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HYBRID APPROACHES FOR HANDLING MOBILE CRANE LOCATION PROBLEMS IN CONSTRUCTION SITES

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ABSTRACT

Mobile crane location (MCL) in modular construction is a complex problem that affects both constructionsafety and efficiency. Sub-optimal MCL planning increases the number of crane relocations and the overall project cost. Interestingly, recently, research on crane operation planning and analysis focused on determining crane configurations, boom lengths, and radii to enable lifting given a crane location. However,with a large number of feasible locations, finding the best solution becomes a harder task. In this respect, finding a single crane location ensures an optimal lift plan, e.g., minimizing the number of pick-location. As a result, this paper aims to bridge this gap by providing a hybrid approach using heuristics, grid-based,and combinatorial optimization algorithms to find the least required lifting points. The proposed approachis tested on a case study of a modular building. The study contributes by minimizing the number of crane relocations to enhance budget and cost planning.

1 INTRODUCTION

In recent years, modular thinking has gained traction among construction professionals to the point that the construction industry is slowly leaning towards off-site manufacturing, making traditional on-site construction a concept from the past. Although small and isolated projects can still be built in place, large and complex heavy construction projects (e.g., oil refineries) must be modularized and fabricated in a controlled environment to ensure full control of the quality of the components as well as the delivery time.As a result, within this new paradigm, often referred to as industrialized or off-site construction, projects are viewed as modules that need to be manufactured off-site (within controlled environments) and then delivered to the construction site for their final assembly.

While the implementation of off-site construction has leveraged ideas and technologies developed in the manufacturing sector to rapidly move forward, on-site activities still need additional scrutiny to unveil areas where improvement can be made, especially in relation to automating upstream processes. One such aspect is (mobile) crane operation analysis and planning since this particular item is the cornerstone of any modular project, particularly in heavy industrial projects. Mobile cranes are widely utilized in the construction industry primarily for their capacity, which nowadays can exceed 1000 metric tons, and their versatility (Görçün and Doğan 2023). Regarding versatility, the wide range of mobile cranes' types and configurations make them ideal for short-term projects that could be completed within a few days and for those that are large and complex, which can last for

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months. The flexibility of mobile cranes in terms of mobility can turn out to be an important factor for efficiency and increased productivity (e.g., installation of wind farms, pick and walk, etc.). Beyond the purely technical aspects of mobile cranes that revolve around capacity and mobility, these cranes have also been equipped, in recent years, with eco-friendly features such as low-emission engines, allowing a reduction of construction sites' carbon footprint and a contribution toa cleaner environment. Mobile cranes are essential in many industries for lifting and transporting heavy equipment and materials, and they have enormously enhanced the efficiency and safety of many building construction and manufacturing processes. As a result, although a large body of knowledge has been devoted to cranes over the years, additional studies are frequently contributed by researchers seeking to improve the efficiency of crane operations and utilization with a view to enhancing safety, reducing cost, and lowering energy consumption (Park and Han 2019). In this respect, several topics have been explored in the literature, including crane location selection (Al-Hussein et al. 2005; Hasan 2013; Guo et al. 2022), crane selection (Azami et al. 2022; Wu et al. 2011), lift path planning (Zhu et al. 2022; Zhang et al. 2023; Mousaei et al. 2021), crane productivity improvement (Mansoor et al. 2020; Mansoor et al. 2023), and visual simulations (Han et al. 2012; Han et al. 2015; Tak et al. 2021).

Despite the many contributions provided by previous studies, a universal tool for optimal pick-up location selection is yet to be developed. Therefore, a more precise and efficient way of selecting the optimal mobile crane location based on safety and productivity considerations is still needed. In lightof these limitations, the current study proposes an approach that combines heuristics, grid-based, and combinatorial optimization algorithms. Combining multiple methods can leverage the strengths of each approach and mitigate their weaknesses. The heuristic approach defines the possible region for the mobilecrane location. The grid-based approach is used to generate an initial set of candidate crane locations fromeach region, which is refined using heuristics to optimize the placement of each crane, and the combinatorial optimization algorithms are then applied to determine the optimal location, considering factors suchas load weight and crane capacity. One of the advantages of this approach is that it improves the efficiencyand effectiveness of the mobile crane location problem while reducing the risk of sub-optimal solutions.

The rest of the paper is organized as follows: Section two tackles the literature review on previously used algorithms in crane layout planning, section three demonstrates the study methodology, section four discusses the testing of the approach on a real case study, and finally, the summary and conclusion are presented in section five.

2 LTERATURE REVIEW

This section discusses various previous studies on crane operations. As mentioned above, a substantial portion of the case studies that have been examined in the literature focused mainly on the type of mobile crane to be used and lift path planning, especially in the context of congested heavy industrial projects. Crane locations, on the other hand, received little attention since, in many instances, these locations are sparse. However, when the spatial density of the latter is high, their significance in optimizing crane operations may increase dramatically (Hamid et al. 2019). Indeed, when a large solution space for crane locations is available, past experience, rules of thumb, and qualitative thinking are likely to lead to a sub-optimal choice. Clearly, working manually from a rough plan is inefficient and error-prone, especiallyin the early stages of a project where the project scope is subjected to changes and information is still volatile. As a result, it is paramount to develop a systematic approach that can output a (near) optimal location globally, which positively impacts crane utilization, collision identification, productivity, workers'safety, and operator visibility (Hamid et al. 2019).

Several methods have been proposed to determine the optimal mobile crane location, depending on the specific needs of the job site and the load being transported. One of the standard methods is using a *grid-based approach* (Wang et al. 2010; Bin et al. 2015). In this method, the available crane location areasare discretized as cells forming a grid where each cell represents a candidate crane location. The feasibilityof these cells is examined under existing constraints to determine one or more (near) optimal locations.In general, constraints may include various factors such as a crane's capacity, boom length, proximity to obstacles, configuration (e.g., super lift), and distance from other cranes in scenarios where multiple cranesare utilized, etc.

The above-cited method is relatively simple to implement, and the grid structure can be easily definedand computed for small site layout scenarios. However, for complex projects, a global optimization of craneoperations involving a high density of crane locations may be computationally intensive hence making liftplanning a challenging activity that requires effort and time to be completed. In addition to having a large number of cells, discretizing the areas eligible for crane locations can lead to limitations in precision sincedividing an area into cells having a pre-defined size can limit the precision of the mobile crane's position and result in a sub-optimal crane placement, reducing efficiency and productivity.

Alternatives to the simple method described above used meta-heuristic algorithms such as genetic (Penget al. 2018), simulated annealing (Guo et al. 2021), and ant colony optimization to search for feasible cranelocations. These methods can efficiently handle complex constraints and provide near-optimal solutions, but they may not be suitable for all situations due to their limited scalability, parameter dependence, sensitivityto initial conditions, and the inability to guarantee optimality.

Besides, genetic algorithms have also been used in optimizing pick-up locations. Tam and Tong (2003) used genetic algorithms to select supply and demand points by optimizing the transportation costs. Furthermore, integer linear programming has also been used in crane layout planning. For instance, Huang et al. (2011) developed a mixed linear-integer programming model to select optimal locations for tower cranes that are used to transport heavy materials. Similarly, Huang and Wong (2018) targeted the optimization ofhook movement sequences and material handling scheduling by developing a Binary-Mixed-Integer-LinearProgramming model.

To this end, several limitations are identified in the previous studies. In particular, most mobile crane location optimization approaches aim to find the optimal location for the crane based on the required boomlength and radius. This optimal location is typically determined based on several factors, such as the lifting load, the available space, and the location of other equipment and structures on the site. In a real application, the ideal scenario would be to have a single crane location from which all modules will be lifted. This solution which is referred to as a "*single pick*" or "*single lift*" is often sought since it avoidsthe cost associated with the disassembly, relocation and re-assembly of the crane. Of course, in the case where relocations are inevitable, their number needs to be minimized.

3 PROPOSED METHODOLOGY

In this section, we describe the method for computing the optimal mobile crane location while minimizingcrane relocation and avoiding spatial conflicts at a job site.

The methodology presented in Fig.1 describes the mobile crane location approach. The hybrid approach considers various factors as input, such as site layout, crane capacity chart, and object lift information (weight, width, length, and height, etc.). The outputs include not only the selected mobile crane location and ensure collision-free crane paths but also the 3D visualization, which is helpful for inspecting the lifting operation and ensuring that it is safe and efficient.

In this paper, we assume that the following points are considered in developing the model:

- Temporary facilities are divided into rectangular areas to simplify the problem.
- Buildings are not divided into rectangular areas as in previous studies. Work zones and site layout properties are identified with significant accuracy.
- Temporary facilities and site constraints locations are assumed fixed.
- The mobile crane is assumed to have a circular area.
- Determine the distance between each pick and set point using Euclidian distance.
- The impact of crane configuration, load capacity, boom length, and boom angle on the allowable lifted load is taken into consideration.
- Crane loading and unloading times are not modeled since they do not impact the MCL selection process.

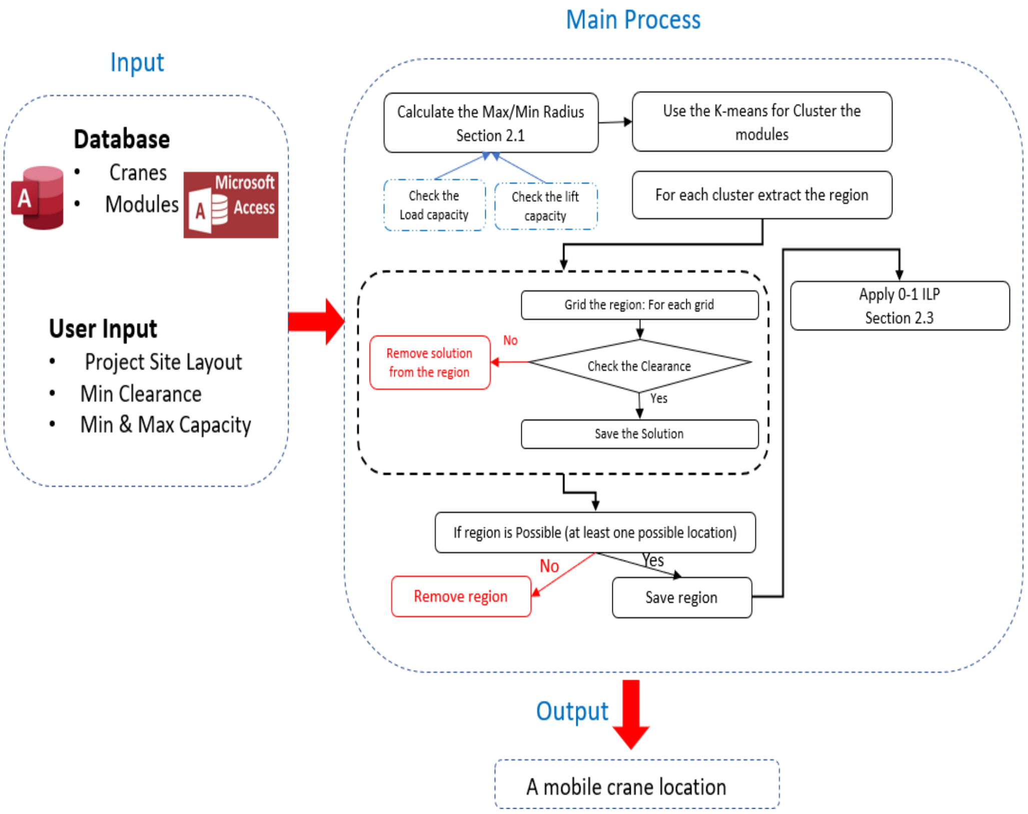

Figure 1: The proposed methodology.

Table 1: Abbreviations.

H	Lifting height	H_M	The module height.
d_{cr}	The distance between the center of rotation of the crane structure and the ground surface	W_h	Hook weight
M_e	The module elevation	W_m	Lift or object weight
G_e	The ground elevation	W_c	Max Crane capacity
H_R	The height of the rigging	W_r	Rigging weight

First, we define the crane location problem.

Definition 1 The MCL problem is an optimization problem that involves determining the optimal location(s) for mobile cranes in a given facility or site layout so to minimize the number of relocations required duringlifting, which in turn reduces the total cost and time required to complete the lifting operation.

In order to calculate all feasible locations that minimize the number of relocations of the mobile crane, itis necessary to verify the following configurations with regard to all the modules and whether the operating parameters of a mobile crane meet the lift requirements and ensure safety and efficiency:

1. Check the crane reachability. It is crucial to check whether a crane can reach a specific area on thesite and whether it can lift the load from the pickup area to the designated area by assessing thelift objects weight W_h and the maximum crane capacity W_c .
2. Performing boom-line intersection tests to eliminate unfeasible locations, using the module, lifting heights (H_M and H) as well as module and ground elevation (M_e andG_e) as seen in Table 1.
3. Modeling the expected motion of a crane and detecting possible collisions between a crane and existing building structures.

The first step (1) eliminates all unfeasible locations before executing the next step. The second step (2) checks the main boom collision with any surrounding structures. Any locations where the main boom intersects with an erected structure or other obstacles are considered unfeasible. The third step (3) prevents crane collision. Any selected locations that fail in one of the three tests are considered unfeasible and do not need to be considered.

3.1 Cluster

Typically, the common approach for solving mobile crane location problems is based on the circular working area defined by the crane's main boom length and radius, named working envelope. The crane location can be chosen randomly within this working envelope or based on heuristics or optimization algorithms to minimize the number of required crane movements. Once the crane location is selected, the feasibility of the lift is checked by verifying whether the modules are within the crane's reach and whether the boom or rigging will interfere with any existing structures or obstacles. This approach is not always the most efficient. Randomly choosing a location and then checking its feasibility can result in many locations being checked, which can be time-consuming.

To address this problem, the first step is to extract the optimal location(s) consists in defining a maximum and minimum radius for each lifted module. This ensures the crane can reach all necessary modules without moving around excessively. For the sake of simplicity, each module is doubled with two different locations (the pick area and the set area location). Now, each module is represented by its centroid point, and two circles are created around each module's location representing the maximum and minimum radius, respectively, extracted from the crane capacity chart as follows:

$$R\_max \ = \ \max\{(Raduis)|W_c > W_G \ and \ H_c > H_G\} \qquad (1)$$

$$R\_\min = \ \min\{(Raduis)|W_c > W_G \ and \ H_c > H_G\} \qquad (2)$$

The calculation of the maximum radius for each module is based on verifying the two preliminary conditions: load capacity and lifting height. The first part of the condition aims to confirm whether or not the crane can lift the module; the maximum value of the radius must satisfy that the crane capacity W_c should be greater than or equal to the global lift weight:

$$W_G \ = \ W_m \ + W_h \ + W_r$$

The second part of the condition aims to verify the lifting height (depending on the boom and jib combinations). The lifting height H_c must be greater than the minimum lifting height:

$$H_c \ > \ H_A \ + \ H_B \ + H_C$$

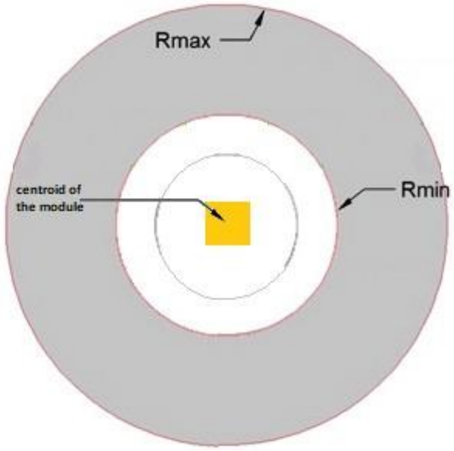

Figure 2: Plan view.

By verifying these two conditions, the maximum radius for each module can be determined to ensure that the crane can safely lift and move the module without exceeding its capacity. The next step involves finding all the intersection regions of these circles to determine the possible crane location(s). To ensure the crane base area, the overlapping area between the minimum radius circles of all modules (pick and set areas) is excluded. Finally, the mobile crane needs a clear space to move and operate without any obstacles or interference.

Generally, a mathematical formula to calculate the intersection between the maximum radius circles of all the modules is well-defined and accurate (Kershner 1939). However, if the number of modules is large and the intersection is complex, then k-means (Mohiuddin et al. 2020) clustering with modified distance could be a useful approach to identifying the intersection between the maximum radius circles. In this paper, we used the heuristic method to cluster the module; instead of using only Euclidian distance, we propose to group the modules if the distance between the module Mi and the module M_j is less or equal to the sum of their radius.

$$Dist(M_i, M_j) < R_{M_i} + R_{M_j}$$

Once the regions are extracted, three cases are distinguished:

i. One unique region. The intersection of all the circles for all the modules forms a single region where the mobile crane can be positioned to reach and lift all the modules without needing to move. (Fig 3.a)

ii. The empty region. There is no intersection between the maximum radius circles of all the modules; therefore, the crane cannot reach all the modules from a single location. In this case, the crane will have to be relocated for each module, and the maximum number of modules that can be lifted from a single point is 1. (Fig 3.b).

iii. Different regions (standard case). The crane can reach a certain number of modules from each region. These regions can be ordered by the number of modules they can reach, starting from the region that can reach the maximum number of modules to the region that can reach the minimum number of modules. This ordering can help decide the sequence of crane movements to minimize the overall relocation cost. (Fig 3.c)

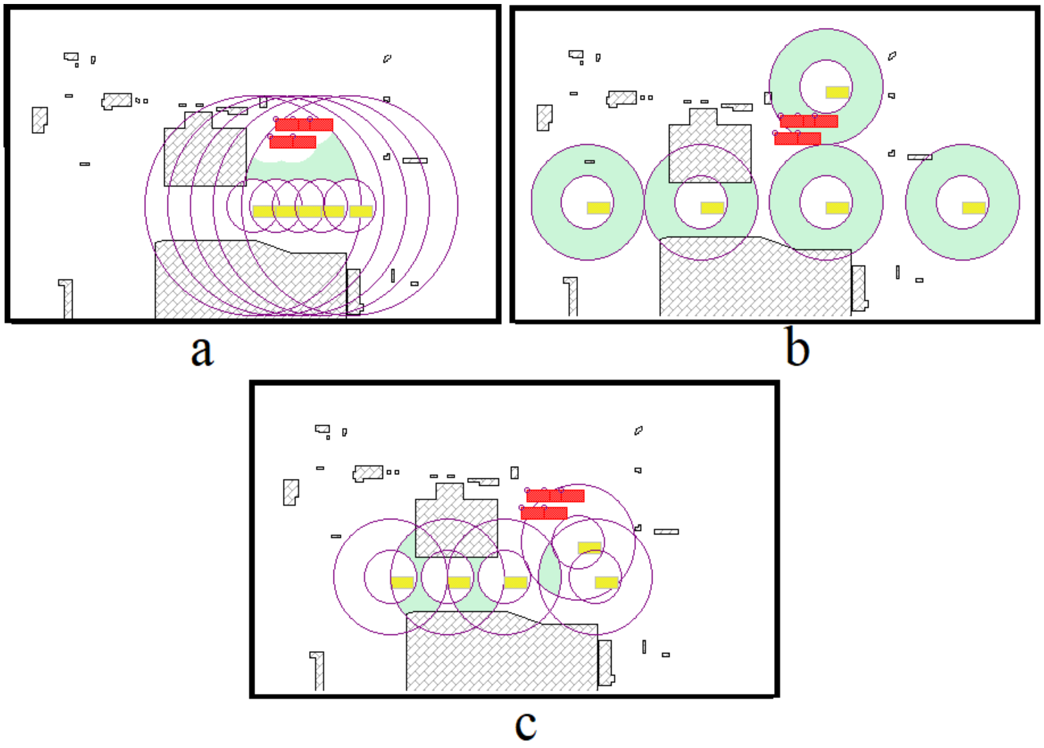

Figure 3: Feasible task mobile crane area.

Where the green area represents the potential region, the red area represents the pick location area, and the yellow area represents the set location area.

3.2 Clearance checking

The first step in the MCL process is the initial feasible lifting region. This latter is obtained by eliminating locations where a crane cannot perform a lifting task due to an unfulfilled capacity, boom length, and angle condition. The next step is to consider the presence of obstacles and buildings by detecting clashes and eliminating those locations. As a result, it is necessary to perform clearance checks to verify thatno collisions or other issues are preventing the crane from safely lifting and moving the modules in the identified potential regions (Hussein and Zayed 2021).

This paper uses 2D and 3D clearance-checking methods to provide more comprehensive results and reduce the risk of any accidents or potential collisions (Al-Hussein et al. 2006; Lei et al. 2013; Hanet al. 2015; Han et al. 2017). First, the clearance checking is performed in 2D as it is simpler and faster to perform. It allows identifying primary obstacles and potential collision points by using mathematical computations based on the object's pick and set positions, project obstruction information, feasible mobilecrane region, and clearance distance. Then, the 3D clearance checking is used for confirmation.

3D animation can simulate the movement of the mobile crane and the objects, providing a more realisticand detailed view of the project site, which can provide more precise information about potential collisionsand clearance issues

3.3 Integer 0-1 linear program

You This subsection aims to represent the mobile crane location as an optimization problem. The selection of the optimal mobile crane location is done by determining a list of a subset of feasible regions. In this context, we provide an encoding of the problem of mobile crane location as an integer linear program (ILP) (Graver 1975). Integer linear programming is a linear optimization technique with a special constraint thatrequires all variables to be integers.

The goal is to determine the optimal location of mobile cranes. Let's assume that there are *n* feasible regions for the mobile cranes $R = \{r_1, r_2, \ldots, r_n\}$, and there are m lifting modules that need to be reached $M = \{m_1, m_2, \ldots, m_m\}$. The mobile crane location problem can be represented using the following decision variables:

- Each region $r_i \in R$ is represented by decision variables as binary variables, where

$$r_i = \begin{cases} 1 & \mathit{if} \text{ the crane is located at candidate region i} \\ 0 & \mathit{Otherwise} \end{cases}$$

- The aim is to minimize the number for the crane to be relocated during the lift:

$$\sum_{i=1}^{n} F_j * r_i$$

where F_i is the distance between location j and the task that requires the service of crane.

- Each module C_m gives rise to a constraint C_j which says that this module should be lifted bychoosing at least one of the regions it contains:

$$C_j = \sum_{m \in R_i} R_i \geq 1$$

A constraint solver tool included in the IBM ILOG CPLEX Optimization Studio is called Constraint Programming Optimizer (CPO). ILOG was a well-known software business specializing in supply chain and optimization issues. The creation of a generic optimization suite, combining CPLEX to handle mixed integer linear programming (MILP) problems and CP Optimizer for CP problems, has received a lot of attention since ILOG, the maker of the well-known CPLEX mathematical programming tools, was acquiredby IBM in 2008.

4 CASE STUDY

A case study of a concrete construction site is presented in this section to validate the proposed framework. The case study is in Edmonton, Alberta, Canada. Figure.6 displays the construction site's geometrical properties; the site dimensions are 780 × 1260 m. Additionally, the sections highlighted in red are restricted areas to the mobile crane. The construction site comprises 23 modules. Each module has different properties such as weight, length, width, and height, a sample of which is displayed in Table 2.Furthermore, the construction company plans to use one mobile crane to transport the modules. The selected crane model is Crane Main Boom LR 1300; this crane model is selected based on one largely utilized model in the industry. However, other crane models were explored and validated, and the Main Boom LR 1300 is used to illustrate the efficiency of the developed framework. This model is dedicated to a small project, and its properties are summarized in Table 3. The objective of this case study is to choose a minimal number of mobile crane locations to complete the task of transporting each module from its pick points to the final set.

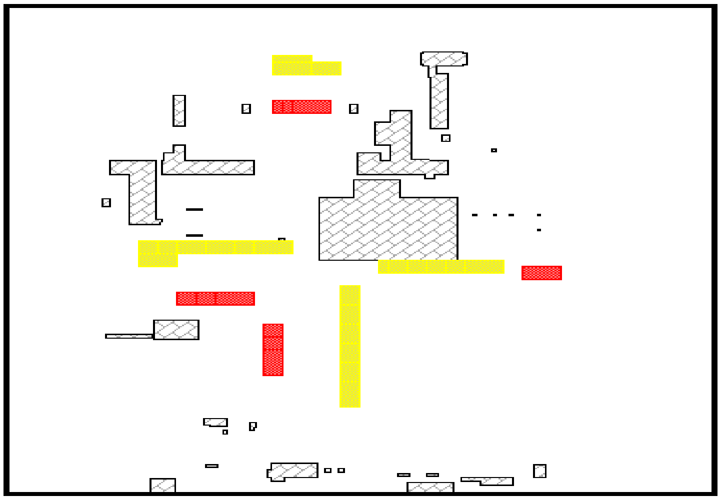

Figure 4: Construction site layout.

Table 2: Module's database.

Type	Length	Width	Height	Weight	Supply Location	Demand Location	Orientation
PE	40	20	20	230	(330, 240)	(310,200)	0°
PE	40	20	20	230	(370, 240)	(340,200)	0°
PE	40	20	20	230	(370, 240)	(240,450)	90°

The hybrid approach for determining the optimal mobile crane location first involves calculating all the radii for each module (Figure 5.a), then extracting all the possible regions. Once the potential regions are defined, the next step consists in checking the clearance (Figure 5.b). At the end of this step, a list of feasible regions is obtained. In this project, 9 feasible regions were extracted for the 23 modules.

Table 3: Module's database.

ID	Configuration	Mainboom	Radius	MBAngle	Height	LoadCapacity
1	Main boom	66	40	61.9	63	301
2	Main boom	66	45	56.6	60	260.9
3	Main boom	66	50	50.9	56	224.9
4	Main boom	76	70	34.5	47	142.6

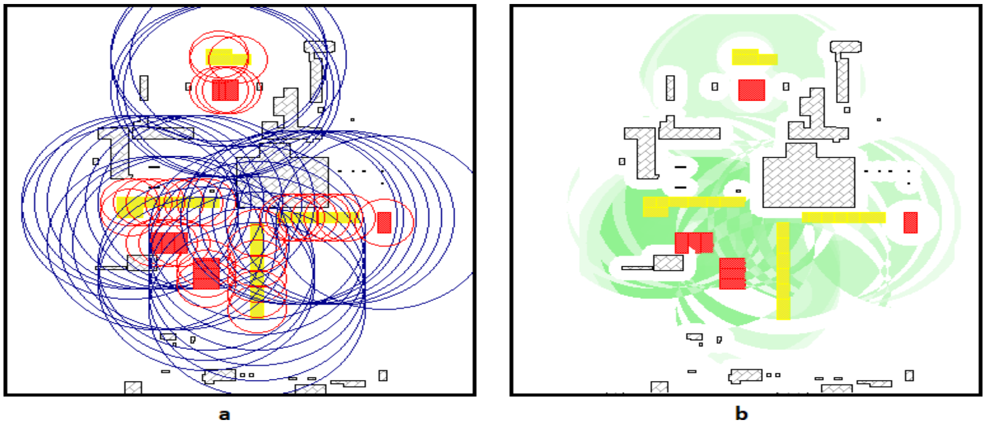

Figure 5: Feasible regions after clearance checking.

The ILP obtained for the project is as follows:

Minimize: $F(r_1).x_1 + F(r_2).x_2 + F(r_3).x_3 + F(r_4).x_4 + F(r_5).x_5 + F(r_6).x_6 + F(r_7).x_7 + F(r_8).x_8 + F(r_9).x_9$

Subject to:

$C_1 : x_1 \geq 1$
$C_2 : x_1 \geq 1$
$C_3 : x_1 + x_2 \geq 1$
$C_4 : x_1 + x_5 \geq 1$
$C_5 : x_2 + x_3 + x_5 \geq 1$
$C_6 : x_3 + x_2 + x_7 \geq 1$
$C_7 : x_3 + x_8 \geq 1$
$C_8 : x_3 + x_4 \geq 1$
$C_9 : x_6 + x_9 \geq 1$
$C_{10} : x_6 + x_2 + x_7 \geq 1$
$C_{11} : x_6 + x_3 \geq 1$
$C_{12} : x_6 + x_5 \geq 1$
$C_{13} : x_6 + x_8 \geq 1$
$C_{14} : x_6 + x_3 + x_5 \geq 1$
$C_{15} : x_6 + x_2 + x_7 \geq 1$
$C_{16} : x_6 + x_8 \geq 1$
$C_{17} : x_3 + x_2 + x_7 \geq 1$
$C_{18} : x_6 + x_4 \geq 1$
$C_{19} : x_6 + x_2 \geq 1$
$C_{20} : x_6 + x_9$
$C_{21} : x_3 + x_4 + x_8 \geq 1$
$C_{22} : x_6 + x_4 + x_5 \geq 1$
$C_{23} : x_3 + x_9 + x_7 \geq 1$
$x_i \in \{0, 1\} \ (1 \leq i \leq 23)$

In this work, the solution of our ILP consists by choosing x_1, x_3 and x_6.

5 CONCLUSION

In this paper, we propose a hybrid approach to select the most suitable mobile crane location from the potential locations based on safety and productivity considerations. Our approach leads to a more efficient and effective selection of the mobile crane location, which can significantly impact the lifting operation's success. First, a heuristic algorithm uses cluster regions and simplifies the comparison. Then, a grid-based approach is used to check the clearance and ensure the selected location is safe and suitable for the mobile crane. Finally, the optimization algorithm allows one to choose the best location among the feasible ones. The developed model is not project-oriented, meaning the method can be applied to different projects. However, one limitation concerning increasing the scale of the project is that some factors can emerge that were not considered in this study, which might undermine the overall performance.

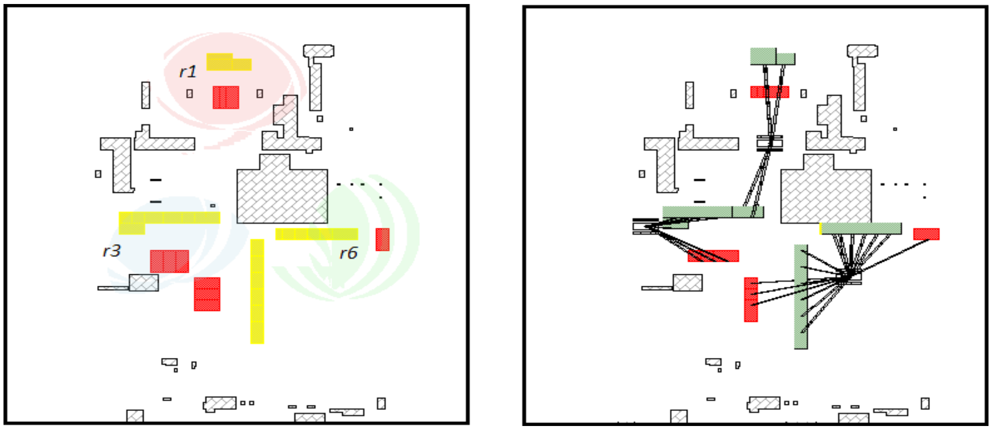

Figure 6: Mobile Crane location Solution.

In future work, we plan to implement the developed method in various projects using a more extensive set of crane model types and extracting their results which are then contrasted and compared with heuristic methods to evaluate the performance of the developed tool in different scenarios. Furthermore, other heuristic methods and machine learning techniques will be explored to cluster modules to enhance the performance of the developed approach. Additionally, a combination of rule-based and machine-learning models to optimize the operation of the cranes will be implemented to develop a decision-making tool for multiple crane location selection.

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