OPTIMIZING JOINT OPERATION OF TWO TOWER CRANES THROUGH LOOK-AHEAD PLANNING AND PROCESS SIMULATION

Malak Al Hattab[1], Emile Zankoul[2] and Farook Hamzeh[3]

ABSTRACT

Proper planning of on-site operations is critical to the effective delivery of a construction project. Many construction works, especially in high-rise buildings, require using tower cranes. In fact, early planning of tower crane operations before site execution helps reduce operational costs, enhance site safety, and optimize the works' schedule. Lean principles and look-ahead planning in particular, along with 4D scheduling (time and location) of tower crane activities allow achieving optimal use of cranes. The purpose of this paper is to optimize the use of two tower cranes by simulating the scheduling of tasks in the overlapping work zones to achieve shorter operation durations and higher crane utilization rates. Early experimentation with the system and real-time assessment of alternative solutions reduce on-site problems and delays. In this respect, an optimization model based on parametric variation is developed for studying two cranes by using, as input, the construction schedule detailed down to daily operations through look-ahead planning. The model is also applied on a pilot case study to demonstrate the logic and outcomes of the model. The research contributes towards providing engineers, planners, crane operators, superintendents, and foremen with a model that can be used daily to better plan, in advance, the tasks to be executed by the cranes. The model can therefore provide a balanced workload schedule for both cranes and achieve the best utilization rates while reducing idle times to ultimately boost the production of the cranes while reducing project duration and cost.

KEY WORDS

Tower Crane Operations, Optimization, Look-ahead Planning and Scheduling, Simulation, Lean Construction

INTRODUCTION

Early planning of construction processes is tightly coupled with the delivery of a facility that meets time, cost, quality, design requirements, and the expectations of the client(s). Proper administration of the construction phase is crucial for avoiding

[1] PhD Student, Civil and Environmental Engineering Department, American University of Beirut, Beirut Riad El-Solh 1107 2020, Lebanon, Mobile +961 70 931272, mja28@aub.edu.lb

[2] Graduate Student, Civil and Environmental Engineering Department, American University of Beirut, Beirut Riad El-Solh 1107 2020, Lebanon, Mobile +961 3 180628, efz00@aub.edu.lb

[3] Assistant Professor, Civil and Environmental Engineering Department, American University of Beirut, Beirut Riad El-Solh 1107 2020, Lebanon, Phone +961 1 350000 Ext: 3616, Farook.Hamzeh@aub.edu.lb

rework, delays, cost overruns, and safety hazards on site. While major operations are premeditated in the pre-construction stage, planning specific tasks early on is not realistic and not an adequate means for ensuring a smooth workflow on site. Therefore, the emergence of lean principles, and look-ahead planning in specific, served as an effective means for more practical planning. Look-ahead planning breaks down and modifies the master schedule, then scopes it to the nearest future to optimize the detailed level operations based on actual resources available and accomplishment of prerequisites (Chua et al., 1999).

The research described in this paper focuses on planning the operations of two tower cranes. Many construction works, especially in high-rise buildings, require using tower cranes (Hasan et al., 2010). In fact, early planning of tower crane operations before site execution helps reduce operational costs, enhance site safety, and optimize the works' schedule. Planning for lifting critical loads, accounting for physical interferences, and scheduling operations of tower cranes require thorough analysis and assessment of each specific situation. Any error in planning and execution of tower crane operations can have detrimental impacts on safety, costs, and schedules. Therefore, conducting a comprehensive study prior to the daily tasks to be carried out by the cranes is a crucial requirement.

In practice, cranes function in ad-hoc manner without a detailed schedule of tasks, and stakeholders are not aware of the effects of sub-optimal management of crane operations. The situation is even more critical when two or more cranes are involved, where overlapping work zones and the respective allocation of cranes to tasks and their scheduling are linked to cost, time, quality, and safety factors. Therefore, this research proposes a model to optimize the scheduling of tasks located in the overlapping zone of two tower cranes. In this manner, each task in the common work zone is assigned to either crane, based on the look-ahead plan, cranes' status as idle or occupied, and the best combination that balances the workload between both cranes and shortens the schedule.

LOOK-AHEAD PLANNING IN CONSTRUCTION

Traditional planning of construction works is based on forecasting. The problem with forecasting is that it is never right and is based on detailing too far in advance which creates errors and faulty assumptions (Nahmias, 2009). In addition, traditional planning starts off with setting a master schedule and detailing it at the beginning of the project. This neglects the requirements the tasks need to be conducted, which is the main issue for why such schedules are not applicable to actual site operations.

The Last Planner System emerged to solve the problems faced in the conventional way of planning. The application of look-ahead planning is critical for effective and efficient construction planning. Derived from lean principles, look-ahead planning targets the reduction of construction wastes such as rework, over processing, idle times and delays, and unnecessary transport of resources. By making prerequisites ready and checking for the presence of the required resources, look-ahead planning also ensures that tasks broken down to operation level can be actually executed as planned (Ballard, 1997; Hamzeh, 2009, Hamzeh et al. 2012).

OPERATIONS OF TOWER CRANES

Tower cranes are major equipment used on construction sites, where almost any high-rise building, medium to large sized project, and fabrication yard, requires them for carrying out construction and fabrication operations. The operational, maintenance, and purchasing or rental prices of cranes are relatively costly. Furthermore, most of the critical tasks that might delay a project, such as formwork and reinforcement erection, are majorly dependent on cranes. Hence, they should be optimally utilized on site and proficiently managed to avoid cost and time losses.

Previous research efforts were directed towards location optimization and resolving spatial interferences associated with single or multiple cranes (Irizzary and Karan, 2012; Paz and Franzese, 2010; Zhang et al., 1999), and for high level scheduling of crane activities, 3D visualization, and 4D simulation (Shi and AbouRizk, 1997; Al-Hussein et al., 2006; Leung and Tam, 2003).

However, the operational level of scheduling through look-ahead planning and balancing the workload of the common zone tasks of two or more tower cranes was not explored before. Therefore, this paper tackles these issues using look-ahead planning and lean based principles for the optimal planning of the joint area of tower cranes to reduce total duration, minimize idle times, and ensure a continuous and balanced workflow of crane activities.

RESEARCH METHOD

The purpose of this research is to optimize, through a computer simulation, the allocation of tasks falling in the overlapped work zone of two cranes. The specific aims identified in this study include: (1) using look-ahead planning to determine operation level tasks of the two cranes, (2) selecting an optimized allocation of cranes to the tasks in the overlapped area, (3) developing a model that can be adopted by planners and engineers, and (4) minimizing the total durations of tasks to be carried out, balancing the workload of the cranes, and reducing their idle times.

To achieve the above research targets, the following research methods were followed: (1) translating the look-ahead schedule to crane tasks per zone (2) developing a computer simulation model for optimization, and (3) running the model on a pilot case study to test the validity, logic, and contribution of the developed model. The proposed framework in figure 1 describes the methodology.

PREPARING DAILY SCHEDULE FOR CRANE OPERATIONS

A high level of activities is not convenient for managing cranes as they require a very detailed operational level of planning. Therefore, general tasks are first broken down into crane related activities that can be handled on daily basis, through look-ahead planning. The resources, in this case the cranes, are assigned to each task. However, the situation being studied here is for optimizing the tasks falling in the overlapping area of the two cranes. Therefore, the first step to the procedure is to use look-ahead planning for preparing a daily schedule of crane tasks. This can be done manually using Excel, or any scheduling software.

DEVELOPING AN EXCEL-ANYLOGIC BASED OPTIMIZATION MODEL

The second step is to develop a model that takes as input the crane schedule and outputs the optimal choice of crane allocation for the different tasks. The model is developed using Excel and AnyLogic 7.0.0 simulation software. AnyLogic is a multi-simulation tool supporting several kinds of simulation: discrete-event, agent based, and system dynamics. For the purpose of this study, the daily task schedule is prepared using Excel, where total durations and idle times are calculated depending on the cranes' allocation for the scheduled tasks. After that, it is plugged into AnyLogic that uses a parameter variation engine that tests all the combinations of the tasks within the common work zone of the two cranes. The results from AnyLogic show the least durations and the least idle times of the cranes, from which the best combination of cranes' schedules is selected. The results can then be transferred back to Excel as the two platforms are interoperable. Moreover, the model is generic, user friendly, and can be further developed and customized for any number of cranes and activities depending on each project.

TESTING ON A PILOT CASE STUDY AND SELECTING THE OPTIMAL CHOICE

To test the validity and to assess the contribution of the model to the proposed research targets, it is applied on a pilot case study of a tower (selected from a 3 towers project). By applying the generic model on a real case study, the logic behind the model will be better clarified, and the outcomes of the parametric variation of the possible cranes' allocation combinations can be clearly visualized, assessed, and documented.

EXPERIMENTAL SETUP

DEVELOPING THE EXCEL-ANYLOGIC BASED OPTIMIZATION MODEL

A generic model was developed using Excel and AnyLogic 7.0.0 simulation software in order to optimize the best sequencing and allocation of cranes to tasks. The proposed framework in figure 1 presents the required steps to develop the model.
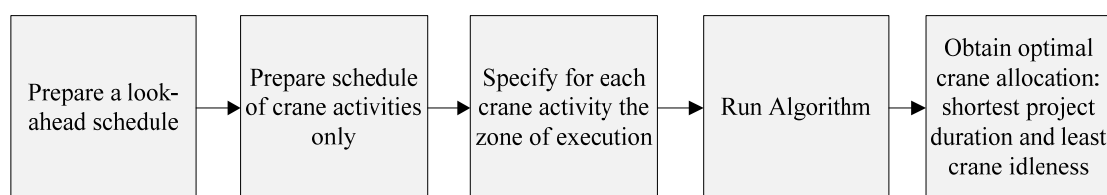

Figure 1: Proposed framework for model development

After preparing the look-ahead schedule, each task requiring the use of the cranes is sub-divided into crane level tasks. This schedule was developed using an Excel file and then exported to AnyLogic 7.0.0 for optimization analysis. Each crane task includes the following characteristics:

- **Relationship with other tasks:** the logical sequence of occurrence of the tasks in relation to the rest (Finish to Start, Start to Start, Finish to Finish…). In this regard, a project is normally divided into work sets. Each work set is assigned a step priority, i.e., all the crane tasks within a set of step priority "n" need to be completed before any of the tasks within the successive set of step priority "n+1"

can start. For instance, slab reinforcement set (including all crane tasks) is precedent to the slab concrete pouring set. To simplify the logic of the model, it is considered that tasks having the same step priority and falling within the same set can be executed in any order as they are independent of each other.

- **Location:** the spatial location within the project, and whether that area is covered by crane 1 or crane 2 only, or in the overlapped area of both. For example, if a project is divided into zones, then each zone can be assigned to a respective crane if it falls within the reach of that crane only. For zones that fall within the overlapping area of both cranes, the allocation of cranes to the tasks of that area is based on the optimization analysis. In the Excel model, the table specifies the zone in which each task will be taking place. Cells for the crane allocation of the tasks falling in the overlapped zones are highlighted and can take either value of Crane 1 or Crane 2. This is what the Excel-AnyLogic model will determine based on the optimal solution that will minimize durations, idle times, and balance the workload. Also, the Excel sheet provides the floor on which these tasks are occurring, but it has no significance in the model, unless a minute or second based analysis is conducted (height of floor and position affects detailed timing of crane movement).
- **Duration:** the duration required for the task to be completed by the crane only (excludes other involved equipment or labor crews). The durations can be detailed in minutes or seconds or approximated in hours depending on the desired level of accuracy.

Each set is handled independently of the others although they follow a predecessor-successor sequence. Therefore, the optimization can be done separately for each work set. The two cranes will be operating in parallel, so the respective duration will be equal to the longest duration of the operation of either Crane 1 or Crane 2. In addition to reducing the set duration, the idle times for each crane are calculated to minimize them as well during the optimization process. To calculate the idle times, the shortest duration of crane operation is subtracted from the longest one within each set. The Excel cells containing tasks falling in the overlapped zone can take on values, either 1 or 2, depending on whether the task falling in the common area is to be executed by Crane 1 or Crane 2. This matter is to be decided by the optimization model, since the choice of either 1 or 2 affects the phase durations as well as the idle times of the cranes, that the model is attempting to minimize.

As a result of several tasks potentially falling in the overlapped area and the presence of two crane choices for each task, there are a relatively large number of combinations to be analyzed. Manual experimenting is time and effort consuming. For this reason, the Excel file was transferred into a simulation mode in AnyLogic 7.0.0, which is a simulation software that exhausts all possible combinations at a high execution speed. The Parameter Variation type of experimentation in AnyLogic 7.0.0 was used where the parameters to be varied are the values of crane options of range 1-2 with an increment of 1, i.e., they take on a value of either 1 or 2. While these values are varying for each task in the overlapped area, the respective phase duration and cranes' idle times are monitored.

The link between Excel and AnyLogic 7.0.0 is conducted by creating parameters in AnyLogic 7.0.0, where each parameter represents the respective cell in Excel of the tasks in the common area. Before each simulation run, the parameters of the

considered set are varied and it computes the durations and idle times of all possible combinations.

PILOT CASE STUDY

A pilot case study was selected to test the validity of the model, demonstrate the logic behind it, and show a real output and how the best choice is selected. The project is composed of three towers. For the sake of testing the model, one tower was selected out of the three. It is composed of 18 floors, with varying layout and areas. For this study, typical floors composed of 4 apartments each are selected. The mobilization plan in figure 2 shows the locations of the cranes, the overlapped area on which the optimization is to be conducted, and the division of the tower into 8 zones for the purpose of assigning tasks to the cranes.
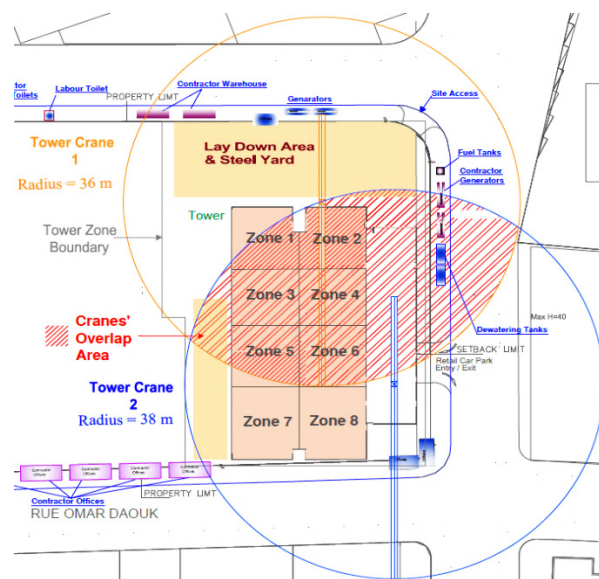

Figure 2: Mobilization plan for the tower

PREPARING THE DAILY SCHEDULE FOR CRANE TASKS

In order to apply the model, a daily detailed crane based schedule of tasks was prepared. Based on the master schedule provided by the general contractor's team, the authors selected a few packages, prepared an interim look-ahead schedule at the level of operations, and then estimated the daily to be handled by the cranes. Afterwards, the crane tasks were sequenced. Since the purpose of the case study is to test and demonstrate the use of the model, a few assumptions were placed to simplify the analysis to clearly show the logic of the model. The assumptions are:

- Zones 1 and 2 are assigned to Crane 1 as they are closer to the laydown area
- Zones 7 and 8 are assigned to Crane 2 as they fall exclusively within its reach
- Zones 3, 4, 5, and 6 are to be assigned to the optimal crane choice which will be selected through optimization
- There are 5 selected work sets: (1) Slab Formwork, MEP fixes, and Masonry, (2) Slab Reinforcement and MEP fixes, (3) Slab Concrete Pouring, (4) Columns, Cores, and Walls Formwork and Reinforcement, MEP fixes, and

Masonry, (5) Columns, Cores, and Walls Concrete Pouring. They are to be optimized separately as they follow a "finish-start" relationship. The Concrete Pouring set has the exclusivity of the cranes tasks as it should be carried in a continuous manner without interruption

- Tasks, within a single work set, of zones 1 to 8 can be carried out without any specific priority order. For example, tasks of slab reinforcement of all zones are assumed to have the same step priority

Table 1 below represents a sample of the crane tasks, as divided within the project activities, with their approximated durations and zones.

Table 1: Sample crane schedule

Crane Task #	Concrete Works (Per Typical Floor)		Dur.
Project Activity 1	**Slab Formwork Erection**		
1	Crane Task Zone 1	Crane lifts slab formwork panels and unloads them	*1 hr*
2	Crane Task Zone 2	Crane lifts slab formwork panels and unloads them	*1 hr*
3	Crane Task Zone 3	Crane lifts slab formwork panels and unloads them	*1 hr*
…	…	…	...
Project Activity 2	**Slab Steel Reinforcement**		
9	Crane Task Zone 1	Crane lifts slab steel rebars batches and unloads them	*2 hrs*
10	Crane Task Zone 2	Crane lifts slab steel rebars batches and unloads them	*2 hrs*
…	…	…	...

Figure 3 shows a portion of the precedence network diagram prepared using MS Project. Note that the sequencing of tasks within a certain set is an example of the different possible combinations since the order is not of concern.
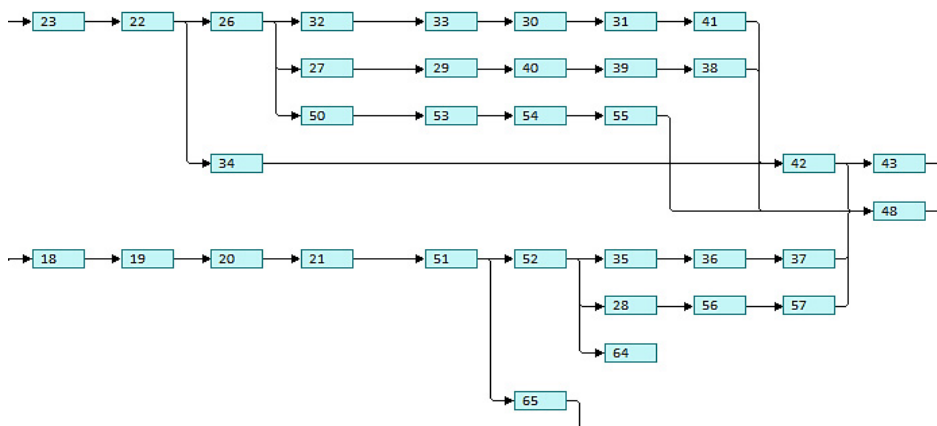

Figure 3: Portion of the crane tasks' precedence network diagram

The next step is to arrange the crane tasks into sets to be handled for optimization through the Excel-AnyLogic model.

APPLYING THE EXCEL-ANYLOGIC BASED OPTIMIZATION MODEL

The crane tasks that were detailed for daily operations are divided into 5 sets, where each set presents a list of several crane tasks and are assigned, as mentioned earlier, a step priority depending on the sequence of execution. Table 2 presents a sample crane task distribution schedule derived from the breakdown schedule shown in table 1, with their respective durations, zones, step priority numbers, and cranes' allocations. The cells highlighted in yellow are the allocation of the cranes that were determined through optimization. The values could be 1 for Crane 1 or 2 for Crane 2. Each set duration and idle crane duration were determined after optimization and depend on the values of the crane allocation. The model selects the best combination that reduces the duration and the idle time exhibited by the cranes, and provides a balanced workload so that one crane is not too overloaded or too idle as compared to the other.

In AnyLogic, parameters were added to the experiment, where each parameter represents a yellow cell. Each parameter in this case takes on a value of either 1 or 2 representing the choice of Crane 1 or Crane 2. Since there are several crane tasks that fall in the overlapped zone, and there are two crane options, there is a wide variety of combinations that need to be tested. Therefore, AnyLogic was used for faster processing and more exhaustive coverage of all combinations. The optimization tackles the reduction of total duration of each set, the idle time exhibited by each crane, and the result will serve to provide a workload that is balanced between the two cranes.

RESULTS AND DISCUSSION

After running the model to achieve system optimization, the results of crane allocations to the tasks in the overlapped zones, the optimal duration, and least idle times are presented in table 2. The minimum duration and crane idle times combination is selected from several options as shown in Figure 4 below. The graphs represent the durations and idle times for different crane allocation combinations for one of the crane task sets.
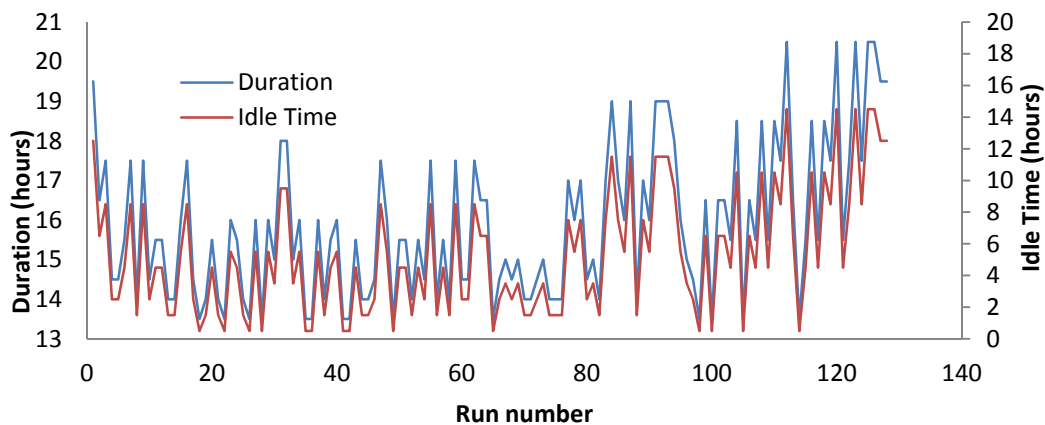

Figure 4: Graph of different combinations of crane allocations

In addition to assigning the optimal crane choice to these activities, it is important to highlight noteworthy outcomes inferred from the analysis of the result.

Table 2: A sample Excel table showing crane tasks, zone, and allocation

Work Package	Set of Crane Tasks	Floor	Step Priority	Site Zone	Crane Zone	Crane	Dur. (hrs)	Set Dur.	Crane Idle Time
Structural	Crane lifts slab formwork panels and unloads them	5	1	1	1	1	1		
Structural	Crane lifts slab formwork panels and unloads them	5	1	2	1	1	1		
Structural	Crane lifts slab formwork panels and unloads them	5	1	3	1,2	2	1		
Structural	Crane lifts slab formwork panels and unloads them	5	1	4	1,2	2	1		
Structural	Crane lifts slab formwork panels and unloads them	5	1	5	1,2	2	1		
Structural	Crane lifts slab formwork panels and unloads them	5	1	6	1,2	2	1	9.5 hrs	Crane 2: 0.5 hrs
Structural	Crane lifts slab formwork panels and unloads them	5	1	7	2	2	1		
Structural	Crane lifts slab formwork panels and unloads them	5	1	8	2	2	1		
MEP	Loading of E/M Second Fix equipment	2	1	1 & 2	1	1	1.5		
Masonry	Loading of CMUs, lintels and Jambs	3	1	1	1	1	3		
Masonry	Loading of CMUs, lintels and Jambs	3	1	2	1	1	3		
Masonry	Loading of CMUs, lintels and Jambs	3	1	3	2	2	3		
Structural	Crane lifts slab steel rebars batches and unloads them	5	2	1	1	1	2		
Structural	Crane lifts slab steel rebars batches and unloads them	5	2	2	1	1	2		
Structural	Crane lifts slab steel rebars batches and unloads them	5	2	3	1,2	2	2		
Structural	Crane lifts slab steel rebars batches and unloads them	5	2	4	1,2	1	2	13.5 hrs	Crane 2: 0.5 hrs
Structural	Crane lifts slab steel rebars batches and unloads them	5	2	5	1,2	2	2		
Structural	Crane lifts slab steel rebars batches and unloads them	5	2	6	1,2	2	2		
Structural	Crane lifts slab steel rebars batches and unloads them	5	2	7	2	2	2		
...		...		...	...	...	...		

Table 3: Results of some sets from the optimization

Step Priority Number	Number of Activities located in Overlapping Zone	Total Number of Activities	Reduced Duration Time (hrs)	Reduced Crane Idle Time (hrs)
1	4	12	4	8
2	7	12	7	14
4	**11**	**20**	**7.5**	**15**
5	4	8	4.5	1

In reference to table 3, there is a correlation between the number of activities in the overlapping zones and the amount of reduction in set duration and crane idle time. There is also a correlation between the total number of activities (whether overlapping or not) and the reduction in duration and crane idle time. The set with priority number 4 has the highest number of crane tasks falling in the overlapping cranes zone, with the highest reduction of tasks duration and crane idle time. Moreover, by comparing step priority 1 and 2, both have the same total number of activities (12), but step priority 2 has more activities in the overlapped zone, and respectively has a higher reduction in duration and crane idle time. In addition, by comparing step priority 1 to step priority 5, both have the same number of activities in the overlapped zone. However, step priority 1 has a higher number of total crane tasks and exhibited higher reduction. Therefore, a pattern exists showing that the more overall crane activities there are, and the more activities that are in the overlapped zone, the higher the reduction of duration and idle time is. The optimization hence seems to be more efficient with more activities in the project and the bigger the overlap zone is, which increases flexibility and creates room for improvement.

By comparing the best and worst combinations in table 4, the importance of proper crane allocation on reducing the duration of crane tasks and total crane idleness times can be observed. A considerable improvement results from optimizing crane allocation for tasks in overlapping areas.

Table 4: Comparison between least efficient and best results

	Least Efficient Results	Optimal Results	Improvement (%)
Duration of Crane Activity (hrs)	82	54.5	33.5
Total Crane Idle Times (hrs)	48	1	97.9

Although the number of activities is an important factor, the duration of each crane task is also of importance. In fact, the workload of each crane is related to the number of crane tasks assigned to it and the duration of each task. As a result, the workload within each set is correlated with the level of optimization and model efficacy. Also, results obtained show that multiple combinations of crane allocations yield several optimal results. These results should be carefully analyzed and the selected allocations should ensure that there are no collisions within the overlapped area.

FUTURE WORK

The research can be further extended by developing the model to accommodate for more than two cranes present on large construction sites with multiple overlapping areas and constraints to be accounted for, such as physical and spatial interferences. Instead of having a parameter that takes into account a value of 1 or 2 given two cranes, the more overlapping the cranes are, the more values are required to be shuffled (for 3 cranes overlapping: values of 1, 2, or 3). This produces many combinations that can be exhausted and optimized similarly.

CONCLUSIONS

Construction planning requires early efforts for analysis and conducting thorough assessments of different alternatives of execution means and methods. Even when the master schedule of the construction phase is decided upon and analyzed properly, there still remain several shortcomings during on-site execution due to the lack or poor day-to-day planning for critical operations. Among such critical and important operations are tower crane lifts as they pose high risks, have cost implications, and impact a large portion of site activities. Therefore, an adequate level of tower crane management can yield higher productivity, reduced durations, and lower idle times. Specifically, the presence of several overlapping cranes presents a complicated allocation problem and an option for optimization due to available flexibility.

The model developed in this paper targets the optimal allocation of two tower cranes to tasks present in the overlapping zone. The aims of the optimization model are to reduce simultaneously the total duration of the tasks conducted by the cranes and the idle times exhibited by them. The procedure is based on incorporating a daily schedule produced through look-ahead planning with an Excel-AnyLogic based optimization model. Several combinations are analyzed and the optimal solutions are selected. Results from the application of the model on a case study show that the proper crane allocation to tasks in overlapping areas is an effective and efficient method for improving the use and performance of tower cranes. The degree of efficacy of the optimization model and the significance of the results are higher when there is a bigger overlap zone, a larger number of tasks to be executed by the cranes, and a considerable workload flexibility for the tower cranes. The higher the flexibility provided to optimize the crane allocation and scheduling, and the larger the scale of the project, the more apparent and significant the improvements will be.

Through proper planning of tasks that are usually conducted by experience or best practice, there is always room for improvement. Performance can be enhanced by changing traditional practices to adopt new methods to improve efficiency, reduce project schedules, and prevent cost overruns while maintaining a continuous flow of work. This approach incorporates principles from lean thinking to reduce common wastes during construction by adopting a proactive approach. By simply performing look-ahead planning and assessing different scheduling alternatives before actual execution through simulation, workload is balanced, continuous work flow is achieved, and construction operations are continuously improved.

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