utilization rates will be generated based on the overall scheduled tasks and the dependencies within them. Therefore, the optimization process considers the interactions between tasks within and outside the overlapping area and optimizes the allocation by satisfying the whole, not only a part of the schedule.

The DES model presented in Fig. 7 takes the files named ExcelPar (Table 2) and ExcelDur file (which calculates durations in Microsoft *Excel*) as inputs for the optimization process. Also, N is the parameter for the number of daily crane tasks, and X crane1 and Y crane1 are coordinates of one crane with respect to the other. The counters i, j, k, and c are used to update the status of the simulation model after executing an event. The columns of the data summarized in Table 2 are translated into as arrays in the simulation model. Variables such as X 1temp and Y 1temp are used to compare the position of one crane when executing the current task to the position of the other crane at the same time in order to check for any clashes.

Activities (crane tasks) listed in the Microsoft *Excel* sheet enter the system based on the specified dependencies between them. The model then routes each task to either of the cranes based on the resource specified in Table 2, executes the task with its calculated duration, and finally the task leaves the system as done. When the task falls in the joint work zone and thus needs to be assigned to one of the cranes, the optimization process allocates a crane based on the crane's status (busy or idle) as well as which crane allocation sequence combination provides the shortest total crane schedule duration. The model then outputs the total duration of the crane tasks for all possible allocation combinations and the utilization rates of the cranes, and detects any clashes. The simulation model can be performed up to the desired number of runs to provide the required accuracy of results. Because the optimization algorithm incorporates a metaheuristic approach, the simulation can be terminated when the optimal solutions converge to a specified set of values where the differences are very minimal.

Investigating and Removing Clashes within the Overlap Zone

Clashes can be categorized based on the crane's movement status (i.e., moving, loading and unloading, or idle), or based on which part of the crane is colliding with another crane (e.g., jib, sling, carried object). Clashes that can occur while at least one of the two cranes is moving require the operator to adjust the crane's movement path to avoid the clash. During loading and unloading, the crane position is static and laborers are working to either hook or unhook material to the crane. In fact, if a crane needs to be loaded or unloaded at the same location the other crane is being loaded or unloaded, there is nothing the operator can do to avoid

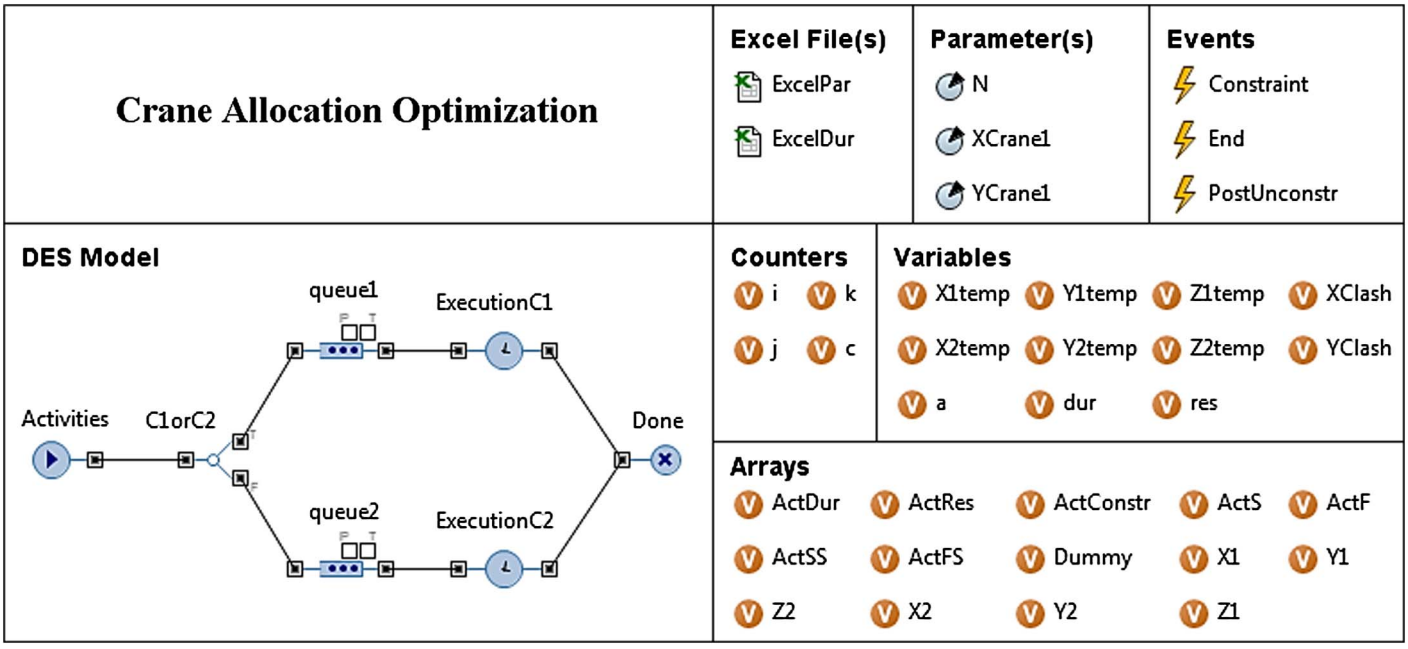

Fig. 7. Simulation model and parameters for optimizing crane allocation

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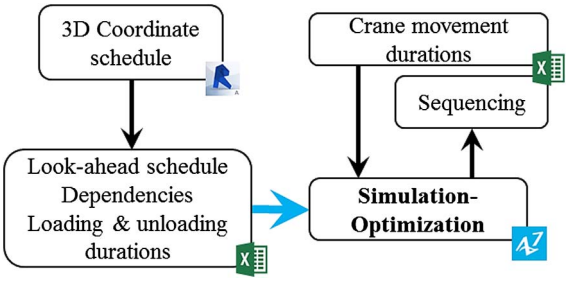


Fig. 8. Interface of the LAP simulation model

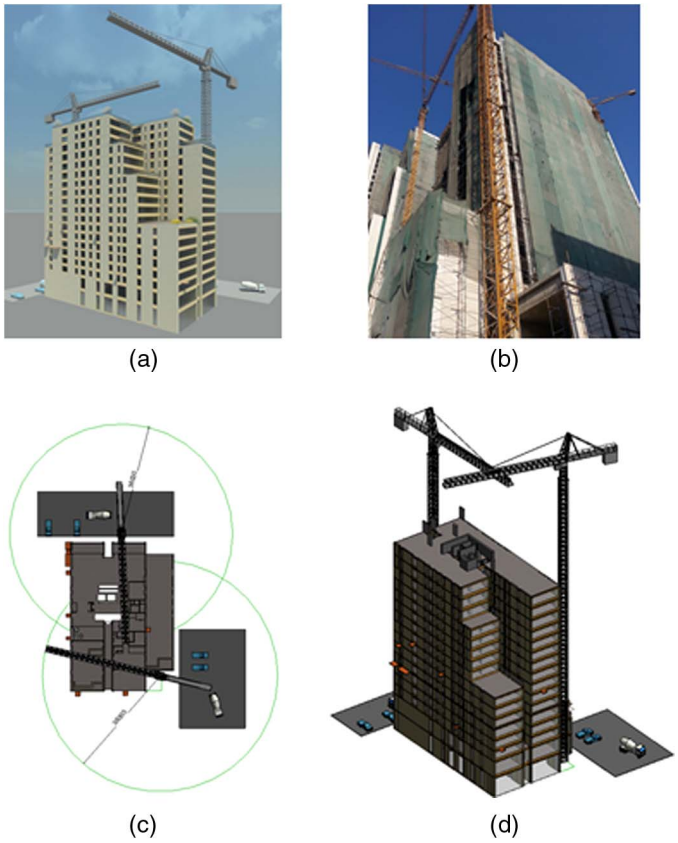


Fig. 9. Tower case study: (a) tower model in Revit; (b) real image of the tower (image by Malak Al Hattab); (c) laydown and overlap areas of cranes; (d) progress of construction on Floor 16

the clash but wait until the other crane has finished loading or unloading.

To detect these types of clashes, the clash detection algorithm in the model evaluates the coordinates of the Crane 1 position and those of Crane 2 at the same time of operation. It also accounts for the object size being carried by adding a margin of ±2 m to the coordinates. The algorithm in this sense checks how the cranes are positioned with respect to each other at each given instance in time. The clash process is based on checking for any collisions between the motion areas and paths of the cranes. If the zone covered by the hook and the object of one crane overlaps with the respective zone of the other crane, a clash will occur and is detected by the mathematical algorithm. Future work will focus on the effect of potential clashes during crane movement to assess the extent of their effect on delays and the required measures to avoid them. Resolving collisions would require a rearrangement of crane allocation sequences that yield similar optimal results, or if the results turn out to be suboptimal after the rearrangement the initial LAP schedule of the daily tasks should be modified. The process of optimization and LAP is therefore iterative.

The optimization method integrates three main processes that interact in the manner depicted in Fig. 8. The 3D coordinate schedule obtained through *Revit* is used as input for the daily look-ahead schedule tabulated in Microsoft *Excel* to automate the calculations of crane task durations, which are listed along with the task dependencies and loading and unloading durations. Then the simulation model performs metaheuristic optimization in *AnyLogic7* using the Microsoft *Excel* parameter file as input, then outputs the crane allocation sequence back into Microsoft *Excel*. Because some of the crane tasks that fall in the joint zone are not initially assigned to a specific crane, an iterative process of calculating the duration of such a task with reference to the center of each crane is required to obtain the final crane movement duration and crane allocation sequence. Therefore, an iterative loop exists between the SO results and crane movement calculation to select the optimal allocation of the crane and the respective crane movement duration based on the coordinates of the resulting assignment.

Case Study

The developed research methodology and simulation model were applied to a case study of a high-rise building within a residential tower complex. The tower, shown in Fig. 9, consists of 18 stories with apartment sizes varying between 255 and 1,197 m^2. A Potain 428G (Manitowoc Company, Manitowoc, Wisconsin) crane with a radius of 36 m and a Potain 764E crane with a radius of 38 m are employed on the tower for lifting operations. The two cranes overlap at an approximate area of 993 m^2.

The time frame of the study was selected during the concrete phase of Floor 16 with finishes, mechanical, electrical, plumbing (MEP), and masonry works occurring at the lower levels concurrently. The crane load intensity level (demand) through a given day is considered to be normal (no peak in demand). The master schedule and 2D shop drawings were provided by the general contractor.

The master schedule for the concrete, MEP, masonry, and finishing was broken down into weekly work packages according to the framework shown in Fig. 2. The weekly packages were then detailed into daily work tasks at the onset of the working week as outlined in Fig. 10. The daily work tasks project the expected site demand for the cranes. Out of each daily work schedule, tasks requiring the use of cranes are filtered, and then they are detailed further into crane-specific task movements. The breakdown in Fig. 10 was performed for all packages, resulting in a daily schedule of crane tasks, each with a specified name and code. The crane zone indicates where each task falls, either in the zone of Crane 1 alone, Crane 2 alone, or in the common zone for both cranes. All tasks falling in the common zone have a crane assigned based on the optimization process.

To calculate the coordinates for the locations of crane tasks, a 3D BIM model in *Revit* was used. A 3D BIM model (Fig. 10) was built to obtain the coordinate schedule. Although coordinates are annotations in *Revit* and thus cannot be directly retrieved from the schedule, a simple family was created for this purpose. The family consists of a model line, with an origin point placed at the center point of the crane in the *Revit* model and an ending point placed at the location of the task or material laydown area. Then, two dimensions (assigned as parameters that will be retrieved in the schedule) are defined to allow for measuring the horizontal (X) and vertical (Y) distances to the specified locations. This process automates the generation of the schedule of coordinates. Fig. 11

	Master Schedule Milestones	Timeline	Crane Zone	Code	Complete Concrete Works	Crane Zone	Code	Complete MEP Works
Look-ahead Planning	Weekly Work Processes	Week 1		SEC16	Complete Steel Erection for Columns on floor 16		MEP2F10	Complete MEP 2nd fixes on floor 10
				FEC16	Complete Formwork Erection for Columns on floor 16		MEP2F11	Complete MEP 2nd fixes on floor 11
				CPC16	Complete Concrete Pouring and curing for Columns on floor 16		MEP3F8	Complete MEP 3rd fixes on floor 8
				FPS17	Complete formwork placement for Slab on floor 17			
				EEI17	Complete embedded equipment installation on floor 17			
				SPS17	Complete steel placements for Slab on floor 17			
				CPS17	Complete concrete pouring and curing for Slab on floor 17			
		Week 2		…	Complete Steel Erection for Columns on floor 17		…	Complete MEP 2nd fixes on floor 12
				…	Complete Formwork Erection for Columns on floor 17		…	Complete MEP 2nd fixes on floor 13
				…	Complete Concrete Pouring and curing for Columns on floor 17		…	Complete MEP 3rd fixes on floor 9
				…	Complete formwork placement for Slab on floor 18			
				…	Complete embedded equipment installation on floor 18			
				…	Complete steel placements for Slab on floor 18			
				…	Complete concrete pouring and curing for Slab on floor 18			
	Daily Tasks	Day 1		SEC16T1	Complete steel erection for 4 columns on floor 16		MEP3F8T1	Complete MEP 3rd fixes on floor 8
				FEC16T1	Complete formwork erection for 4 columns on floor 16			
		Day 2		…	…		…	…
		…		…	…		…	…
Allocation Optimization	Tasks involving cranes	Day 1		SEC16CRT1	Complete steel erection for 3 columns on floor 16		MEP3F8CRT	Complete MEP 3rd fixes on floor 8
				FEC16CRT1	Complete formwork erection for 3 columns on floor 16			
	Crane Operations	Day 1	Common	SEC16CO1	Lift steel batch to column 6 on floor 16	2	MEP3F8CO1	Lift HVAC system components to floor 8
			Common	SEC16CO2	Lift steel batch to column 6 on floor 16	2	MEP3F8CO2	Lift HVAC system components to floor 8
			Common	FEC16CO1	Lift formwork panels to column 5 on floor 16	1	MEP3F8CO3	Lift HVAC system components to floor 8
			Common	FEC16CO2	Lift formwork panels to column 5 on floor 16	1	MEP3F8CO4	Lift plumbing components to floor 8
			Common	SEC16CO3	Lift steel batch to column 7 on floor 16	2	MEP3F8CO5	Lift fire fighting system components to floor 8
			Common	SEC16CO4	Lift steel batch to column 7 on floor 16	2	MEP3F8CO6	Lift plumbing components to floor 8
			Common	FEC16CO3	Lift formwork panels to column 5 on floor 16	2	MEP3F8CO7	Lift fire fighting system components to floor 8
			Common	SEC16CO5	Lift steel batch to column 6 on floor 16			
			Common	SEC16CO6	Lift steel batch to column 6 on floor 16			
			Common	FEC16CO4	Lift formwork panels to column 5 on floor 16			
			Common	SEC16CO7	Lift steel batch to column 7 on floor 16			

Fig. 10. Sample of LAP and crane task definition

illustrates a sample of the *Revit*-based coordinate schedule, with the "Mark" column identifying the task name or code and the (X, Y, Z) coordinates. This *Revit* schedule lists the crane tasks (developed through LAP) with their respective coordinates, and it is then used as input for the SO model.

The durations of crane movements were calculated based on the location of the laydown areas and tasks, taking into account task sequence as well as the location of the initial and destination points. In order to benchmark the results of the LAP and optimization model and its impact on tower crane operations, two scenarios were created: Scenario 1 with insufficient planning and Scenario 2 with proper LAP. The simulation model was then executed for each scenario to obtain the optimal results as well as the suboptimal results in order to assess the effects of optimization.

Therefore, by exploring two setups of LAP and two results of optimization (suboptimal and optimal), four different cases are generated: (1) Insufficient planning with suboptimal case results; (2) insufficient planning with optimal case results; (3) proper LAP with suboptimal case results; and (4) proper LAP with optimal case results. The results of the four setups are compared to measure the combined impact of LAP and optimization. The same list of crane tasks and dependencies was used in all scenarios to have a similar basis for comparison. The scenarios in this study represent a few samples out of several. The results would therefore vary depending on the setup done by the responsible parties.

Scenario 1: Insufficient Planning

A scenario was selected to reflect insufficient planning performed by the engineer, planner, or supervisor. In this regard, the planning process did not account thoroughly for aspects such as balancing resource assignment, planning locations of laydown areas, and making use of the overlapping work zone area. Looking at the LAP, 27% of the tasks were assigned to the overlapped work zone, 54% of the tasks were assigned to the work zone of Crane 1, and the remaining tasks were assigned to the work zone of Crane 2. The major laydown area (steel, formwork, MEP equipment, interior finishes, cladding, masonry, just-in-time delivery trucks) was improperly positioned to be in the reach of Crane 1 only, whereas Crane 2 was assigned a separate steel and formwork laydown area only.

Given this setup, Crane 1 is overloaded with tasks as opposed to Crane 2. The overlapping work zone area is not loaded properly such that a few tasks are assigned to either Crane 1 or 2 and therefore have less operational flexibility. Moreover, the laydown areas are not conveniently located to supply both cranes equally, a situation that necessitates the utilization of Crane 1 to assist Crane 2 in delivering material midway.

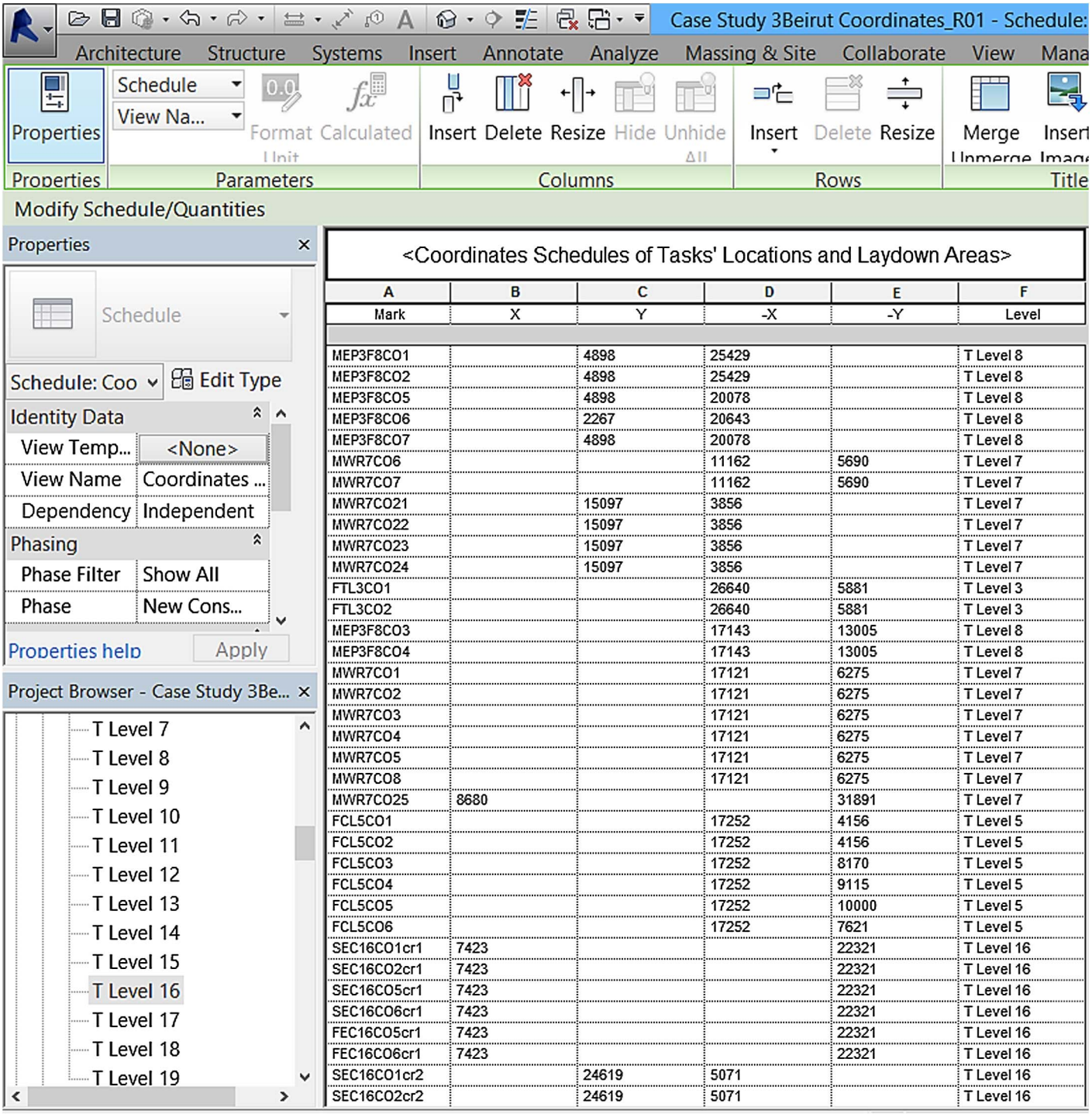
Scenario 2: Proper Look-Ahead Planning

This scenario assumes that the responsible parties (e.g., engineer, planner, supervisor, crane operator) have performed sufficient LAP. The crane tasks were assigned according to the following distribution: 50% of tasks to the overlapping work zone, 27% of tasks to Crane 1, and 23% of tasks to Cane 2. In addition, two major laydown areas were allocated to both cranes so they are able to reach the material without requiring assistance from the other crane.

This setup implies that the overlapping work zone was loaded properly to increase flexibility of crane assignment to the tasks, the work demands of Cranes 1 and 2 are similar to some extent, and the laydown areas would fully supply each crane and save on assistance needed.

Results and Discussion

After completing the planning process, the simulation model shown in Fig. 8 was applied to both scenarios to obtain the durations and utilization rates for the different combinations. Because the optimization algorithm is based on a metaheuristic approach, suboptimal



<Coordinates Schedules of Tasks' Locations and Laydown Areas>

A	B	C	D	E	F
Mark	X	Y	-X	-Y	Level
MEP3F8CO1		4898	25429		T Level 8
MEP3F8CO2		4898	25429		T Level 8
MEP3F8CO5		4898	20078		T Level 8
MEP3F8CO6		2267	20643		T Level 8
MEP3F8CO7		4898	20078		T Level 8
MWR7CO6			11162	5690	T Level 7
MWR7CO7			11162	5690	T Level 7
MWR7CO21		15097	3856		T Level 7
MWR7CO22		15097	3856		T Level 7
MWR7CO23		15097	3856		T Level 7
MWR7CO24		15097	3856		T Level 7
FTL3CO1			26640	5881	T Level 3
FTL3CO2			26640	5881	T Level 3
MEP3F8CO3			17143	13005	T Level 8
MEP3F8CO4			17143	13005	T Level 8
MWR7CO1			17121	6275	T Level 7
MWR7CO2			17121	6275	T Level 7
MWR7CO3			17121	6275	T Level 7
MWR7CO4			17121	6275	T Level 7
MWR7CO5			17121	6275	T Level 7
MWR7CO8			17121	6275	T Level 7
MWR7CO25	8680			31891	T Level 7
FCL5CO1			17252	4156	T Level 5
FCL5CO2			17252	4156	T Level 5
FCL5CO3			17252	8170	T Level 5
FCL5CO4			17252	9115	T Level 5
FCL5CO5			17252	10000	T Level 5
FCL5CO6			17252	7621	T Level 5
SEC16CO1cr1	7423			22321	T Level 16
SEC16CO2cr1	7423			22321	T Level 16
SEC16CO5cr1	7423			22321	T Level 16
SEC16CO6cr1	7423			22321	T Level 16
FEC16CO5cr1	7423			22321	T Level 16
FEC16CO6cr1	7423			22321	T Level 16
SEC16CO1cr2		24619	5071		T Level 16
SEC16CO2cr2		24619	5071		T Level 16

Fig. 11. Sample of coordinate schedule extracted from *Revit*

and optimal results are reached in the searching process. A total of 2,000 runs for each setup are executed to ensure the values do not change after the suboptimal and near-optimal have been reached. For each scenario, the simulation model is run 2,000 times to reach the suboptimal case out of many combinations, and then 2,000 runs are simulated to reach the optimal case.

The suboptimal and optimal results for Scenario 1 are plotted in Figs. 12 and 13 respectively, and those of Scenario 2 are plotted in Figs. 14 and 15, respectively. The *x*-axis represents the number of runs (combinations) and each gray point represents a combination of a crane allocation sequence. The *y*-axis indicates the duration of the daily tasks schedule in minutes. The solid line traces the trend of either the optimal (lowest) durations as in Figs. 12 and 14, or the suboptimal (longest) durations as in Figs. 13 and 15.

The simulation output plotted in Figs. 12 and 13 shows that the optimization outcomes for the suboptimal and optimal results of insufficient planning converge to near-optimal solutions after a lower number of runs (approximately 100). On the other hand, the output in Figs. 14 and 15 shows that the suboptimal and optimal results are obtained after a higher number of runs (from 600 to 950) for proper LAP. This pertains to insufficient planning having

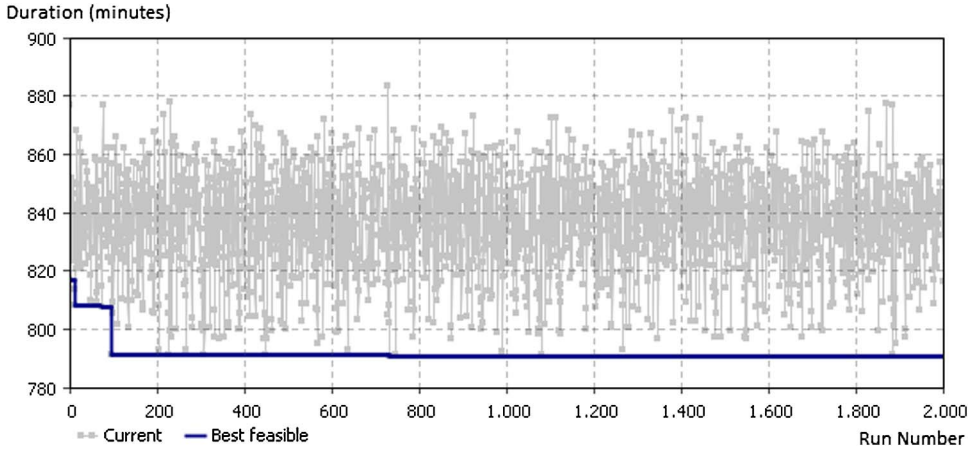


Fig. 12. Shortest simulation runs duration results for insufficient LAP

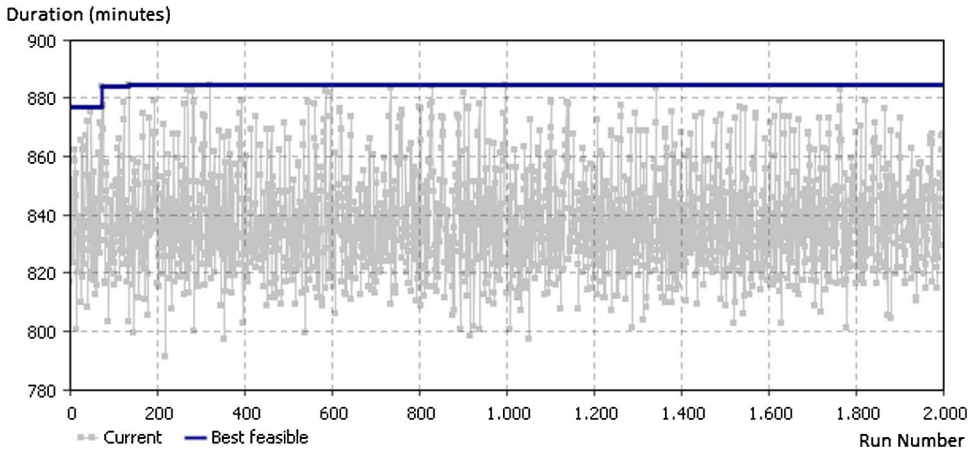


Fig. 13. Longest simulation runs duration results for insufficient LAP

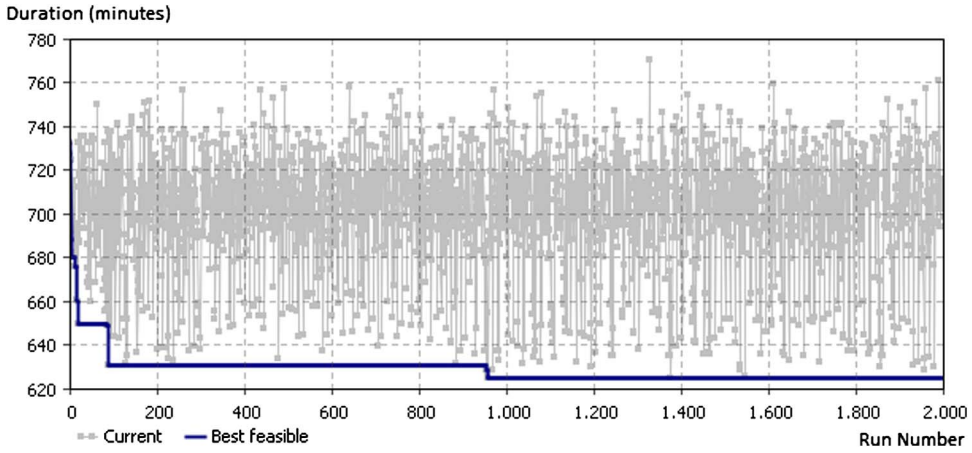


Fig. 14. Shortest simulation runs duration results for proper LAP

only 27% of tasks in the overlapping area as opposed to 50% of tasks assigned during proper LAP (almost double the percentage). With the increase in number of tasks in the overlapping area, the number of combinations to be explored grows rapidly, and it takes more runs to reach a converging value for the optimal solution.

Schedule Duration

The results illustrated in Figs. 12–15 are summarized and graphed in Fig. 16. Insufficient planning results in a suboptimal total crane schedule duration of 884 min, which is longer than the suboptimal duration of proper LAP (792 min). The shortest schedule duration

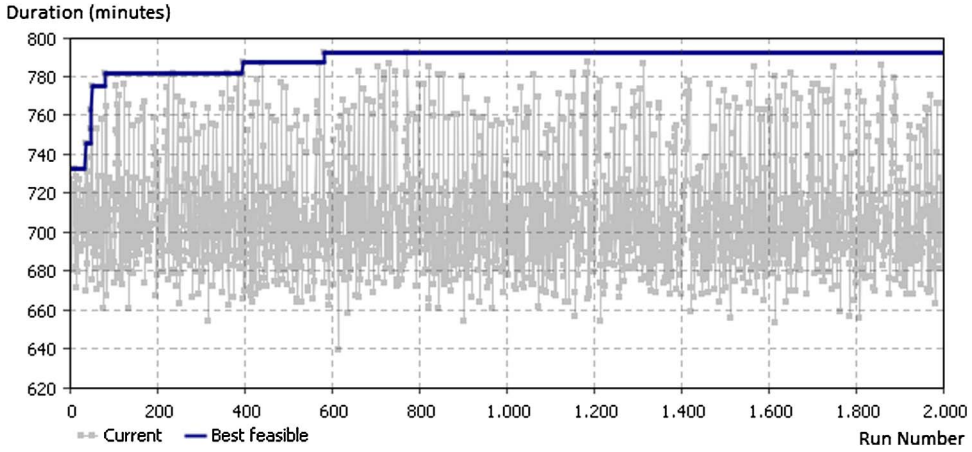


Fig. 15. Longest simulation runs duration results for proper LAP

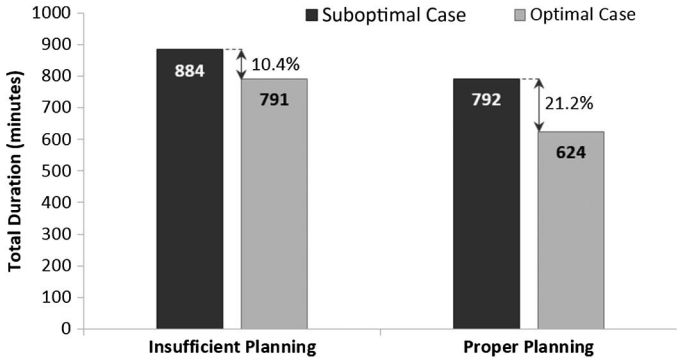


Fig. 16. Impact of optimization and proper planning on schedule duration

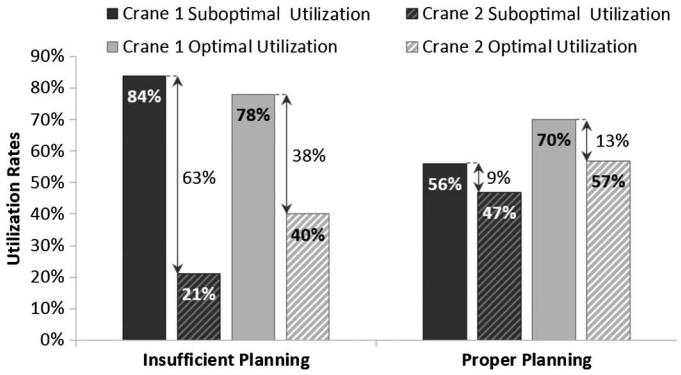


Fig. 17. Impact of optimization and proper planning on crane utilization

of insufficient planning resulted in 790.72 min, reflecting a 10.4% reduction in total crane schedule duration as a result of performing optimization. On the other hand, the shortest duration of proper LAP yielded a shorter duration of 624 min, which is lower than the optimal case of insufficient planning (791 min), and reflects a 21.2% reduction in total crane schedule duration attributed to optimization. The improvement resulting from optimization was doubled for proper planning.

The proper use of the overlapping work zone area and allocating tasks accordingly allows greater opportunity to reduce the overall project duration. This is due to the fact that this approach provides greater flexibility and identifies better allocation sequences through optimization. Given the same list of tasks and dependencies in each planning scenario, the initial proper planning effort combined with optimization yielded better improvement. The optimization employed allows the reduction of total duration by targeting the task load within the coverage area instead of only focusing on crane coverage as an optimization criterion.

Resource Utilization

The utilization rate for each crane obtained by the SO model is plotted in Fig. 17. The rate for Crane 1 reached 84% under suboptimal results of insufficient planning, whereas Crane 2 had a much lower rate of 21%. The optimal results of insufficient planning showed a slight decrease to 78% for Crane 1, with an increase in the utilization rate of Crane 2–40%, hence reducing the imbalanced demand gap between Cranes 1 and 2 from 63 to 38%. The peak utilization rate of Crane 1 as opposed to Crane 2 can be attributed to the inconvenient distribution of the crane tasks where Crane 1 was initially overloaded. Moreover, with the major laydown area supplying Crane 1 only, more demand is therefore transferred to this crane to assist Crane 2 in the material supply process. With only 27% of tasks assigned to the overlapping work zone, there is less flexibility for improvement, resulting in a large imbalance in the work demand of both cranes, even after optimizing for the most balanced results.

The suboptimal work demand output of proper planning resulted in utilization rates of 56 and 47% for Cranes 1 and 2, respectively, with a 9% gap. The optimal results of optimization show an increase in both utilization rates to 70 and 57%, respectively, with a slight increase in the gap to 13%. Both utilization rates were enhanced upon optimization, and the work demand can be considered balanced when compared with the rates of insufficient planning. These results can be attributed to the proper initial planning where tasks were assigned relatively similarly to both cranes, and nearly 50% of the tasks were assigned to the overlapping work zone. This in turn increases flexibility and improves the results of the optimization process.

On the other hand, the utilization rates in the proper planning scenario did not reach 100% for each crane. In fact, the sequence in which the optimization of crane allocation takes place is geared toward reducing the total duration. For example, one sequence might be chosen over another when it is preferable for one crane to remain idle than handle an upcoming task, causing the other

crane to be much idler and extending the overall time. Therefore, the utilization rates will be more balanced even if they do not reach 100% each.

The crane demand during a single day is considered average in this study. Therefore, the utilization rates for both cranes might be much higher because more tasks will be handled by the cranes during the daily working hours. It is expected that this model will be more beneficial when used with a higher demand on cranes, where optimization of crane allocation might be impossible using traditional optimization methods. However, this claim requires further study.

The potential reduction in duration, balancing of crane utilization rates, and safe execution of crane operations depends on the range of the overlapping area and the work demand distribution in each zone. The determination of the convenient overlap area that yields optimal results requires further study in order to specify the extent of overlap that can maximize the desired benefits without compromising factors such as safety, speed, and idleness.

Conclusions and Future Research

This paper presents a near-real-time model for optimizing the operations of tower cranes by considering the overlapping space as well as distributing and matching work demand and crane coverage requirements. Assuming preset crane locations, the study targets the work and matches it with the coverage requirements for each crane in order to balance the demand and reduce the total duration of tasks. Look-ahead planning and crane task definition allow users to prepare a reliable daily schedule of tasks to be performed by the cranes when all task prerequisites are made ready. The durations of these tasks are then calculated based on a set of mathematically derived equations and a BIM-based coordinate system. This schedule is then used as input to a SO model that applies metaheuristics to search for optimal sequences of crane allocations and detect any collisions. In order to benchmark the impacts of LAP and optimization, two scenarios were created for a case study, one for insufficient planning and another for proper LAP. Simulation-optimization was then executed on each scenario to obtain the suboptimal and optimal results in order to compare the combined impact of both LAP and optimization.

Results from the case study indicate that the crane schedule duration and utilization rates of proper LAP can be further improved through optimization. On the other hand, optimization has minimal impact if the initial planning process is not performed adequately. Therefore, an enhanced sequence of the allocation of tower cranes can be obtained if the initial LAP is performed properly, followed by optimization. With good input, the optimization model can yield improved results, thus the combined impact of LAP and optimization provides better outcomes.

This paper contributes to research on optimization of tower cranes, providing the industry with a near-real-time planning and optimization process and tool that can be easily used on a daily basis to plan and optimize crane operations. This reduces the overall crane schedule duration, better distributes demand and crane coverage, and enhances crane utilization rates while maintaining clash-free motion paths. Future research is needed for the allocation of multiple overlapping cranes, identifying and resolving clashes simultaneously in a four-dimensional environment.

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Notation

The following symbols are used in this paper:

AFD_{ji} = fixed component of crane j's activity i duration, corresponding to either loading or unloading time;

AFDO_i = fixed component of crane j's activity i duration, corresponding to either loading or unloading time in the crane overlap area;

AVD_{ji} = variable component of crane j's activity i duration, corresponding to crane maneuvering time from supply to demand points; it is a function of the activities' sequencing and the resource allocation, which corresponds to the model's decision variables, and is a function of $R_{1,i}$ and $R_{2,i}$, that is, $\mathrm{AVD}_{ji} = f(R_{1,i}; R_{2,i})$; AVD_{ji} is calculated through the model;

AVDO_i = variable component of crane j's activity i duration in the crane overlap area, corresponding to crane maneuvering time from supply to demand points; it is a function of the activities' sequencing and the resource allocation, which corresponds to the model's decision variables, and is a function of $R_{1,i}$ and $R_{2,i}$, that is, $\mathrm{AVDO}_{ji} = f(R_{1,i}; R_{2,i})$; AVDO_{ji} is calculated through the model;

D_r = radial distance moved during trolleying;

D_v = vertical distance moved during hoisting;

IV_j = crane j's idle time; similar to AVD_{ji}, it is a function of R_1 and R_2 where $IV_j = f(R_{1,i}; R_{2,i})$;

k = coefficient for site conditions (e.g., wind, obstruction);

n_j = number of crane activities located exclusively in crane j's work area;

s = number of crane activities located in the common work area of Cranes 1 and 2;

T = total time of movement from Point 1 to Point 2;

T_a = time of slewing in minutes;

T_h = time of horizontal movement in minutes;

T_l = time of loading or unloading;

T_r = time of trolley movement in minutes;

T_v = time of hoisting in minutes;

V_a = angular velocity (m/min);

V_r = radial velocity (revolutions per minute);

V_v = vertical velocity (m/min);

X = horizontal coordinate;

Y = vertical coordinate;

Z = elevation (floor-level) coordinate;

Z_{clr} = clearance of hook (~2 m);

α = simultaneity degree of horizontal plane movements;

β = degree of simultaneity of vertical plane movements;

$\Delta\theta$ = angle moved during slewing;

θ_1 = polar angle of Point 1; and

θ_2 = polar angle of Point 2.

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