Evolution of the crane selection and on-site utilization process for modular construction multilifts

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ABSTRACT

Modular construction technology has been used in building construction for decades, having been widely utilized on sites with high traffic volume, restricted accessibility/storage, or business operations which cannot be interrupted by long construction time. A key challenge in this method of construction lies in planning and executing lifts within a short timeframe. In this regard, proper crane selection and site layout optimization can significantly increase productivity and shorten the lifting schedule. This paper thus proposes a methodology for the crane selection process and introduces mathematical algorithms to assess the construction of multi-lift operations. The modular lift process is divided into three stages: crane load and capacity check, crane location, and boom and superlift clearance. Each stage’s parameters are introduced, analyzed, and graphically explained. The methodology logic is supported by a generalized mathematical algorithm and is applied and tested on a case study involving the construction of five three-storey dormitories in 10 working days for Muhlenberg College in Allentown, Pennsylvania.

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1. Introduction

Modular construction refers to the process of dividing a house or apartment building into smaller units (module or panels), to be manufactured on a production line at a fabrication facility and then moved to the construction site for assembly. However, modular construction projects are often incorrectly associated with individual modular units, which have historically provided shelters for a variety of outdoor projects and activities at remote and urban locations. Over the last decade the modular method of constructing offices, dormitories, hotels, and government facilities has warranted a second look. Due to time savings and high production quality at factory assembly lines, more individual businesses and organizations are recognizing the convenience of having a building erected with minimal onsite construction time. The decreased construction time compared to conventional stick-built construction benefits all parties involved in a building construction project.

Modular construction is not new to the construction industry; however, this term is primarily associated with single-family homes, or at most low-rise, multi-family housing. There are few studies available describing a means of automating the CAD model development process or using robotics in modular construction, although several articles have praised the concept of modular construction with respect to its ability to add modular units to existing structures or significantly reduce onsite labor [4, 14, 24]. Modular construction also plays an important role on sites where a large number of units need to be assembled within a short construction time for an international event. However, the most significant niches for this type of building are school facilities, campus/dormitory living, and affordable housing [2, 5, 9]. These units are not limited to low-rise accommodations; in fact, the construction of high-rise facilities using a modular approach has also been considered [6]. Other examples of successful implementation have been airport roofs; the NASA spacecraft building; and health care units, from single check-up rooms to operating theaters or pharmacy centers [10, 11, 15, 17]. These facilities or units can be customized over the Internet similar to the manner in which an automobile may be customized by the purchaser [3]. Ready modules are delivered to the site for assembly, and in this respect a heuristic algorithm can be effectively utilized [7].

Crane selection is the most critical equipment for handling materials on a construction site. Many factors contribute to the selection of the type, number, and location of cranes, and expert judgment is essential in this process. Due to the increasing complexity of construction site layouts, a number of computer applications have been developed to assist practitioners in the selection and use of cranes [13, 23]. Computer models have been developed for crane lift planning. The approach described by Tam [18] as well as by Tam and Tang [19] has analyzed a
The crane lift area and used a genetic algorithm (GA) to optimize tower crane operations. Matsuo [20] and Sivakumar [25] have concentrated on developing a path planner for two crane lifts. Ali Deen [8] and Mashood [12] have continued with this research topic, employing GA to address the challenge of effectively utilizing equipment on congested construction sites. Al-Hussein [1] and Moselhi [16] have introduced an algorithm by which to select an optimal crane with respect to lift capacity, using 3D animation for visualization.

The present contribution is based on a case study in which five, three-storey dorms for Muhlenberg College in Allentown, Pennsylvania were assembled on site in just 10 working days. The extremely tight schedule combined with the substantial number of lifts to be performed necessitated minute analysis of the cost and constraints of each operational step. In this context, and since the crane was the master element of the project, its positioning and interaction with surrounding objects were crucial for maintaining high efficiency of equipment operations and meeting the planned schedule.

Addressing problems as they are encountered on site in specified situations is a reactive approach typically leading to “quick fixes” that comprise efficiency and productivity. With regard to crane utilization for major projects, the challenge facing planners is to envision ideal crane lift operations without any interruption, where each movement of the lifted object is predefined. Planners must also seek to minimize unpredicted crane and lifted object movements. The aim of this paper is to support decision making with respect to these challenges by addressing some of the unknowns involved when crane lift planning issues are encountered. The main objective of the research is to break down the crane operation process into smaller components that can be captured in the software language for the purpose of optimization and ultimately for full crane lift automation operations.

2. Methodology

The crane selection and utilization methodology encompasses four stages, as illustrated in Fig. 1. The input section contains available lifted object parameters and crane/rigging configuration arrangements. The main process includes a crane load capacity check, crane location assessment, crane boom clearance arrangement, and lifted object trajectory optimization, the latter of which is outside the scope of this paper. The main process is subject to restrictions including lifted object size, crane rental cost, specific ground preparation for crane placement, schedule, and weather conditions. As an output the user may extract information from each stage or analyze the final results, such as object path, obstruction conflicts, or lifted object sequence priority suggestions.

The methodological concepts presented below were developed in connection with a modular construction project in which five three-storey buildings were erected on a hill with a slope exceeding 7%. Each building required six modules per floor, plus the roof and the bridge connecting the ground level to the second-floor main entrance. For the purpose of the project described in Section 3, the most appropriate crane was selected following the three steps presented in Fig. 1: (i) crane capacity check; (ii) crane reach based on the selected optimal location; and (iii) boom and counterweight clearances.

2.1. Crane load capacity check

The crane lifting capacity must exceed the weight of the lifts and their associated rigging, which is calculated satisfying Eq. (1).

\[ p(OC) \geq T_w = L_w + H_w + SL_w + SB_w. \]

Where:
- \( OC \): Lifted object gross capacity
- \( T_w \): Total lift weight
- \( L_w \): Lift weight
- \( H_w \): Hook weight
- \( SL_w \): Total weight of slings
- \( SB_w \): Total weight of spreader bar.

The term, \( p \), introduced in Eq. (1), is a factor which is generally selected to be lower than 1 (usually 0.85). In practice, it increases the safety of the lifting operation by setting a limit on the object’s weight.

Fig. 1. Methodology of the main process.
at $p\%$ of the maximum allowable load for the specific crane selected for the job.

2.2. Crane placement location

This is a far more complex operation than a simple load capacity check. Extensive research has been conducted on single-lift crane analysis\cite{1,13,16} and multi-lift crane position placement\cite{21,22}. For our research, which involves multi-lifts, the crane location input comprises three data segments corresponding to the site, crane, and lifting object parameters. Site data provides information about available layout areas, surveying and ground density, and obstructions under and above ground level. Crane-related data includes outriggers, configuration, counterweight, and superlift space requirements, as well as spreader bar availability or boom attachment additions. Lifted object data includes weight, geometric center (GC), lifting lug dimensions, and information about additional supports for temporary storage.

In the context of the case study upon which the present contribution is based, the time factor related to the swing angle has been ignored, since the most critical issue is positioning the crane such that it is able to lift objects from pick points to destinations. In this respect, the crane location is expressed as an optimization problem described by the following objective function:

$$\min \left[ \sum_{k=1}^{n} m_k d_k + \sum_{p=1}^{p} m_{\text{max}, p} \delta_p \right]$$  \hspace{1cm} (2)

Where:

- $m_k$: Mass of object, $k$
- $d_k$: Distance of object, $k$
- $m_{\text{max}, p}$: Maximum weight from pick point
- $\delta_p$: Pick point distance from the crane.

It is important to note here that the masses are included as part of the objective function since it is the moments which determine whether or not a lift is possible. There are three types of constraints, as follows:

1. The location of the crane determined using Eq. (2) leaves sufficient clearance for maneuverability, satisfying Eq. (3):

$$d(Q_k, C) > R_{\text{CVW}} + C_{\text{CVW}}$$  \hspace{1cm} (3)

Where:

- $d(Q_k, C)$: Counterweight of closest distance to object $k$
- $R_{\text{CVW}}$: Counterweight swing radius
- $C_{\text{CVW}}$: Counterweight-object clearance.

In contrast to a tower crane, the counterweights of which are attached to the boom, which swings high above any obstruction, a mobile crane has its counterweights located at the base. As a result, the positioning of a mobile crane not only needs to satisfy capacity constraints, but also needs to allow the counterweight to swing freely, even when surrounded by multiple obstacles. Although Fig. 2 is specific to the case study addressed later in this paper, it nonetheless illustrates the issue of counterweight clearance, a common problem with mobile cranes on congested construction sites.

To determine whether a candidate crane location, $C : (x_C, y_C)$, is acceptable, we need to ensure that the assembled objects in the surrounding area do not interfere with the swinging of the counterweight. This issue is depicted in Fig. 3.

An algorithm is devised to test each candidate crane location $C : (x_C, y_C)$ for sufficient clearance between the counterweight and surrounding objects. This algorithm is described by a pseudo-code, as presented in Fig. 4.

To prepare the above pseudo-code for implementation, the coordinates $\Omega : (\Omega_x, \Omega_y)$ are provided satisfying Eq. (4):

$$\Omega_x = x_A + \frac{(x_B - x_A)(x_C - x_A)}{(x_B - x_A)^2 + (y_B - y_A)^2} - \frac{L}{2} \sin(\alpha) \Delta \cos(\alpha - \varphi) + \sin(\alpha - \varphi) \delta - L \cos(\alpha)$$  \hspace{1cm} (5)

The above equation is non-linear in the variable $\alpha$ and can only be solved numerically. The solution is subject to two constraints reach and lifting capacity which are addressed in another paper by the same authors. At this juncture it is important to note that when the boom is not extended a corresponding formula for the boom angle can be directly derived from Eq. (5) by setting $\varphi = 0$, thus leading to Eq. (6):

$$d \sin(\alpha) - H \cos(\alpha) = \Delta.$$  \hspace{1cm} (6)

Eq. (6) can then be transformed into a quadratic equation, $(d^2 + H^2) x^2 - 2dA x + (A^2 - H^2) = 0$, where $x = \sin(\alpha)$ and for which solutions can be obtained manually.

3. The crane is able to reach the pick and set points:

$$d_C < R_{\text{max}}(m_k) \leq L \cos(\alpha) + L_{\text{ext}} \cos(\alpha - \varphi).$$  \hspace{1cm} (7)

Where: $R_{\text{max}}(m_k)$ is the maximum reach of the crane lifting $m_k$. In this respect, a manufacturer generally provides information about the
The relationship between the crane's boom length and the maximum lifting capacity at that length. However, if such data is not available, basic statics principles can be used to express the maximum reach as a function of the lifted mass. According to Fig. 6, the crane is able to lift the mass, $m_k$, only if the following relationship is satisfied:

$$d_k^2 + m_k = d_k - p(M + D).$$

(8)

Where:

- $M$ Counterweight
- $D$ Distance from the hinge point of the boom

As a result, the maximum reach allowed for the crane is:

$$R_{\text{max}}(m_k) = p(M + D) / (7) + m_k.$$

Since the distances occurring in the above equations involve Cartesian coordinates, the leading optimization problem is non-

/* We are only considering the X, Y plane */
/* Accept: Sets the acceptance Boolean flag to true */
/* Reject: Sets the acceptance Boolean flag to false */

$R_{\text{CW}}$ : Counterweight swing radius
$C_{\text{CW}}$ : Counterweight clearance requirement
$C: (x_c, y_c)$: Current candidate for crane location

For each pair of consecutive corners (A,B) do:

Let $\Omega : (x_\Omega, y_\Omega)$ be the projection of $C$ onto the line (AB)

If( $\Omega \in \text{segment} \ [AB] \ )$ then:

If( $d(C, \Omega) < R_{\text{CW}} + C_{\text{CW}} \ )$ then:

Reject ($C$)
Endif

Else:

If( $d(C, A) < R_{\text{CW}} + C_{\text{CW}} \text{ or } d(C, B) < R_{\text{CW}} + C_{\text{CW}}$ ):

Reject($C$)
Endif

Fig. 3. Obstruction clearance.

Fig. 4. Testing of counterweight clearance for a given candidate crane location.
the crane location is chosen as the object’s center of mass (centroid). In this respect, the crane coordinates are calculated according to the following equations:

\[
\begin{align*}
\bar{x} &= \frac{\sum_{i=1}^{n} m_i x_i}{\sum_{i=1}^{n} m_i}, \\
\bar{y} &= \frac{\sum_{i=1}^{n} m_i y_i}{\sum_{i=1}^{n} m_i}, \\
\bar{z} &= \frac{\sum_{i=1}^{n} m_i z_i}{\sum_{i=1}^{n} m_i},
\end{align*}
\]  

(10)

where \( n \) is the number of objects to be lifted, while \( m_i \) and \((x_i, y_i, z_i)\) are the mass and geometric center coordinates of object \( i \), respectively. When the crane location is calculated using Eq. (10), the pick point information is not considered. In practice, to ignore pick point information is acceptable, provided there is at least one area which satisfies the lifting constraint, namely:

\[
\sqrt{(x - \bar{x})^2 + (y - \bar{y})^2 + (z - \bar{z})^2} \leq R_{\text{max}} \left( m_{\text{max}} \right), \quad p = 1, 2, \ldots, P
\]  

(11)

Here \((x_p, y_p, z_p)\) gives the coordinates of the pick-point and \( R_{\text{max}}(m_{\text{max}}) \) expresses the farthest crane reach calculated for the heaviest load to be lifted from pick point \( p \). However, in addition to the above constraint, an even greater issue may be encountered when the coordinates \((x, y, z)\) are used as the location of the crane. Indeed, since the centroid is essentially the weighted average of the distances between \( n \) objects and the crane, the crane location will be attracted to the heaviest object. As a result, a crane may be located in a position that cannot reach some destinations. To illustrate this case, let us assume that a 16-m reach crane is used to serve four destination points as illustrated in Fig. 7. Using the data in Fig. 7, the crane is located at the coordinates (5 m, 5 m). Accordingly, the upper right corner in the above figure will be out of reach since its distance to the crane is 21.21 m. Fortunately, for the purpose of our case study, the masses of the objects are sufficiently close, thus allowing the crane to reach every destination point. To complete the algorithm, Eq. (10) needs to be supplemented by a test similar to that defined in Eq. (11), to ensure that a crane located at the centroid can reach every destination point. Formally, this test can be written as:

\[
\sqrt{(x_k - \bar{x})^2 + (y_k - \bar{y})^2 + (z_k - \bar{z})^2} \leq R_{\text{max}} \left( m_{\text{max}} \right), \quad p = 1, 2, \ldots, P
\]  

(12)

in which \((x_k, y_k, z_k)\) are the destination point coordinates of object, \( k \), with mass, \( m_k \).

Fig. 8 shows the site layout of the Muhlenberg College project, and Fig. 9 shows the project’s geometric center in reference to one building.
2.3. Outrigger clearance

To finalize the crane placement location analysis, the outrigger or crawler layout is evaluated accordingly. It is important to mention that even though the formula described below is specific to the case study configuration described by Fig. 10, it can easily be modified to fit other site layouts. Fig. 10 shows the clearance outrigger layout \( \text{CL}_{\text{ol}} \) dimension, which is calculated satisfying Eq. (13):

\[
\text{CL}_{\text{ol}} = y_D - y_c - \frac{W_{\text{ol}}}{2}
\]

where \( y_c \) and \( y_D \) are the coordinates of the crane set point and one of the corners of the module referred to as “\( 3 \times 2 \)”, respectively. In the figure, in the ellipsoidal code “\( 3 \times 2 \)”, it should be noted “\( 3 \)” represents the building number, “\( x \)” represents the elevation of the module from 1 to 3, and “\( 2 \)” represents module type from 1 to 6. (Since the example illustrated in Fig. 10 is a top-view, the elevation is represented by the variable “\( x \)”.) As obtained from the manufacturer, \( W_{\text{ol}} \) represents the outrigger’s (or crawler’s) width. The calculated crane outrigger clearance \( \text{CL}_{\text{ol}} \) must be at least the predefined minimum object distance (MOD) value to ensure that the evaluated crane configuration will not be rejected from the list.

2.4. Boom clearance to slope surface analysis

During the course of the Muhlenberg College project which motivated this research, clearance between crane components and surrounding objects was a major challenge which needed to be accurately evaluated in order to determine whether or not the required lifts could be safely performed. The derived formulas to calculate outrigger, counterweight, and boom clearances that would ensure crane maneuverability and usability in the presence of obstacles have been presented above. In addition to deriving these formulas, as the buildings were assembled it was necessary to investigate the clearance between the main boom the sloped roof, which is a special type of obstruction. Although specific to the case study, this interaction, which is not addressed in the current literature, constitutes an extension of the case of a boom–flat roof interaction previously developed by Shapiro. Since the boom angle can impact the clearance, we propose the establishment of a relationship between these two quantities using a limited set of parameters, essentially the coordinates of the edge of the roof (assumed to be a line) and the crane location, which is assumed to be centered on the origin (without any loss of generality), as shown in Fig. 11. Since the aim is to link \( \alpha \) to the clearance \( \Delta \), the equation of the boom axis is conveniently defined by spherical coordinates.
Fig. 9. Site GC to one building.

Fig. 10. Crane outrigger layout clearance.
The starting point for the equations below is the parametric equations of the boom axis and roof edge, which are defined according to Eq. (14).

\[
\begin{align*}
\text{Crane axis} : & \quad \begin{cases} 
  x = \lambda u_x \\
  y = \lambda u_y \\
  z = \lambda u_z 
\end{cases} \\
\text{Roof edge} : & \quad \begin{cases} 
  x = x_1 + \mu V_x \\
  y = y_1 + \mu V_y \\
  z = z_1 + \mu V_z 
\end{cases}
\end{align*}
\]

where \( \lambda \) and \( \mu \) are real numbers. The direction vectors \( \vec{u} \) and \( \vec{v} \) are defined according to Eq. (15),

\[
\vec{u}(\cos(\alpha) \cos(\psi_0), \cos(\alpha) \sin(\psi_0), \sin(\alpha)) \quad \vec{v}(x_1-x_2, y_1-y_2, z_1-z_2).
\]

Note that for the case study, the value of the angle \( \psi_0 \) is arbitrary insofar as it is constant. In order to calculate the smallest distance between the boom and the roof edge, we start by defining a line orthogonal to the boom and intersecting the edge of the roof. Since such a line is orthogonal to the direction vector \( \vec{u} \), its dot product with \( \vec{P}_2 \vec{P}_3 \) satisfies Eq. (16):

\[
\sum_{r=x,y,z} u_r(r_4-r_3) = 0 \Rightarrow \sum_{r=x,y,z} u_r(\mu V_r - \lambda u_r + r_2 - r_1) = 0. \tag{16}
\]

Using Eq. (16), the objective is to determine the constants \( \lambda \) and \( \mu \) which will lead to the smallest distance \( P_2P_3 \), which also represents the clearance between the boom and the edge of the roof. From Eq. (16), the value \( \lambda \) satisfies Eq. (17),

\[
\lambda = A\mu + B \quad \text{where} \quad A = \frac{\sum_{r=x,y,z} u_rV_r}{\sum_{r=x,y,z} u_r^2} \quad \text{and} \quad B = \frac{\sum_{r=x,y,z} u_r r_1}{\sum_{r=x,y,z} u_r^2}. \tag{17}
\]

At this point the square of the clearance \( \Delta^2 \) that is, \( \min[(P_2P_3)]^2 \) can be expressed according to Eq. (18):

\[
\Delta^2 = \min[(P_4P_3)]^2 = \min \left[ \sum_{r=x,y,z} (\mu V_r - \lambda u_r + r_1 - r_2)^2 \right] \tag{18}
\]

Setting the derivative of Eq. (18) with respect to \( \mu \) equal to 0, one obtains the value \( \mu \) leading to the following clearance value:

\[
\mu = \frac{\sum_{r=x,y,z} (Bu_r + r_1)(V_r - Au_r)}{\sum_{r=x,y,z} (V_r - Au_r)^2}. \tag{19}
\]

Inserting the value of \( \mu \) into Eq. (18) provides the clearance calculated from the axis of the main boom to the edge of the roof. As a result, it is important to subtract the radius of the boom (assumed to be cylindrical), since in practice clearance is calculated from the boom’s envelope to the edge of the roof. Since the relationship between the clearance and the boom angle is non-linear, a trial-and-error procedure is employed which consists of increasing iteratively the angle by small increments until appropriate clearance is reached.

3. Case study

The proposed methodology is best described through a case study which involved the construction of five three-storey dormitory buildings for Muhlenberg College in Allentown, Pennsylvania. The task was to replace out-dated (1981) and inadequate single-level dormitory space units, which accommodated only 56 students. The new three-storey, 771 m² (8300 sq ft) buildings, which accommodate 145 students, were designed by local architects to esthetically complement the surrounding neighborhood buildings with their brick exteriors.

Each of the buildings has six apartments, most comprising one double- and three single-bedroom units, complete with full kitchens. These well-built attractive buildings were assembled from modules manufactured in Lebanon, N.J. by Kullman Building Corporation.
Each building consists of 18 modules which had to meet specific size and weight requirements. These modules not only had to be limited in height and weight to be able to pass under highway overpasses and satisfy crane capacity limitations—the largest modules were 4 × 17.3 m (13 × 57 ft) and weighed 3266 kg (72,000 lb), but also had to withstand the rigors of being transported to the site. For the latter requirement, one advantage of modular which came into play in this project is that fabricated units are structurally superior to those which are stick-built. Figs. 12 and 13 present photographs of the existing single-level dormitory and a CAD model of the new dormitory, respectively. These new dormitories were arranged using a new layout which differed from the existing one. The site elevation scenario (over 7% slope) contributed to the complexity of the assembly process, and the elevation differences between buildings were at least 3 m (10 ft). Once the old units had been demolished, the subcontractor prepared the site to accommodate the new foundation layout and modified the access road for the lifting crane set point area. These activities were planned based on a specific analysis of the crane access path to the final working spot. A temporary storage area near the construction site acted as a buffer for constant crane feed in order to lift modules in accordance with the assigned schedule.

The second access route was prepared to transport the modules that were to be lifted by the selected crane. Due to the project's rigid time constraints, detailed and thorough investigation was required prior to demolishing the existing units. The first investigative task focused on selecting an appropriate crane using a database originally developed by Al Hussein [1]. This database allows researchers to consider possible options based on a number of parameters, including capacity, geometry, crane lift radius, and obstruction proximity. This task led to the selection of the hydraulic mobile crane Demag AC 500-1, with a telescopic boom and a lifting capacity of 500,000 kg (600 tons). Figs. 14 and 15 provide technical details pertaining to the Demag AC 500-1.

The Demag AC 500-1 has several possible configurations. The chosen configuration has a full extended and pinned boom 56 m (183.7 ft), a superlift attached to the boom, and a superstructure with a maximum counterweight balance of 180,000 kg (396,900 lb).

For the next task, efforts shifted to examining the project dynamics. As a result, it was discovered that assembling the roofs and erecting the buildings concurrently on site would cut down the initial duration by more than 50% (10 days instead of 21). The roofs were to be built on the ground and lifted to the top of each building using the same crane that lifted the modules. This alternative was identified after simulating a variety of scenarios for which appropriate triangular distributions were used to estimate project duration. For a project that involved significant lifting, visualization was beneficial since it identified potential challenges (especially interference between lifted modules and existing obstacles) early in the design stage. Use of the CAD model ensured accurate results and proper resource management so as to circumvent delays in the final product delivery.

Fig. 16 shows the generated CAD model, while Fig. 17 gives the actual aerial view. Roofs, visible in Fig. 17, were assembled on the nearby tennis court and temporarily placed on the building foundations. This operation eliminated the roof assembly from the scheduled critical path. The final roof assembly was directly lifted from the tennis court with an added boom extension as shown in the CAD model snapshot in Fig. 16.

Following the crane location optimization simulation, construction operation optimization simulation, and final project schedule creation, virtual 4D construction was executed for visualization checking purposes. Intelligent digital objects were assigned proper material properties and texture mapping. Concatenation sets of separate hoist, swing, placing, and returning operations allowed planners to create optical representations of 4D construction operations. Another advantage of running the animation several times, especially in the presence of the rigging crew, was that it served as a teaching tool which allowed the crew to envision and familiarize themselves with planned activities. The rigging crew demonstrated nearly optimal productivity at the beginning of assembly, in part due to the decreased learning curve resulting from the crew having viewed the animations.

3.1. Methodology implementation

3.1.1. Capacity check

Capacity checking plays a significant role in selecting the optimal crane to lift modules and place them at their final locations. While capacity must be considered, in practice it is insufficient to consider capacity only, since one must also factor in assembly flexibility, and
Fig. 13. New dorm CAD model exploded view.

Fig 14. Demag AC 500-1 mobile crane body.
site accessibility, especially in relation to the ground configuration. From Eq. (1) the crane must accommodate the heaviest load lifted. In the case of this project, the heaviest load is calculated as follows:

$$\text{max}(T_W) = \max(L_{W1}) + SL_W + SB_W = 72,080 + 500 + 5600 = 78,180 \text{ kg (172,040 lb)}.$$  

And without spreader bar lift weight:

$$T_W = L_{W2} + SL_W = 42,460 + 500 = 42,960 \text{ kg (94,000 lb)}.$$  

Where:

- $T_W$: Total lift weight
- $L_{W1}$: Lift weight, max 32,694 kg (72,080 lb)
- $L_{W2}$: Lift weight, max 19,259 kg (42,460 lb)
- $SL_W$: Total weight of slings 227 kg (500 lb)
- $SB_W$: Total weight of spreader bar 2540 kg (5600 lb).

Figs. 18 and 19 show the typical under-hook configuration with spreader bar and load without spreader bar, respectively.

### 3.1.2. Crane placement and clearance

To define the crane position at the construction site, it is necessary to determine the crane set point coordinates as an optimization problem according to Eq. 2, subjected to constraints (3) and (4). Given each module’s corner coordinates, the corresponding set point is calculated as the geometric center of the corners (assuming that each module has a right parallelepiped). In such a case, the geometric center is defined as the average of the eight corners’ coordinates:

$$x_k = \frac{1}{8} \sum_{i=1}^{8} x_{ik}, \quad y_k = \frac{1}{8} \sum_{i=1}^{8} y_{ik}, \quad z_k = \frac{1}{8} \sum_{i=1}^{8} z_{ik} = 1, \ldots, n.$$  

The coordinates of the module set points are summarized in Table 1, along with the corresponding weights (module and spreader bar and/or slings). Note that only the x and y coordinates are shown, since the moments depend only on the distance of the object from the crane.

In addition, for the current project only one pick point, with coordinates ($x_p = 22.35 \text{ m (880.125 in.)}$, $y_p = 60.33 \text{ m (2375.33 in.)}$), was chosen for the modules. After running the optimization procedure in which the counterweight swing radius was $R_{CW} = 6.14 \text{ m (241.75 in.)}$, the crane set point, which minimizes the sum of the moments while allowing all lifts to be possible, had the coordinates ($x_c = 32.39 \text{ m (1275 in.)}$, $y_c = 33.76 \text{ m (1329 in.)}$) rounded to the nearest cm. Based on these coordinates, the clearance between the counterweight and the module referred to as “3 x 2” was found to be 4.8 cm (1.89 in.). A more practical value for the counterweight clearance may be obtained by re-optimizing the same problem after adding to $R_{CW}$ the targeted clearance. As for the capacity constraint, cf., Eq. (3), a linear relationship was demonstrated between the crane’s capacity and radius (as obtained by inputting the manufacturer’s data).

Capacity (in kg) = 0.453592 ($-1220.193 - 0.3048 \times R \text{ (meters)} + 218.033.537$)

At this point, the results of the centroid method, the simplicity of which motivated its use for this project, should be highlighted. In the context of this case study, the crane set point was defined by the coordinates ($x_c = 33.43 \text{ m (1316 in.)}$, $y_c = 32.11 \text{ m (1264 in.)}$) for which the smallest counterweight clearance was found to be 0.81 m...
(32 in.), corresponding to module “3 x 2”, as was the case in the optimization procedure. The shift between the optimal location and its centroid counterpart was approximately (1.83 m (6 ft)). In order to provide a complete overview of the optimization procedure, in Table 2 the optimal crane location for selected values of the counterweight clearance is presented. The results in the last row of the table correspond to the centroid method.
fed into the simulation engine. In particular, the engine considered the
ance scenarios involving nearby obstructions, and proper data was later
research as a basis for managerial decision making.
the preparation and algorithm results, and ultimately justi
flipped based on its resource
32695 2540 19.260 14.32 48.43 14.55 47.02 3 × 4 32,695 2540 62.66 45.04 15.97 44.50 2 × 4 19,260 227 24.85 9.74 19,260 227 20.77 3 × 2 32695 2540 19.33 9.24 4 × 3 32,695 2540 43.99 7.68 4 × 2 19,260 227 24.85 9.74 2 × 3 32,695 2540 23.78 3.42 4 × 3 32,695 2540 43.99 7.68 2 × 2 19,260 227 24.85 9.74 5 × 3 32,695 2540 59.30 47.39 4 × 2 19,260 227 24.85 9.74 5 × 2 19,260 227 20.77 3.92 4 × 1 17,817 227 38.68 6.23 3 × 6 19,260 227 41.97 52.51 3 × 5 17,817 227 40.94 51.27 3 × 4 32,695 2540 46.35 11.04 3 × 3 32,695 2540 34.26 47.74 2 × 6 19,260 227 51.71 12.45 2 × 5 17,817 227 45.89 16.53 2 × 4 19,260 227 44.50 2.16 2 × 3 32,695 2540 43.99 7.68 2 × 2 19,260 227 44.50 2.16 2 × 1 17,817 227 38.68 6.23 1 × 6 19,260 227 14.32 48.43 2 × 5 17,817 227 43.99 7.68 2 × 4 19,260 227 44.50 2.16 1 × 5 17,817 227 43.99 7.68 1 × 4 32,695 2540 36.61 51.10 1 × 3 32,695 2540 36.61 51.10 1 × 2 17,817 227 38.68 6.23 1 × 1 17,817 227 38.68 6.23

4. Conclusion

The presented methodology has been evaluated based on implementa-
ment on a case project. Over 90 modular units were delivered to
Muhlenberg College in Allentown, Pennsylvania for the assembly of
five new dormitory buildings. Three types of modules were fabricated
to be “ready-to-use” at Kullman Building Corporation’s fabrication
shop in Lebanon, New Jersey. On the construction site, modules were
assembled in much the same manner as a puzzle into three-storey
units with minor hook-ups between compartments. Assembling the
effect of the algorithms used was contingent on the collect-
ded detailed data about the construction site, selected crane, and
building configuration and to reduce the load distance. The
effectiveness of the algorithms used was contingent on the collect-
ded detailed data about the construction site, selected crane, and
laid objects. Each operation was classified based on its resource
requirements and time constraints. Three different values associated
with this operation (optimistic, likely, pessimistic) were develop-
ed to satisfy triangular distribution of the simulation model. The
selected crane boom configuration was evaluated for all possible clear-
ance scenarios involving nearby obstructions, and proper data was later
fed into the simulation engine. In particular, the engine considered the
new clearance relationship which had been identified between the
crane boom envelope and the sloped roof surface. This operation was
based on boom clearance analysis of a flat roof obstruction surface as
described in the literature. Complicated mathematical relationships
have been evaluated and analyzed, creating a new point of reference for
interested professionals. Actual construction assembly validated
the preparation and algorithm results, and ultimately justified this re-
search as a basis for managerial decision making.

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