



Automated Crane Planning and Optimization for modular construction

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ABSTRACT

The majority of industrial projects in Alberta's oil sands are constructed using modular construction. Modules are preassembled components built off-site and transported to the site to be lifted into place with mobile cranes. Heavy lifts include modules as well as major equipment that utilize expensive mobile cranes. Selecting the proper mobile cranes and configurations and finding the best crane position for each lift saves a significant amount of time and cost, while also improving safety. A heavy lift plan facilitates overall site management by reducing extra crane relocations and avoiding dangerous crane clashes. Performing such intensive analysis manually for several hundred lifts and various crane options is a tedious, prolonged exercise. However, no application that carries out such intensive analysis for a number of lifts in modular construction has yet been developed. This paper presents a system, called Automated Crane Planning and Optimization, to automate the above-mentioned analysis for a large-scale project. This system is validated on actual modular projects.

1. Introduction

The heavy lift plan is the backbone of an industrial construction project. Heavy lift mobile cranes on major industrial construction projects are expensive and can run into millions of dollars. Effective management of the mobile cranes is a critical task for safety, cost efficiency and on-time lifting of modules. An effective heavy lift plan results in properly selecting the best types of mobile cranes, crane positions, crane configurations (e.g., boom and jib length, crane counterweight and superlift counterweight, superlift radius), mat configurations underneath cranes, rigging configuration, as well as the appropriate lifting sequence. However, such an intensive analysis on an industrial construction site containing several hundreds of heavy lifts requires the analysis of thousands of variables, including the physical conditions of the site; dimensions, orientations and weights of modules to be lifted; and the lifting schedule, as well as the lift capacities and dimensions of available cranes.

An in-house developed heavy lift software suite, called HeviLift, was developed at PCL Industrial Management Inc. This software analyzes thousands of scenarios in a short time to find a safe, cost-efficient plan for selecting the proper mobile cranes with optimal configuration and positions. This paper reviews the backbone of the HeviLift suite, called Automated Crane Planning and Optimization (ACPO) to automate the process of checking the clearance of crane components with all existing obstructions in a mathematical approach and other lifting objects (e.g.

several millions of cranes' lifting options in an actual large-scale project), identifying the potential crane positions (i.e. grid points) and potential logic issues for all lifting objects, clustering lifting options.

This system is developed for analyzing the total lifts of entire project, not only for a single lift. The main inputs of ACPO application include project boundaries, site clearances, objects data, cranes and configurations. Some of input data (e.g. project boundaries, modules location and specifications) can be easily extracted from CAD or BIM models by utilizing a developed Application Programming Interface (API), and stored in a centralized database.

Optimization is not the main objective of this research, but the developed system provides an intensive backbone for optimization purposes. Identifying the feasible cranes, cranes' configurations, cranes' possible locations for lifts, and lifting logic issues is the main goal of this study.

2. Background and state of the art

Modularization of oil and gas and petrochemical industrial plants in the province of Alberta, Canada has become very popular for various reasons, including reducing cost, enhancing safety and quality, easing site congestion, and compressing project schedules [1]. Modularization involves building prefabricated modules off site, transporting to the construction site, and lifting on site [2]. The maximum size of an Alberta-built module is 24 ft (7.3 m) wide, 27.5 ft (8.4 m) high, and 138 ft

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Fig. 1. Modular construction of an industrial plant.

(42 m) long. Such heavy modules may weigh up to 176 Imperial tons (160 metric tons) to be shipped on the road.

Once those modules and other pieces of equipment have been fabricated and built, they are transported to the construction site and lifted into place. In North American industrial construction, such heavy lifts (Fig. 1) are usually performed with mobile cranes on site [3, 4]. Owning a heavy lift crane is rare, and renting a heavy lift crane is expensive, sometimes requiring several months in advance to book the crane. Moreover, heavy lift operations require a heavy lift crew (as many as 10 people) to perform lift-related activities, including preparing the ground, placing mats underneath mobile cranes, assembling rigging, supervising, and securing the module or vessel in lifting operation.

Heavy lift operations are usually part of the critical path of a project and drive many other activities on the site. Thus, an effective heavy lift plan impacts the overall schedule of a modular construction project, saves millions of dollars, and contributes to safety and quality on the job site.

Traditionally, the selection of mobile cranes and the development of engineered lift studies are analyzed individually. In practice, crane selections are usually based on the heaviest lift and/or largest lift radius, not all of the several hundred heavy lifts that occur during a large-scale project. Thus, such analysis requires a very experienced lift engineer to manually determine potential crane positions with great effort and select positions in the project. Typically, 2D plot plans are employed to position the cranes, and to perform boom clearance checks against objects. Spreadsheets are also used as a quick method of determining boom clearances. 3D models have become more prominent recently due to technological advancements, but these require manual user trajectory paths.

The traditional practice of selecting the best configuration and position of the crane, checking all the clearances, and identifying clash detection issues is a very tedious and challenging process. The selected type and configuration of crane(s) do not necessarily provide the optimum solution for an entire project involving hundreds of heavy lifts. Several studies have been performed in the last two decades to examine automating crane selection and crane configurations [5–8], identifying possible crane locations [3, 4, 9–11], optimizing crane locations [12] and planning the lift path [13–18], and recently some studies focus more on single crane behavior [19, 20].

With advancements in computer technology in the 1990s, some researchers at the University of Texas initiated efforts to employ computer technology for heavy lift planning [13, 21, 22]. This work resulted in the development of a Heavy Lift Planning System (HeLPS). The HeLPS assists the lift planners in analyzing appropriate crane locations, checking lift path clearances, accounting for safety factors, as well as calculating ground support during lift. The HeLPS also utilizes CAD models to animate the motions of crane on a structural job site [23]. However, the scope of this analysis is limited to only one single lift.

Several commercial computer applications (e.g., 3D Lift Plan, Compu-Crane, Lift Planner, Cranimation, kranExpert) also exist to assist the lift planner in heavy lift planning. However, there is no academic or industrial application to perform the analysis for several lifts across an entire modular construction project.

Further efforts over ten years have been undertaken to automate planning multiple lifts and optimize the entire lift plan for a modular construction project at PCL Industrial Management Inc. in conjunction with the University of Alberta, and more recently with the University of Tehran. This work has resulted in a software suite, called HeviLift. The main purpose of HeviLift is to perform the intensive analysis of multiple lift planning for the entirety of a modular construction project, containing several hundred lifts, quickly and efficiently. HeviLift include various components including optimization mobile crane selection and location [24, 25], multiple heavy lift planning [26, 27], 3D-model-based crane selection and logistics [28, 29], Mobile Crane Path Planning [30, 31] and creating automated lift studies and 3D lift animation [32, 33]. This paper introduces the backbone of HeviLift, called Automated Crane Planning and Optimization (ACPO), which automates the process of checking the capacity of a crane and checking clearance of various components of cranes (e.g., boom, jib, car body, superlift, and rigging) with other lifting and non-lifting objects. ACPO also tries to find all lift logic and clash detection issues throughout the project. Implementing ACPO for practical case studies proves a number of benefits, including exploring various what-if scenarios in selecting types, configurations and locations of mobile cranes over the entirety of a modular construction project, ultimately reducing cost and enhancing safety.

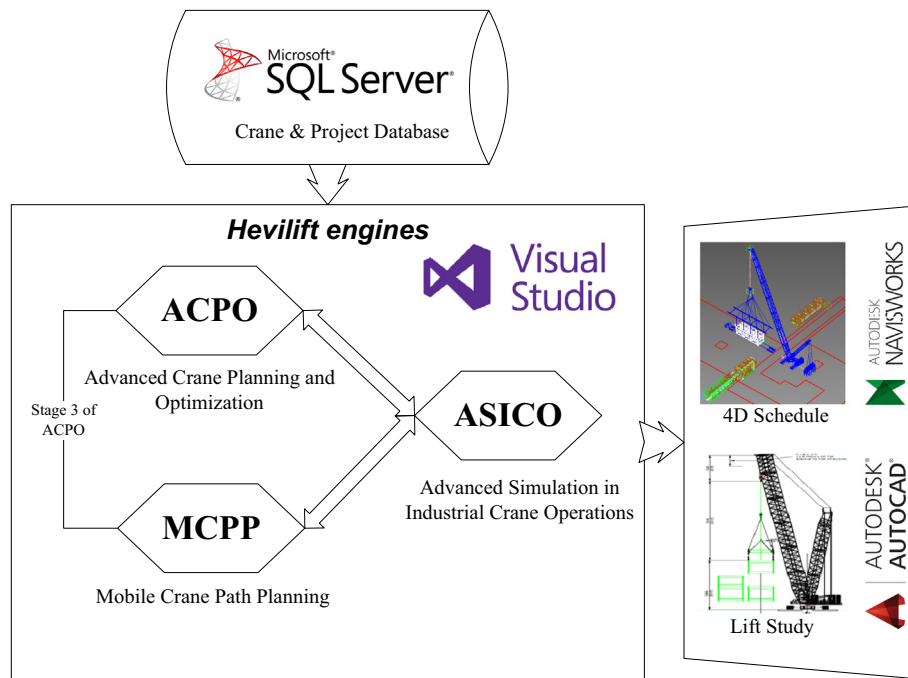


Fig. 2. Various components of the developed heavy lift (HeviLift) software suite.

3. Developed heavy lift (HeviLift) software suite

HeviLift involves several different components collaborating with each other (Fig. 2). The process in HeviLift starts with reading the required information within the crane and project database. Initially, these were two independent Microsoft Access (version 2007) databases located on the local server of the company. However, data was migrated to a database on SQL Server Management Studio (R 2008) for faster data manipulation, more secure data access, and ease of access to Autodesk Application Program Interface (API) codes on 64 bit computers.

Three main processes, shown as HeviLift engines in Fig. 2, are linked to this comprehensive database containing cranes and project information. ACPO, which is the main focus of this research, reads crane and project data and identifies the possible crane location based on boom clearances, crane capacity and project constraints by applying numerical algorithms, and populates the clash-related logic issues. ACPO also provides some mathematical optimization for crane selection and location. Next, HeviLift engages in the Mobile Crane Path Planning (MCP) process, which is the third stage of ACPO. MCP checks the installed objects and site layout to find a feasible lifting path and a potential walking path for crane operations based on the ACPO-suggested locations for cranes [30, 31]. Lastly, Automated Simulation in Industrial Crane Operations (ASICO) is a simulation-based optimization program. ASICO extracts the results obtained from ACPO and MCP to provide logic-optimized lift sequences. Furthermore, an automated system has also been developed to present the calculated results in an appealing visual manner and to provide a 3D lift study and 4D Schedule of one single lift, as well as all the lifts of the project.

4. ACPO methodology and example

Automated Crane Planning and Optimization (ACPO) is written using the Visual Basic (VB) program within the Microsoft Visual Studio 2013 programming environment. It reads crane and project data from a Crane Management database within a dedicated SQL server, performs mathematical and numerical analysis, and populates the results into the SQL server database. The input data, process engine, and the results of

these components are discussed below. This methodology is explained using an illustrative example of an actual petrochemical modular project.

4.1. Input data

The input data of ACPO consists of some general information about the cranes as well as some specific data about different projects. Thus, general database is divided into crane database and project database (Fig. 3)

4.1.1. Crane database

4.1.1.1. Cranes data. The crane database contains about 509 mobile cranes (e.g., crawler, all terrain, rough terrain, and carry deck cranes) commonly used in Canadian industrial projects. This database also captures crane dimensions, weight, and capacity information for common mobile cranes. As an example, Fig. 4 depicts the collected dimensional data for crawler cranes. Dimensional and capacity data of the cranes are all entered in imperial units of measure in the database for the sake of consistency.

4.1.1.2. Configurations data. The crane database contains various configurations for each mobile crane defined earlier. Each configuration corresponds to a specific length of boom, jib, fly, extension, and derrick. It also corresponds to a particular type of boom, jib, fly, and extension. It also specifies counterweight of crane, car body, and superlift. Finally, it determines lift quadrants as well as orientations of crawlers or outriggers. Currently, the database contains data for some highly used mobile cranes (e.g., Demag CC1800-1, Demag CC 2800, Kobelco CK2500-II, Manitowoc 3900W S-2, Manitowoc 4100W S-1) with over 26,000 different configurations. For instance, Table 1 depicts a particular crane configuration for a 600-ton Demag CC 2800-1 crawler crane mobilized with 275.6' boom length. This crane has over 1000 different configurations available in the database.

4.1.1.3. Capacity data. Each crane configuration can cover a particular donut area with a minimum and maximum radius and lifting capacity.

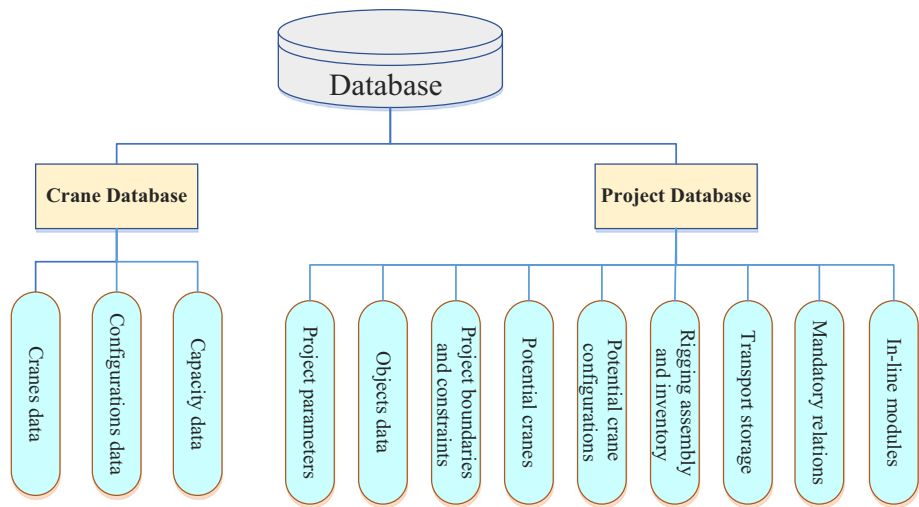


Fig. 3. HeviLift database hierarchy.

Maximum lifting capacity for each lifting radius (i.e., from the center pin of crane to the center of the load) is specified in a lifting chart as well as a capacity table. For example, Fig. 5 shows that the maximum lifting capacity of Demag CC 2800-1 crawler crane for the above-mentioned configuration is 482,800 lb within a 98.4' radius. It also shows that the maximum reach-in radius for this crane's configuration is 242.8'.

4.1.2. Project database

The project database contains data related to various active PCL projects. This data includes:

4.1.2.1. *Project parameters.* This data relates to generic project information, including project ID and description of a project, maximum crane capacity percentage acceptable within project, default ground elevations, transporter height for picking objects, unit of measurement, project shift and calendar, project start date, minimum clearances, and grid size for ACPO analysis.

4.1.2.2. *Objects data.* This data relates to lifting and non-lifting objects (e.g., obstruction buildings) as well as the cranes employed for lifting objects in the project. This data also includes object dimensions, crane lifting configuration information, coordinates of objects in the set and pick point positions, coordinates of cranes in the set and pick point positions, rigging configuration to lift the object, weight information of the lifting object (e.g., estimated weight, actual weight), type of lifting object (e.g., modules, horizontal and vertical vessels, tanks, compressors), object-related schedule (e.g., arrival on site date, scheduled lift date, actual lift date), and lift study information (e.g., drafter, lift engineer, revision history).

4.1.2.3. *Project boundaries and constraints.* The site boundaries, defined as closed polygons, are either Inside Boundary Limits (ISBL) or Outside Boundary Limits (OSBL). ISBL are boundaries in which the crane cannot go, while OSBL are boundaries beyond which the crane cannot go. The OSBL and ISBL boundaries can be easily defined based on the outside limit of the project (e.g., fence lines), and foundation/piling drawings, respectively. These boundaries are drawn manually in AutoCAD by

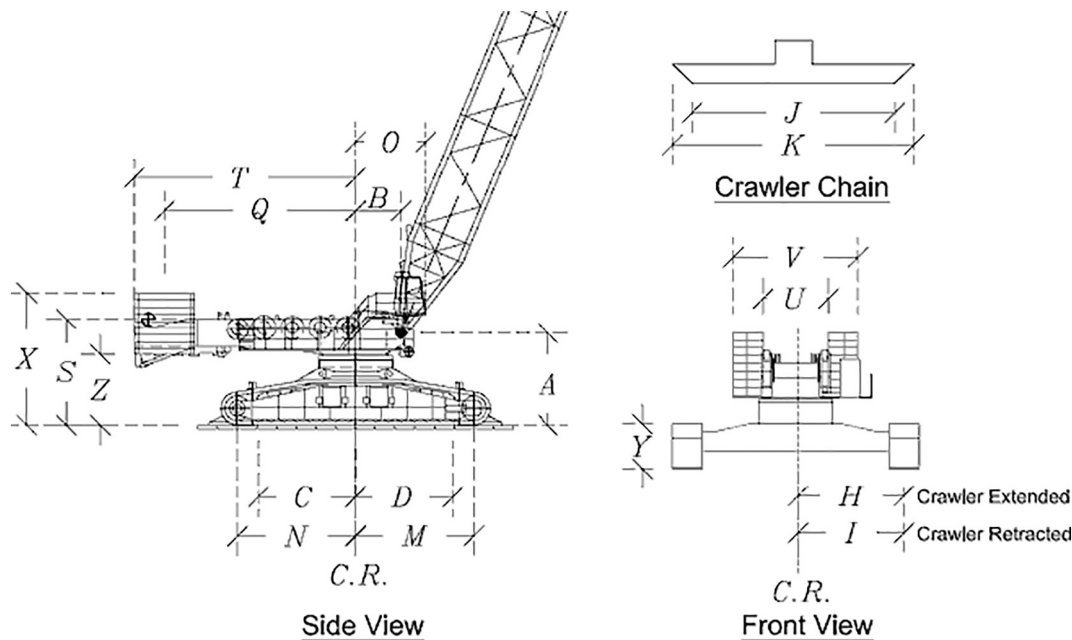


Fig. 4. Crawler crane dimensional data.

Table 1
Employed configuration data of Demag CC 2800-1 mobile crane.

Boom		Counterweight		Superlift	
Type	Length (feet)	Crane counterweight (lb)	Car body counterweight (lb)	Superlift counterweight (lb)	Superlift radius (feet)
SSL	275.6	396,800	132,300	396,800	49.2
Other specifications					
Derrick length (feet)	Jib length (feet)	Quadrants (degree)	Crawler configuration	Fly configuration	Extension configurations
98	×	360	Fully extended	×	×

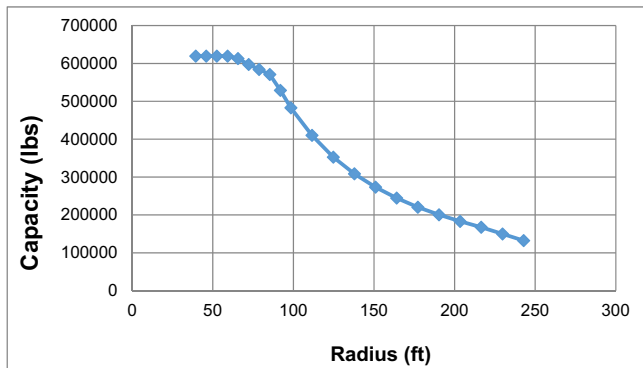


Fig. 5. Capacity chart of Demag CC 2800-1.

polyline tool and transferred to database by AutoCAD API Programming. Fig. 6 illustrates ISBLs and OSBLs for Case 1. The availability periods of these boundaries (i.e., having time-dependent boundaries) are also captured for future ACPO development.

4.1.2.4. Potential cranes. This data includes cranes that potentially could be used in the project and their availability period, rental cost

and other associated costs for mobilization, demobilization, reconfiguration, preparing ground condition, and placing mats.

4.1.2.5. Potential crane configurations. This information includes the potential configurations that may be used within the project, for each potential crane. The crane configuration data (e.g., boom length, jib length, lift quadrant, crane and superlift counterweights, superlift radius and related hyperlinks to capacity charts) is derived from the crane database mentioned above.

4.1.2.6. Rigging assembly and inventory data. Rigging information includes ID, number of pick points, height, weight, dimensions, duration and manpower for related tasks (i.e., rigging up and rigging down), and the cost rate of the assistant crane for rigging assembly. Inventory data includes quantities of slings, shackles, spreader bars, turn buckles, lift ears, and snatch blocks plus their length, capacity, and weight.

4.1.2.7. Transport storage. This information includes storage costs for loading, offloading, storing the lifting objects, mobilizing, and demobilizing the transport equipment.

4.1.2.8. Mandatory predecessors among objects. Logic data includes any

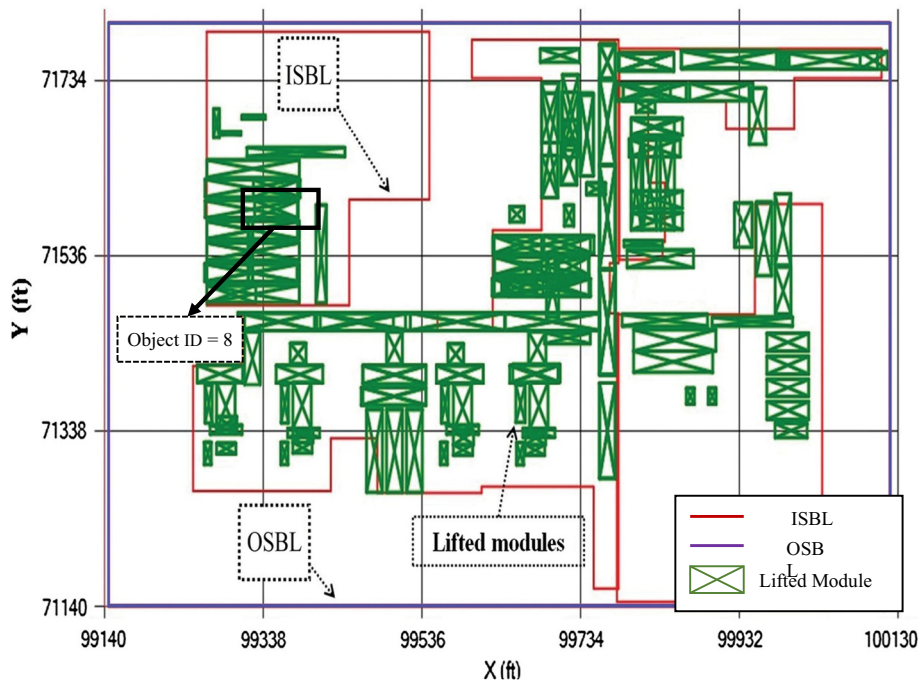


Fig. 6. Site boundaries (ISBL and OSBL) in a modular industrial plant (Case 1).

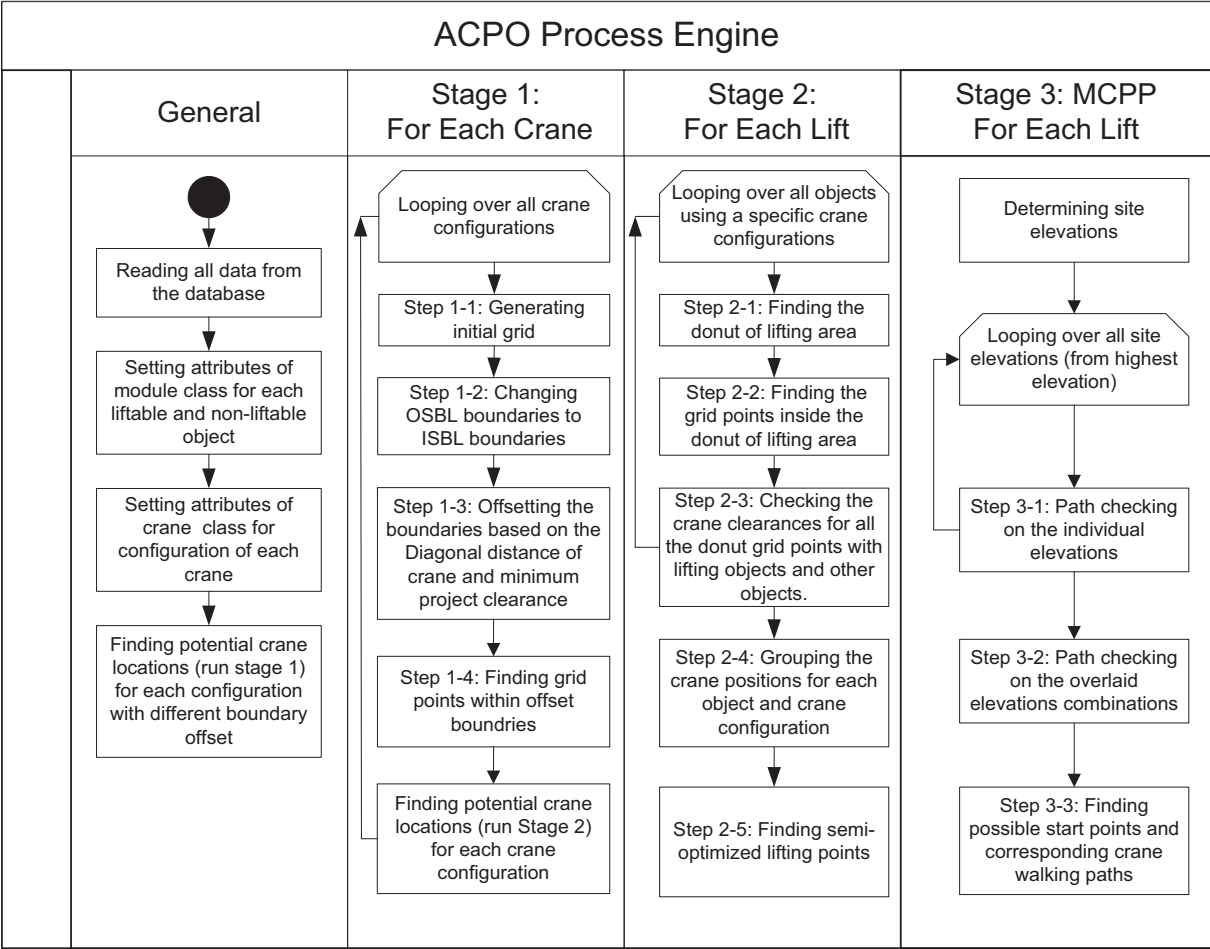


Fig. 7. UML diagram of ACPO process engine.

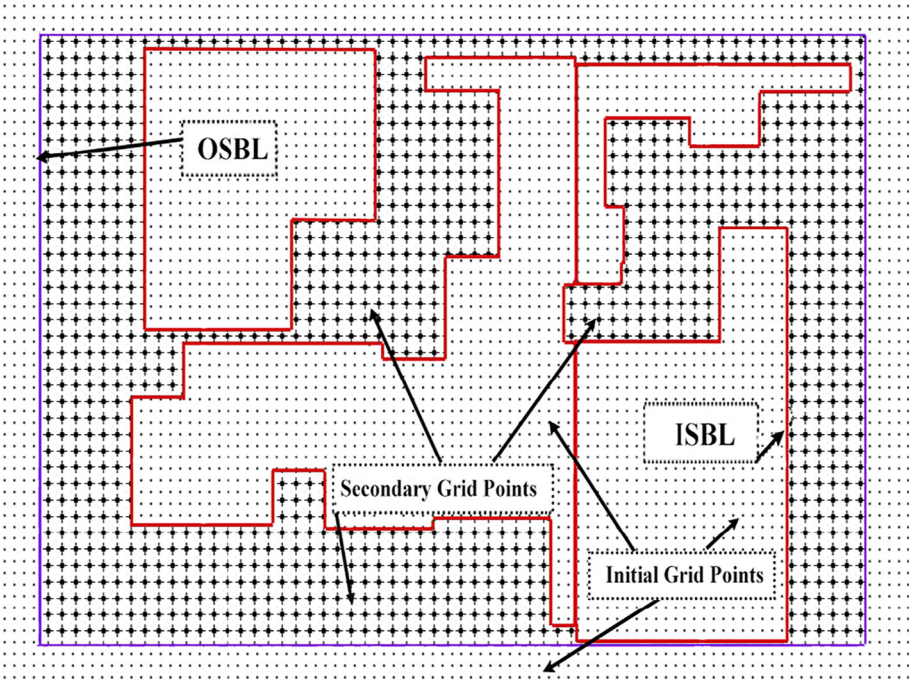


Fig. 8. Initial and secondary grid points (Case 1).

sort of mandatory logics to be considered in the lift schedule (e.g., modules in lower elevation should be lifted first).

4.1.2.9. Group of in-line modules. This information is another practical type of lifting logic data, which facilitates sequencing modules to avoid placing a module between two adjutant lifted modules.

4.2. ACPO process engine

The ACPO process engine calculates possible crane areas and subsequently optimizes crane locations by performing mathematical analysis on both the crane and project databases. This requires checking the boom clearances to identify clashes with site boundaries and adjusting the radius to modify the crane work area. The dimensional complexity of a crane with superlift counterweight configuration is also analyzed. This task is performed for multiple crane options as well as multiple lifted objects. The sequence of this process is shown in Fig. 7.

A. General process: ACPO is initialized by populating input data (e.g., information about selected project, objects, riggings, cranes, configurations, and boundaries) from the crane and project database. The process is proceeded by running Stage 1.

B. Stage 1: For each potential crane, the following steps are processed:

B.1. Step 1–1: ACPO generates initial grid points for each rectangle on the site layout by determining the minimum and maximum coordinates of ISBL and OSBL boundaries. Consequently, all grid points located inside one ISBL or outside all OSBLs are filtered out. Finally, the remaining grid points, called secondary grid points, are saved in the database (Fig. 8).

B.2. Step 1–2: ACPO changes all OSBL boundaries to ISBL boundaries in order to simplify the process of offsetting the boundaries in Step 1–3. This requires breaking a segment (i.e., adding one extra node at the middle of the segment) for each OSBL boundary. Then, the OSBL is converted to an ISBL boundary by offsetting the entire polygon one unit toward the outside (Fig. 9). Each new ISBL boundary is named as a dummy ISBL boundary in the database.

B.3. Step 1–3: To consider sufficient clearance for rotating the body of a crane, ACPO offsets all ISBL boundaries based on the diagonal distance (see Fig. 10) of each crane plus an acceptable minimum clearance defined in the project database (e.g., 3 ft). This process is depicted in Fig. 10 and explained below.

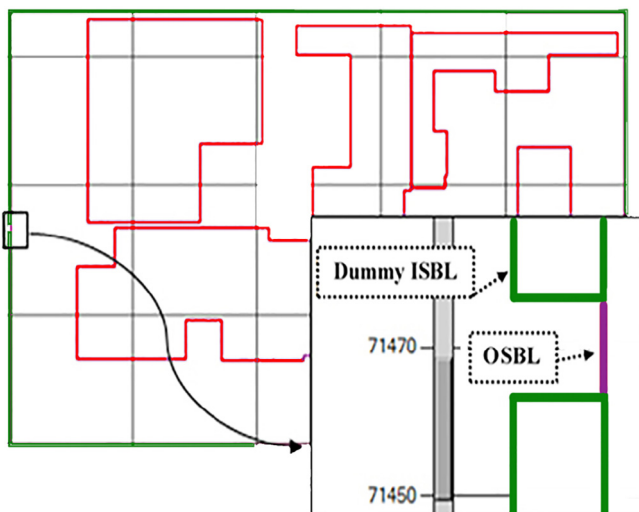


Fig. 9. Changing OSBL to ISBL boundaries (Case 1).

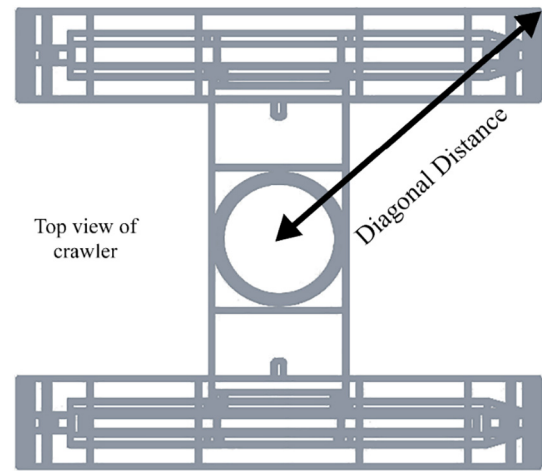


Fig. 10. Diagonal distance of a crawler.

B.3.1. Step 1–3–1: ACPO decomposes all non-convex (i.e., concave) boundaries to a number of convex polygons in order to simplify the process of offsetting the boundaries in Step 1–3–2. In this study, the slab decomposition algorithm [34] is utilized for decomposing a concave polygon into convex polygons (i.e., slabs) by drawing vertical lines through each concave vertex (Fig. 10).

B.3.2. Step 1–3–2: For expanding each ISBL, a circle with a radius of the minimum project clearance is approximated with an N-sided polygon, within each vertex of ISBL polygon. Then, ACPO calculates the convex hull of expanded ISBLs and the generated N-sided polygon, using a gift-wrapping algorithm [35] to offset each convex polygon (Fig. 11).

B.3.3. Step 1–3–3: Finally, ACPO finds the union of all expanded ISBLs and union of all OSBLs separately by employing the General Polygon Clipper library (GPC) algorithm. This algorithm contains four operations including union, difference, intersection, and exclusive-or to clip combination of polygon boundaries with areas of planar drawings. GPC results differentiate hole contours (i.e., ISBL in this study) from external contours (i.e., OSBL in this study) as new OSBL (OSBLN), see Fig. 11. The above algorithm is presented briefly by Eq. (1).

$$OSBLN = \left(\bigcup_{i=1}^n OSBL_n \right) - \left(\bigcup_{i=1}^m ISBL'_m \right) \quad (1)$$

where OSBLN = new OSBL boundaries, ISBL' = expanded ISBL and dummy ISBL boundaries, n = number of OSBLs, m = number of expanded ISBLs and dummy ISBL boundaries.

B.4. Step 1–4: The grid points within OSBLN boundaries are determined by filtering out secondary grid points that are located outside the union of all OSBLNs boundaries, and remaining grid points are saved in database.

C. Stage 2: For each configuration of the crane and for each object, do the following:

C.1. Step 2–1: For each lifting object with a particular crane configuration, ACPO generates the donut lifting area, based on the minimum and maximum crane radii. ACPO extracts the minimum and the maximum radius from the capacity chart of the specific configuration by calculating the total weight of the lifting object. The total weight is calculated based on estimated or actual weights, rigging weight, and deductions. Subsequently, these minimum and maximum radii are modified by considering boom clearances. For this modification, boom angle and jib angle corresponding to the minimum and maximum radii of the crane are

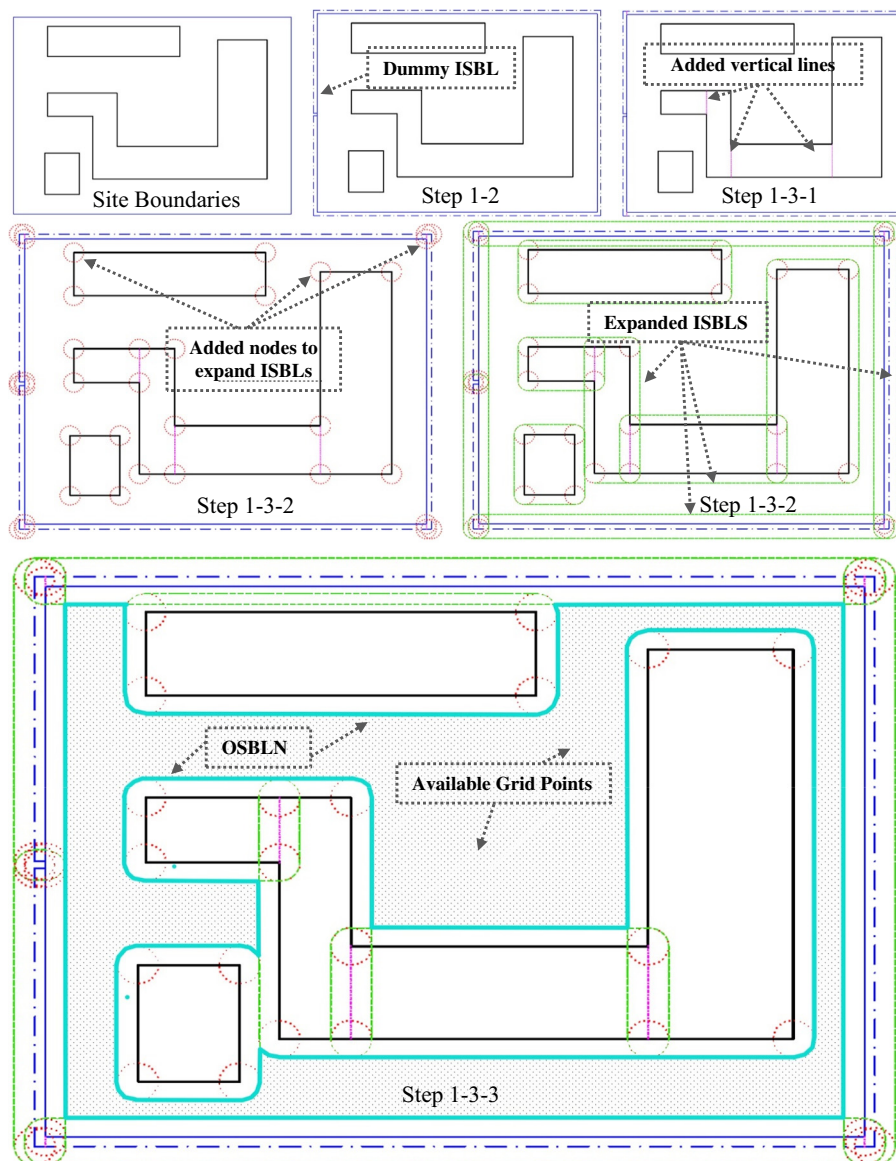


Fig. 11. Example of step 1–3, offsetting boundaries based on tail swing clearance.

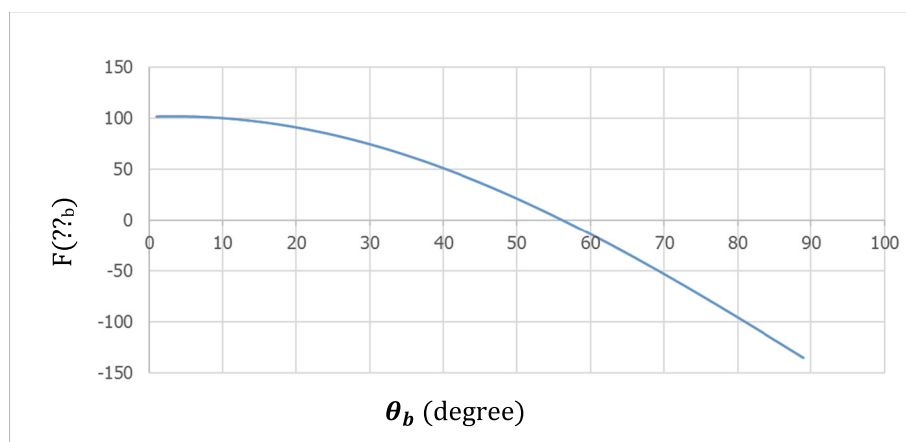


Fig. 12. Example of $F(\theta_b)$, Manitowoc 4100W S-1.

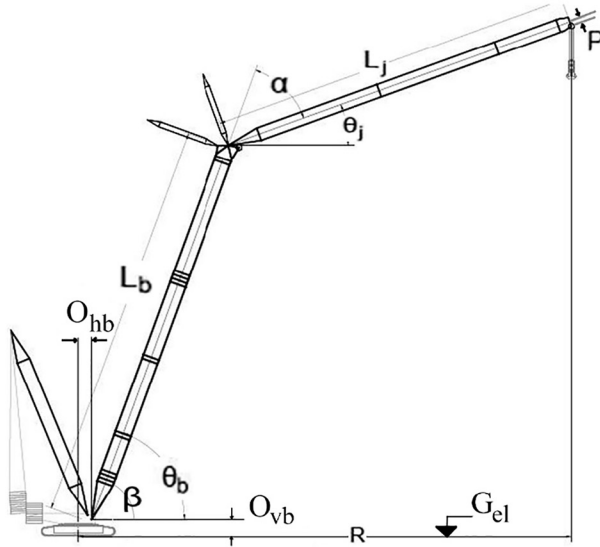


Fig. 13. Lengths and angles of a mobile crane for calculating minimum and maximum radius.

estimated by finding the root of the clearance function based on Newton's method. This numeric method finds the root of a function, where $F(x) = 0$, by iterating the following Eq. (2):

$$x_{n+1} = x_n - f'(x_n)/f(x_n) \quad (2)$$

a) This function and its derivative for two cases below can be defined as following:

No jib or “fix” jib with variable boom angle and initial $x_0 = \pi/3$, Eqs. (3) and (4):

$$f(\theta_b) = L_b \times \cos(\theta_b) + L_j \times \cos(\theta_b - \alpha) + P \times \sin(\theta_b - \alpha) + O_{hb} - R \quad (3)$$

$$f'(\theta_b) = -L_b \times \sin(\theta_b) - L_j \times \sin(\theta_b - \alpha) + P \times \cos(\theta_b - \alpha) \quad (4)$$

b) “Luffing” jib with variable jib and initial $x_0 = \pi/6$, Eqs. (5) and (6):

$$f(\theta_j) = L_b \times \cos(\beta) + L_j \times \cos(\theta_j) + P \times \sin(\theta_j) + O_{hb} - R \quad (5)$$

$$f'(\theta_j) = -L_j \times \sin(\theta_j) + P \times \cos(\theta_j) \quad (6)$$

where θ_b = variable boom angle $\{0 < \theta_b < \pi/2\}$; L_b = boom length; L_j = jib length; P = Pdimension; α = fixed jib offset angle; O_{hb} = horizontal boom offset; R = radius (horizontal distance between center of the crane and object); θ_j = variable jib angle $\{0 < \theta_j < \pi/2\}$; β = boom angle in the case of luffing jib (see Fig. 13).

Fig. 12 illustrates an example of $f(\theta_b)$, for Manitowoc 4100W S-1, Where $L_b = 230$ ft; $P = 4.96$ ft; $L_j = 30$ ft; $\alpha = 20^\circ$; $O_{hb} = 5$ ft, where the θ_b is calculated about 56° .

Further, the rigging height clearance (RHC) in the minimum and maximum radii is calculated using the Eq. (7):

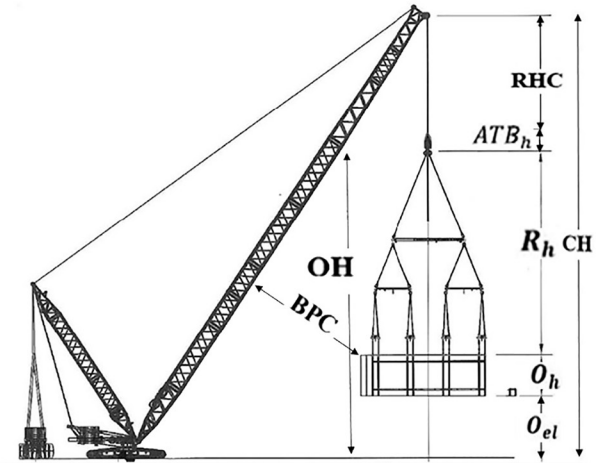
$$RHC = CH - OH \quad (7)$$

where RHC = rigging height clearance; OH = total object height; CH = total crane height (see Fig. 10). OH and CH calculated as Eqs. (8), (9) and (10):

$$OH = O_{el} + O_h + R_h + ATB_h \quad (8)$$

where O_{el} = object elevation; O_h = dimensional object height; R_h = rigging height; ATB_h = ATB height.

a) No jib or “fix” jib with variable boom angle:



$$CH = G_{el} + O_{vb} + L_b \times \sin(\theta_b) + L_j \times \sin(\theta_b - \alpha) - P \times \cos(\theta_b - \alpha) \quad (9)$$

b) “Luffing” jib with variable jib angle:

$$CH = G_{el} + O_{vb} + L_b \times \sin(\beta) + L_j \times \sin(\theta_j) - P \times \cos(\theta_j) \quad (10)$$

where O_{vb} = vertical boom offset; G_{el} = ground elevation.

With these parameters, ACPO revises the minimum and maximum radius by doing the following:

If the RHC of the maximum crane radius is negative, and the RHC of the minimum crane radius is positive, the program finds the intermediate radius where the RHC function is zero based on the above-mentioned Newtonian method, and updates the maximum radius to the calculated radius. If both RHCs are negative, then the allowable rigging clearance is not sufficient, so the minimum and maximum radii are updated to zero. ACPO also modifies the minimum and the maximum radius based on the boom perpendicular clearance of the 3D system. The Boom Perpendicular Clearance (BPC) is calculated in such a 3D algorithm, and the value of the BPC for the minimum and maximum radii are checked (see Fig. 13). If the BPC in the minimum crane radius is negative, and the BPC in the maximum crane radius is positive, the program finds the intermediate radius where the BPC function is zero based on the above-mentioned Newtonian method, and updates the minimum radius to calculated radius. If the BPC for the minimum and maximum crane radii is negative, then both radii are updated to zero.

Finally, ACPO utilizes the difference operation of the clipping algorithm to find the polygon representing the donut between the minimum and the maximum radius, and the offset boundary for the selected crane configuration. The donut polygon is saved in the database as the OSBL boundary (Fig. 14.A).

C.2. Step 2–2: In the following, each of grid points that is not inside of any donuts is removed from the grid points saved in Step 1–4 by converting each of the donut boundaries to an OSBL boundary (Fig. 14.B, C).

C.3. Step 2–3: Other clearances (e.g., boom, jib, counterweight, and superlift clearances) at each of the donut grid points for all configurations with the lifting object and with other existing objects are checked in this step. Middle and corner points of the crane counterweight and crane superlift configuration are found. If any of these points are located inside one of the ISBL boundaries, or not located inside an OSBL boundary, this alteration is recorded as a lifting logic issue, or else the checking process will be continued.

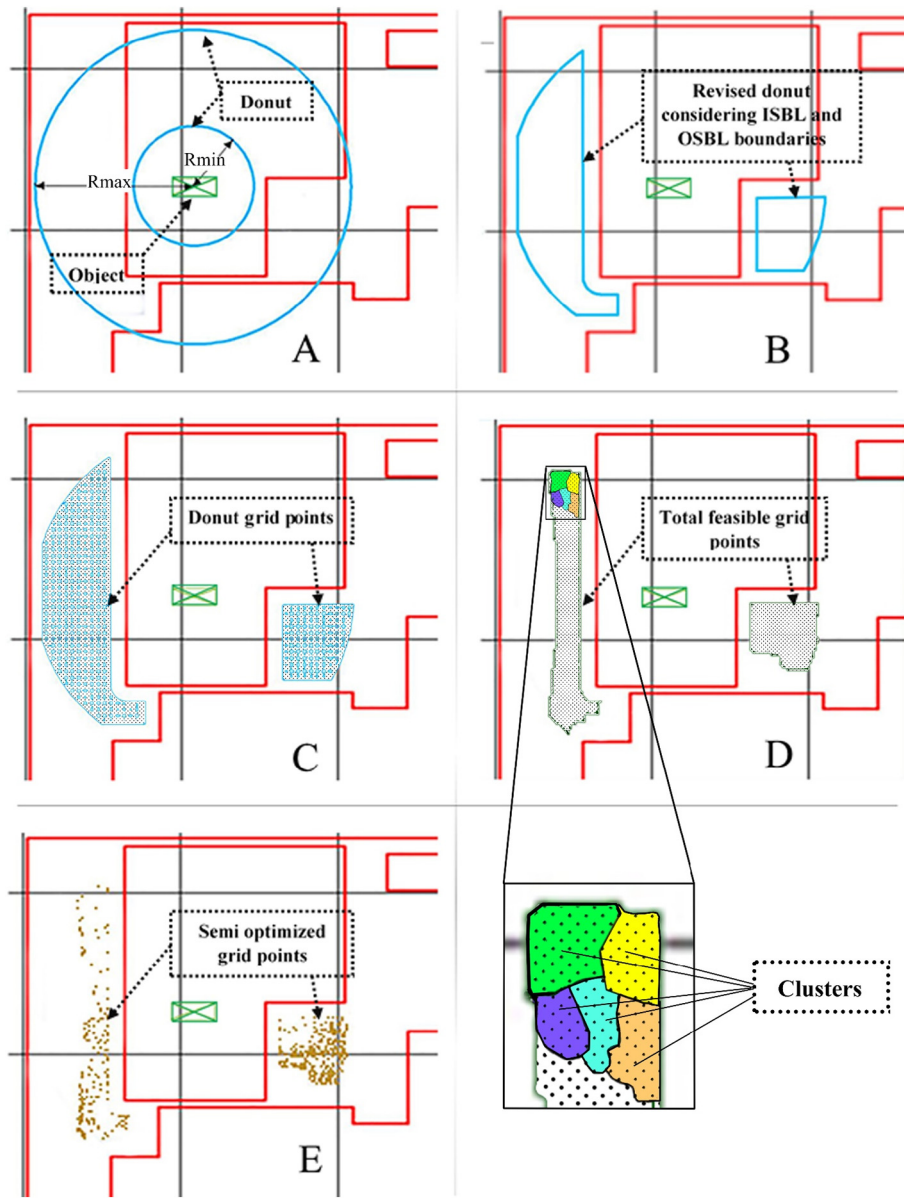


Fig. 14. Steps of Stage 2 for specific object (Case 1 where Object ID = 8).

Afterward, regarding the other lifting objects as rectangular boxes, the minimum clearances are found between the 3D boxes of the lifting object and the surrounding edges of the boom, counterweight and superlift counterweight. If the minimum clearance of any other adjacent objects is less than the project minimum clearance, this lift logic issue is resolved by introducing the adjacent object as a successor for the selected lifting object at the specific selected configuration and grid point. Eventually, each remained grid point is a feasible grid point for lifting operation (Figs. 14.D and 15).

- C.4. Step 2–4: Due to ASICO process of HeviLift suite for sequencing multiple lifts, ACPO is grouping the feasible grid points as clusters. Each cluster defines a discrete zone on each side of the boundaries to lift particular objects. In the other word, from each point of a cluster, same objects could be lifted. Feasible crane configurations and grid points in the same cluster are then populated. Fig. 14.D depicts five clusters for a liftable object on two sides of an ISBL boundary.
- C.5. Step 2–5: Feasible grid points can be semi-optimized by minimizing a utility. This results in minimizing number of logic issues

(i.e. number of successor objects with the same configuration from the selected grid point), maximizing object count to be lifted, minimizing position radius of crane (i.e. lift radius), and maximizing boom clearance (Eq. (11)). These factors have different weights found by experience for industrial construction projects. However, the exact values of the weights (i.e. a to e) are not presented here due to confidentiality reasons.

$$UF = a*[NLI] - b*[OC] + c*[PR] - d*[BC] + e \quad (11)$$

where UF = utility function, NLI = number of logic issues, OC = object count to be lifted form the same cluster, PR = position radius, BC = boom clearance.

For example, three locations for a specific crane option are compared in Table 2 for Case 1, where object ID is 8 (see Fig. 6) and configuration ID is 27323 (see Table 3). The optimization method in this stage is a heuristic approach. However, developing an optimizing algorithm is the key object of future studies.

- D. Stage 3 (MCP): Stage 3 of ACPO focuses on path planning for mobile cranes, called MCP (Mobile Cranes Path Planning).

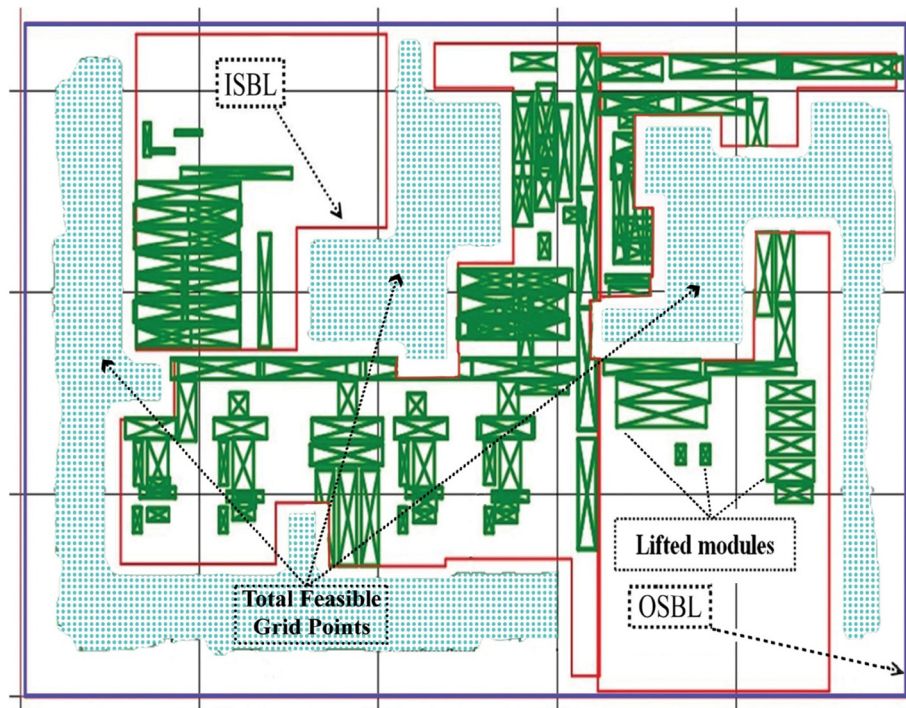


Fig. 15. Total feasible grid points of entire project (Case 1).

Table 2

Three feasible locations and utility function for Case 1 where object ID = 8, configuration ID = 27232.

Location ID	Location (X, Y)	Logic issue	Object count	Position radius (degree)	Boom clearance (feet)	Utility function
1	(99,469, 71,497)	3	23	145.53	48	42.25
2	(99,223, 71,407)	0	40	150.09	68	19.79
3	(99,244, 71,470)	0	54	93.65	22	5.21

Comprehensive studies of this stage have been published already by Lei et al. [30, 31]. MCPP checks possible lift paths for particular objects in selected grid points. In it, the purposed algorithm divides the site's 3D layout into elevations specified by module dimensions. The first step of MCPP checks possible paths at each elevation; if there is no collision-free path, the algorithm checks the lift path for an overlaid combination of elevations [31]. Lifts that are not possible force the mobile crane to make movements and transfers to another position while lifting. Mobile crane walking path planning is studied in the final step of Stage 3 [30].

5. Case study

ACPO, and the HeviLift system, are already applied to many projects at PCL. In the past, selection of cranes and configurations for all lifts

have been processed at length by the company's best lift engineers (spanning up to 3–4 weeks for 300 lifts). ACPO analyzes all lifts usually in less than hour till a day to produce results. Processing time depends on various parameters including size of the project (i.e. number of grid points), number of lifts and potential crane configurations, complexity of boundaries, and computer specifications (e.g. processor, RAM).

5.1. Case 1

Figs. 6, 8, 9, 14 and 15 in the above sections illustrate the analysis Stage 1 and Stage 2 of ACPO on an industrial project containing 199 modules. This project is one of the implementations of a “design one, build many” program at PCL. The project was constructed in 7.5 months, while another similarly-designed project constructed earlier was complete in 10.5 months. Comparative analysis shows that, of a 34% reduction in project time, changing the rigging design of lift frames is responsible for 20%, and implementing the results of HeviLift suite is responsible for 14% of the time savings. Liebherr LR 1300 and Demag CC 2800 cranes with four different configurations are employed, and the ACPO analysis shows that the LR 1300 configuration can lift only 81 out of 199 modules (Fig. 16.D.1 and D.2). Two configurations of the Demag CC 2800 can lift 197 and 198 modules respectively (Fig. 16.A and C), and just one of the Demag CC 2800 configurations can lift all 199 objects (Fig. 16.B). These results are presented in Table 3. Following the overall process of the HeviLift system (ACPO, MCPP and ASICO), this practice connects the database to CAD tools and animation design applications to produce 4D lift plans and lift animations for the project overall (Fig. 17). This procedure is automated by

Table 3

Cranes and configuration analysis for Case 1.

Crane	Configuration ID	Capacity (ton)	Boom type	Boom length (feet)	Super-lift	SL radius	Cost (\$ per month)	Total liftable objects
LR 1300	19403	300	SL	203	✗		130K	81
CC 2800-1	27231	660	SSL	275.6	✓	49.2	200K	198
CC 2800-1	27232	660	SSL	275.6	✓	55.8	200K	199
CC 2800-1	27268	660	SSL	275.6	✓	42.7	200K	197

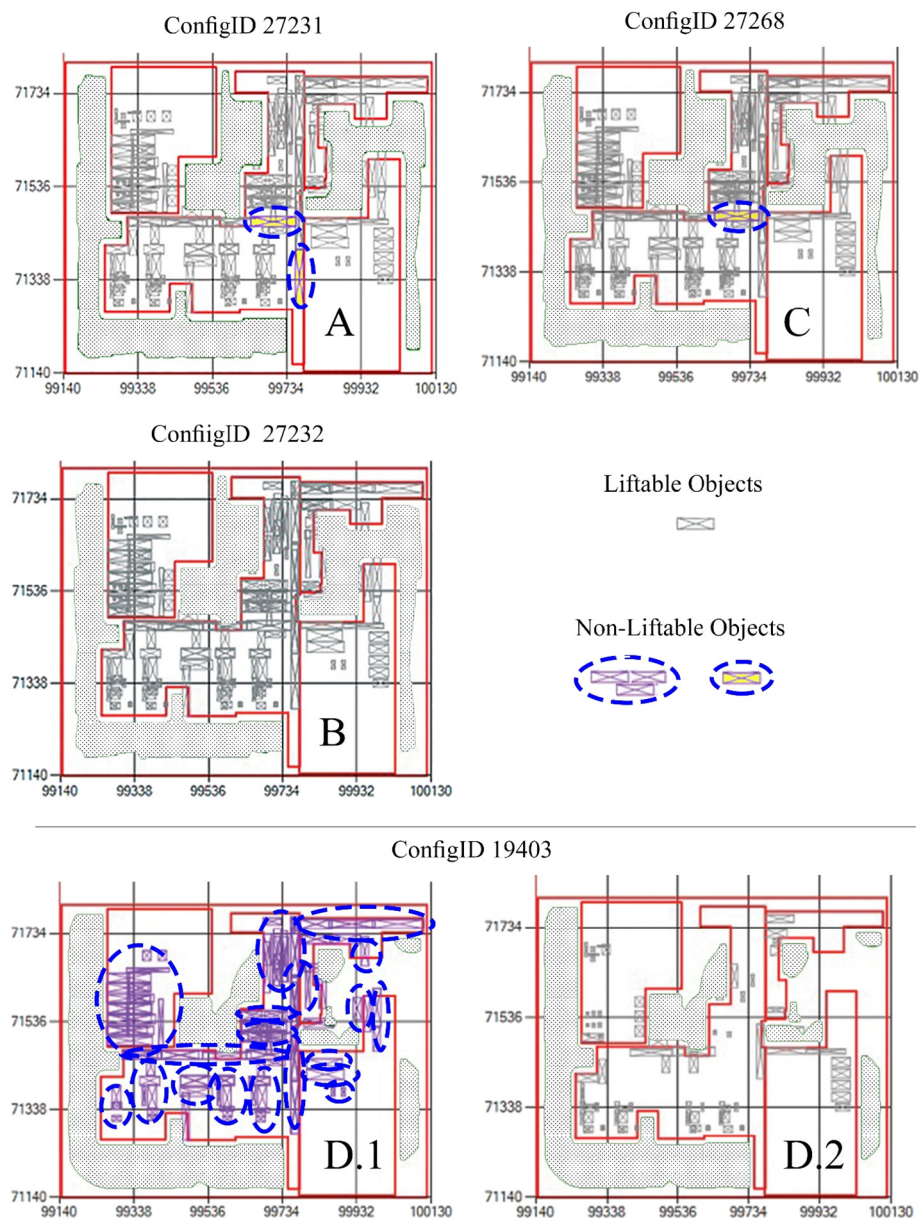


Fig. 16. Case 1 - modular plant.

utilizing Application Programming Interface (API) for the above software tools.

5.2. Case 2

Fig. 18 depicts another industrial plant containing 41 modules. The proposed methodology is applied to 2 cranes within 7 configurations (LR 1400/2 and CC 2800). Table 4 shows the results of ACPO analysis, in which all of the 41 modules could be lifted by CC2800 with superlift, and 40 modules could be lifted by LR 1400/2 with 184' boom length and superlift. Due to the cost of each crane, the LR 1400/2 configuration was employed. Only one module could not be lifted because of limitations in area (ISBL boundary). This object was planned to be lifted using the same configuration matting over foundations inside the ISBL, before beginning adjacent construction activities. In total, project duration was 3 months, at a rate of 1.5 lift per day. Employing LR 1400/2 saves around \$150,000 as compared to CC 2800.

6. Conclusions and future research

Heavy lift operations are often on the critical path for industrial modular construction projects, and generating accurate and acceptable lift plans is key to success. However, traditional methods of selecting mobile crane positions and configurations are very time consuming. New trends in construction necessitate more efficient solutions than traditional analysis for optimizing heavy lift operations. This paper illustrates a novel framework called ACPO (Automated Crane Planning and Optimization) to automate and facilitate the planning of mobile crane operations in modular construction plants. ACPO utilizes mathematical and numerical algorithms to calculate the best position and the best crane configuration for heavy lifts. ACPO processes the related project database to provide results within three main stages. In Stages 1 and 2, this system finds the feasible crane locations for each lift with particular configurations and optimizes these feasible locations. Stage 3 of ACPO works as a separate engine called MCP (Mobile Crane Path Planning) for planning the path of the mobile cranes for total lifts. ACPO, MCP and ASICO (Auction based Simulation in Industrial Crane

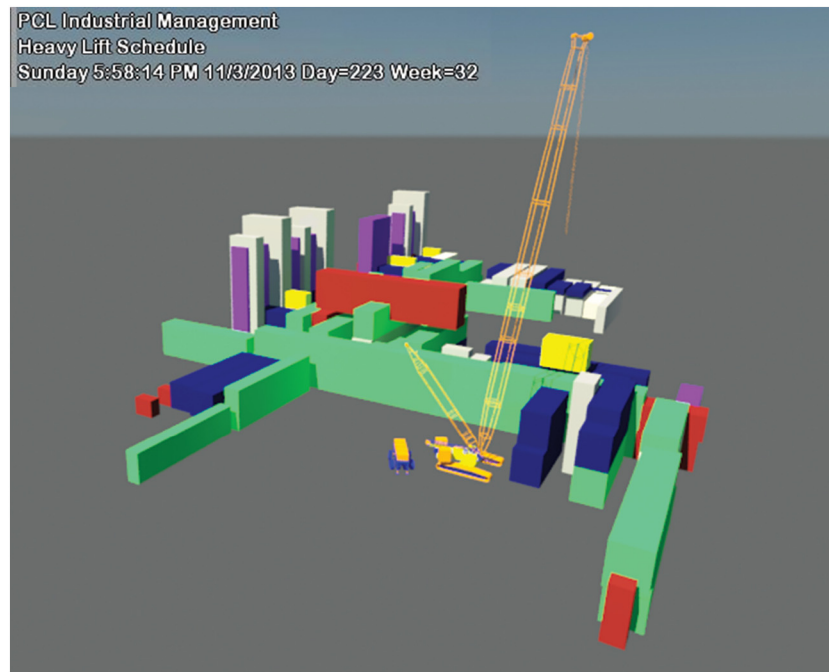


Fig. 17. Lift plan and 4D Schedule for Case 1.

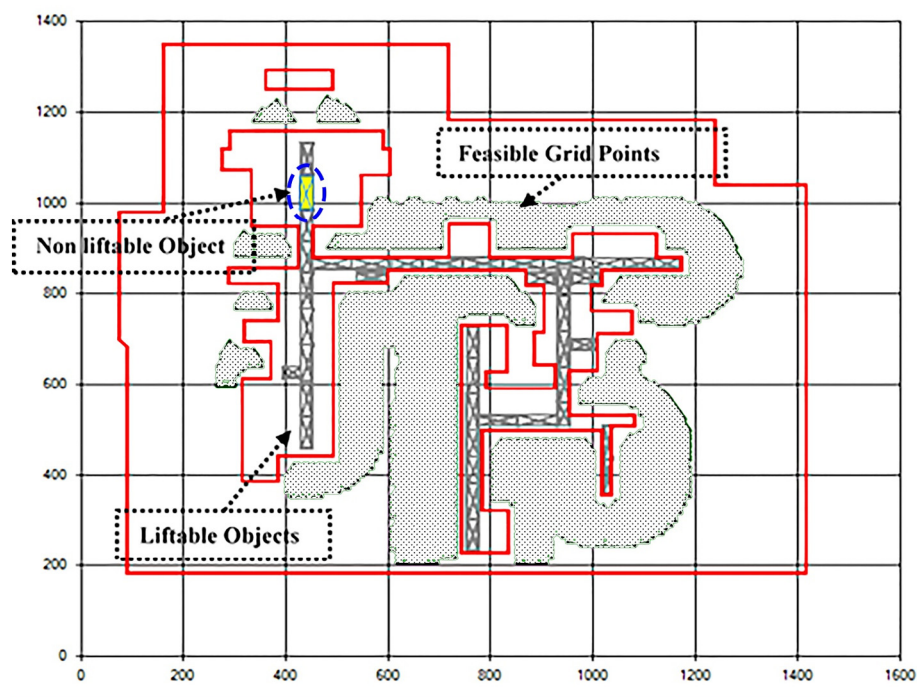


Fig. 18. Case 2 - modular plant.

Table 4

Cranes and configuration analysis for Case 2.

Crane	Configuration ID	Capacity (ton)	Boom type	Boom length (feet)	Superlift	Cost (1000\$ per month)	Total liftable objects
LR 1400/2	18867	400	S	207	x	150	19
LR 1400/2	18866	400	S	184	x	150	19
LR 1400/2	18444	400	S	184	✓	150	40
LR 1400/2	18224	400	L	184	x	150	21
CC 2800	20694	660	S	197	✓	200	41
CC 2800	20625	660	SH	197	x	200	27
CC 2800	20638	660	SH	236	x	200	25

Operations), are parts of the HeviLift software suite developed for heavy lift planning at PCL Industrial Management Inc.

Outputs of this application presented in this paper contain possible lifts, feasible crane positions and potential lift logic issues for each crane configuration. The best lifting options of crane and configurations are nominated for project. The generated lifting options are clustered by the type of lifts. These lifting options have been analyzed in terms of path planning, and optimized sequence, and lift study automation [25, 27, 30, 31]. The outlined methodology has been applied to several real industrial modular projects in Alberta, clearly reducing the time and cost of the heavy lifts. The results of this system can be utilized for developing automated lift studies and 4D Schedule for heavy lift operations in modular construction plants.

There are some limitations for this research. The shape of objects is simplified as 3D boxes and the crane locations (grid points) are discrete. Also, the developed system is not supporting tower cranes yet. Moreover, two-crane lifts are not supported directly yet. Future research will be focused on fully optimizing the locations by developing more accurate utility functions and considering other logics of the project.

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