# Multiple Heavy Lifts Optimization

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**Abstract:** Heavy lift planning has a major impact on construction sequencing, scheduling, budgeting, and safety. This paper addresses problems presented by planning for multiple lifts on a single jobsite. This is a common and particularly challenging planning situation because of the complex trade-offs involved. Conventional intuitive planning procedures lead to suboptimal plans or plans ranked with little quantitative or objective measure. This paper first introduces various factors affecting planning decisions for multiple heavy lifts and then presents an interactive computer-aided process to optimize initial crane configurations and placement locations for multiple lift problems. In the computer-aided planning process, the minimal number of equipment relocations is determined based on an integer programming model, and the precise equipment locations are optimized with an interactive procedure using objective performance functions. Objectives involve cost, safety, and area interference (area sterilization). These optimization procedures are implemented in the critical operations planning environment (COPE). A case study is used to demonstrate the optimization process. It is concluded, based on a case study and external reviews, that the process and algorithms presented help produce good plans for multiple heavy lifts on construction sites.



## INTRODUCTION

Heavy lift planning has a major impact on construction sequencing, scheduling, budgeting, and safety. A typical heavy lift operation involves lifting a prefabricated object of several hundred tons, such as pressure vessel, equipment skid, or electrical stator, and then transporting and precisely placing it in position. Detailed planning is required to determine appropriate equipment and rigging for the lift, to arrange and prepare prelift locations of the objects and the equipment, to verify the equipment lift capacity rating, and to ensure sufficient clearance during the lift.

Major companies have been using computer-aided tools to assist their heavy lift planning practices. Computer-aided drafting (CAD) and three-dimensional (3D) graphical simulation systems are most commonly used. These systems enable planners to interactively create planning scenarios and perform "virtual" lifts on computer screens for the planners to detect potential problems prior to the operations. They are most useful for later detailed planning stages. They are not equipped to handle sitewide planning for multiple lifts at the early stages where critical decisions are made concerning layout of the lifts, and where alternative cranes and rigging strongly influence layout decisions. This problem of planning for multiple heavy lifts can be described as finding the optimal matching of cranes, rigging, and locations based on the objectives of cost, safety, and area interferences.

When the 3D systems are used or conventional drafting is used for multiple lifts, decisions are mainly based on planners' experience and intuition, and it is very difficult to obtain optimal results with these systems. In practice, the fundamental and time-consuming problems of crane and object locating and lift path planning are performed manually. Trial and error is the basic approach for locating cranes and objects and finding lift paths. Automated 3D path planning algorithms are recognized as feasible tools. However, if the crane and lift objects are not located properly, these algorithms are not useful. The most important objectives of heavy lift planning, safety, and cost, mainly depend on location of cranes and lift objects (as well as crane selection) but not the lift path, which primarily affects operational efficiency. This paper thus focuses on planning methods and algorithms for the prelift arrangement of crane locations in the multiple lift situations.

A computer-aided, interactive planning method for optimizing multiple heavy lifts on a single jobsite is presented. This method should be adaptable and complimentary to current 3D systems to enhance their lift planning capabilities.

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## BACKGROUND

Previous research results on heavy lift planning at the University of Texas includes a crane simulation software framework (Dharwadkar et al. 1994), an industry-wide practice analysis (Hornaday 1993; Hamilton 1992), a comprehensive lift planning system implementation integrating database and CAD technology (Lin 1993; Wen 1993), and a path-finding scheme for large cranes and vessels being transported within the jobsite (Varghese 1992). The foregoing resulted in three computerized system platforms. For preliminary planning, a graphical database integrating a relational database management system (ORACLE) and a CAD platform (MicroStation) can be used for lift scenario modeling, crane selection, crane placement, and data management. For 3D visualization, the heavy lift planning system (HeLPS) employed the 3D graphics display shell WALKTHRU to animate crane motion on a construction jobsite utilizing CAD models of site, vessels, and cranes. For site accessibility analysis, a geographical information system (GIS) tool, ArcInfo, and an expert system package, VP Expert, were used to model construction sites and objects and to resolve the accessibility problem in two dimensions.

Major industrial contractors have also built computerized systems to assist in their heavy lift planning practices. For example, the computer-aided rigging (CAR) system developed by Brown & Root (*Computer* 1990) led to further development of a more comprehensive heavy lift planning system by the same contractor (Alexander 1992). CAR is primarily a computerized drafting board that combines basic rigging analysis and a CAD platform to automate the calculation and documentation of professional rigging plans. Bechtel has a system called automated lift planning system (ALPS), which is reported to be a comprehensive planning and visualization platform for developing and documenting heavy lift plans (Bennett and Ditlinger 1994). Major features of ALPS include crane selection, rigging analysis, and 3D lift simulation. More general simulation systems can also be used for planning heavy lifts, such as Jacobus technology's construction simu-



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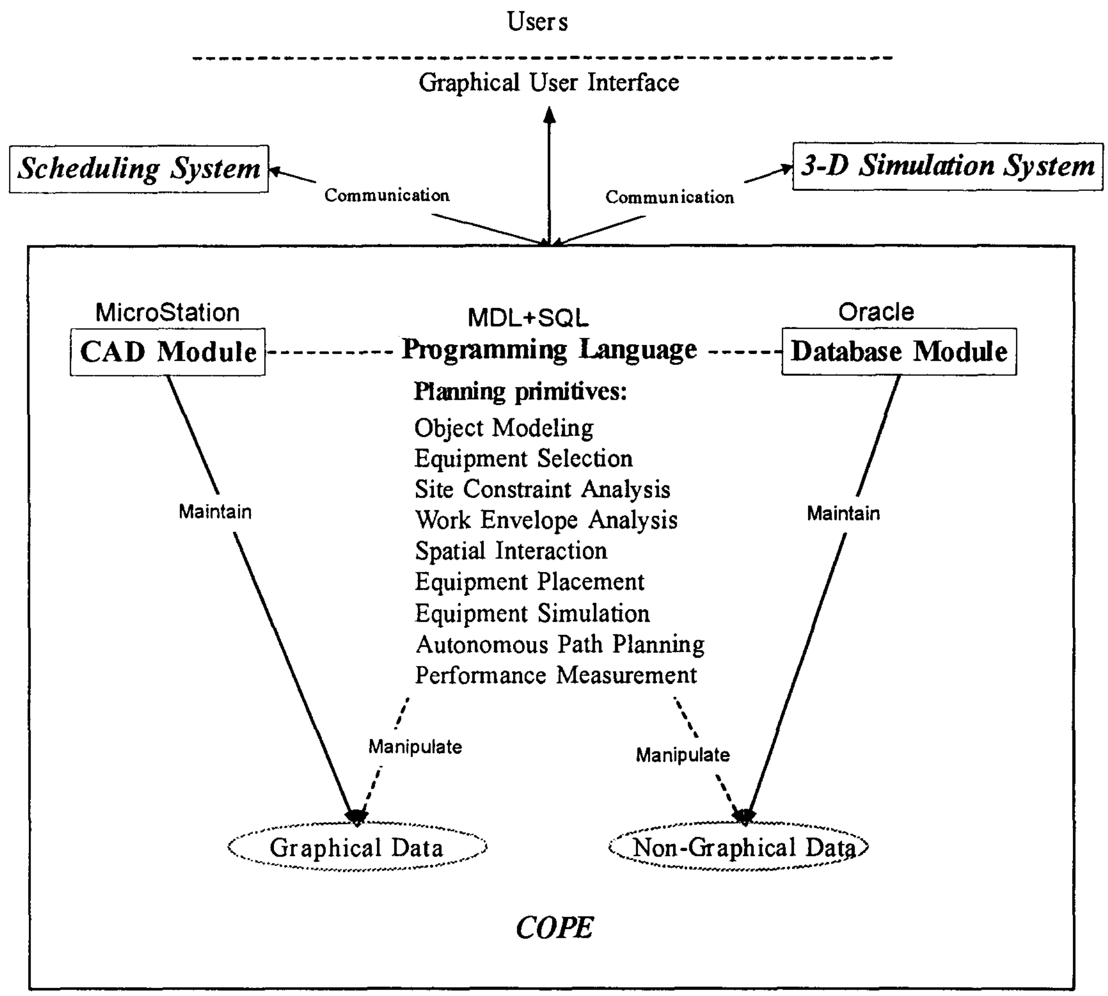


**FIG. 1. Planning Environment Architecture**

lation toolkit, which integrates 3D facility drawings and a construction schedule into a simulation environment (*TeleMetriX* 1993). The schedule is used to run the simulator, and construction managers can observe the construction process as the various components of a structure are assembled.

The planning methods and algorithms described in the paper have been implemented in an interactive planning environment—critical operations planning environment (COPE). COPE employs a CAD platform, MicroStation, a relational database management system, Oracle, and a set of computerized planning primitives to facilitate a visual planning process. Fig. 1 shows COPE's system architecture. COPE is an interactive environment which takes advantage of human reasoning ability to approach a solution, and the computer's storage and computational capabilities to handle time-consuming data searches and complicated calculations. Such a man-machine process can usually generate better solutions than a manual or fully automated process (Tommelein et al. 1991). Details of COPE implementation are described in Lin and Haas (1996).

## PLANNING FOR MULTIPLE HEAVY LIFTS

Multiple heavy lifts are often encountered in new plant construction sites where multiple vessels at different locations are typically erected. To complete the erection, main cranes usually have to be relocated several times, or multiple cranes are required. Relocation costs include time, labor, equipment, and construction of extra foundations. Equipment foundation costs are often a major cost item in heavy lifts (D. Gosch Sr. and D. Gosch Jr., personal communication, May 6, 1994). Most of the time, it is possible to select a feasible crane configuration, rigging design, and placement location for erecting more than one vessel. The major planning concern thus becomes one of how to minimize the number of crane relocations for each crane used, while simultaneously maximizing lift safety within the constraints of the equipment available. More than one crane could be used if justified by project schedule constraints or penalties.

Fig. 2 describes a general interactive process implemented in COPE for heavy lift planning which minimizes iteration and helps a planner move quickly to an optimal or near-optimal solution. Several alternative crane configurations are usually proposed. Preliminary feasibility of each alternative, such as crane availability, lift area accessibility, and lift capacity, have to be confirmed. Then, lift layout including number of crane relocations and exact crane locations is decided for each alternative, while crane assembly feasibility, uprighting (tailing) feasibility, lift path, and area interference are examined and detailed at each crane location. Finally, total lift cost including direct and indirect costs, lift safety, and scheduling impacts are assessed for each alternative so an optimum plan can be determined.

3D graphical simulation may then be used to verify the planning results. This paper focuses on computer-aided methods to minimize the number of crane relocations and optimize crane placement locations for each crane configuration in the lift layout phase. Since the number of crane relocations are part of the indirect lift cost (relocation, foundation, schedule delay, etc.) and the crane locations can impact the lift safety, minimization of crane relocations and optimization of crane placement can contribute to the overall optimization of each

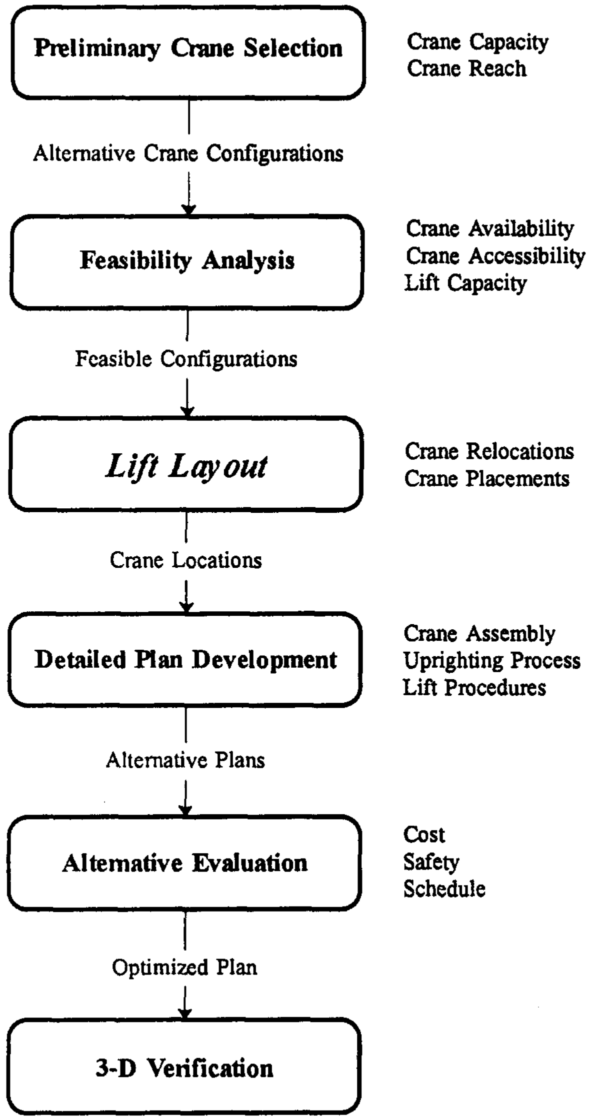


**FIG. 2. Heavy Lift Planning Process**

lift alternative and thus help determine the best lift plan for execution. Fig. 3 describes the multiple heavy lifts optimization process.

## Constrained Work Envelope and Overlapping Concepts

To consider crane placement, the crane area which the crane can reach carrying a specific heavy object should first be determined. This area, called constrained work envelope here, is defined as the crane's workable envelope when lifting a heavy vessel, which is determined based on considerations of the crane's structural/overturning capacity and various 3D interference conditions between the crane, the vessel, the rigging, and the site. Fig. 4 illustrates the maximum and minimum radii of a constrained work envelope because of spatial interferences. A constrained work envelope around a placed crane specifies an area that the crane's boom end (or the vessel being lifted) can reach during the lift without encountering any interference or exceeding the crane's capacity. When the constrained work envelope is centered at the vessel place location, it describes an area where the crane can be placed in order to reach the place location. Detailed derivation of a crane's constrained work envelope is described in Haas and Lin (1995).

An overlapping work envelopes concept is used for identifying, enumerating, and resolving multiple lift problems (Fig. 5). When a crane's work envelope is described centered at two different vessel place locations and the two described envelopes are intersected, the crane can reach both vessel place locations if it is placed within the intersected area. Such an area is referred to as "the sweet spot" among lift planners. Thus, one of the objectives of planning multiple lifts is to maximize the possibility of overlapping.

## Planning Considerations

Planning multiple lifts is a complicated decision-making process. Planners have to consider broad strategies, including (1) using larger cranes with greater operating radii to minimize the number of relocations so that the foundation, moving, and setup cost can be reduced; (2) using smaller cranes which require more relocation and more foundations but have lower leasing cost; or (3) using more cranes to reduce schedule duration. The trade-off between crane leasing cost, foundation cost (and/or cut and fill cost), safety, and schedule impact controls the decision. Thus, when a crane configuration is being evaluated, planners have to figure out how many relocations would be necessary with this crane selection in order to calculate the foundation cost (and/or cut and fill cost). Furthermore, when determining the number of relocations, planners have to consider which vessels are to be lifted at each crane location. A hypothetical multiple lift situation illustrates the complexity (Fig. 6).

Another major problem for multiple lift planning is alternative evaluation. Even when the minimum number of locations can be determined, there is often more than one alternative for laying out feasible crane areas with the minimum number of relocations. For example, in the lift scenario in Fig. 7, it can be determined that for a given crane configuration at least two crane locations will be required for reaching all five vessel placement locations. However, there are four possible layouts for two crane locations. It is a challenge to determine which alternative is most favorable. Intuition has limitations. Thus, there is a need for more efficient methods or tools to help planners determine the minimum number of crane locations and to evaluate alternative layouts given vessel placement locations to be reached and respective work envelopes. The methods developed for these purposes are described in the following sections.

## Minimizing Relocation

An algorithm based on linear programming and spatial operations is developed for computing the minimum number of crane locations and displaying all possible alternative layouts for the minimum number of locations. This algorithm analyzes the feasible crane areas for reaching each vessel location, area obstructions, and possible overlapping between neighboring envelopes and then determines the minimum number of crane relocations required to complete the lift. Based on these results, planners compare each alternative by examining site access, lift area access, crane assembly, lift path clearance, site obstacles, and schedule impact, while considering the tradeoffs discussed earlier. Feasible layouts must still be optimized. An interactive approach, using the dynamic display of performance measures as the crane is moved within its feasible zone, is followed.

The example in Fig. 7 is used to illustrate the algorithm developed for computing relocations. In this example, six vessels are being lifted. All the respective envelopes are determined and placed at the vessel place locations as shown in Fig. 8(a). Fig. 8(b) is a network representing the relationship between the envelopes. Each vessel place location is represented as a node in the network. A link between two nodes (vessel place locations) means that the respective two enve-



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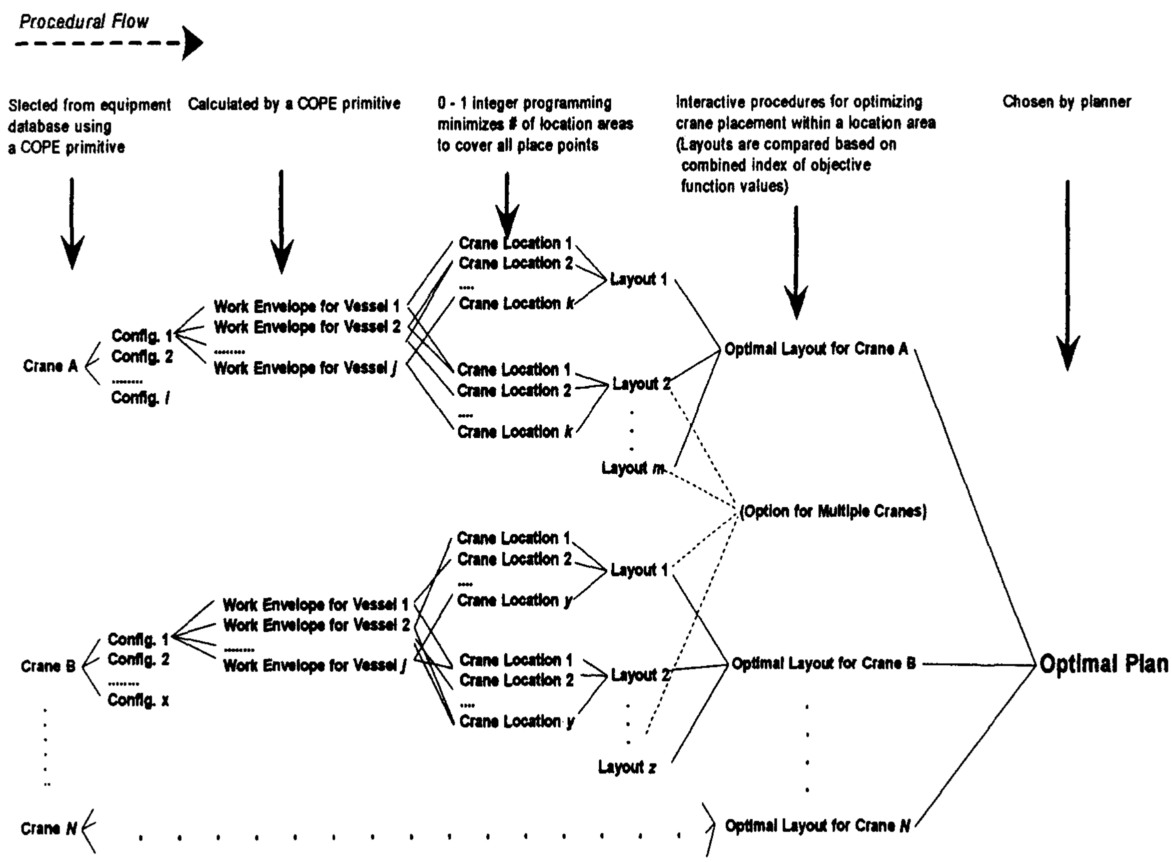


**FIG. 3. Multiple Heavy Lifts Optimization**

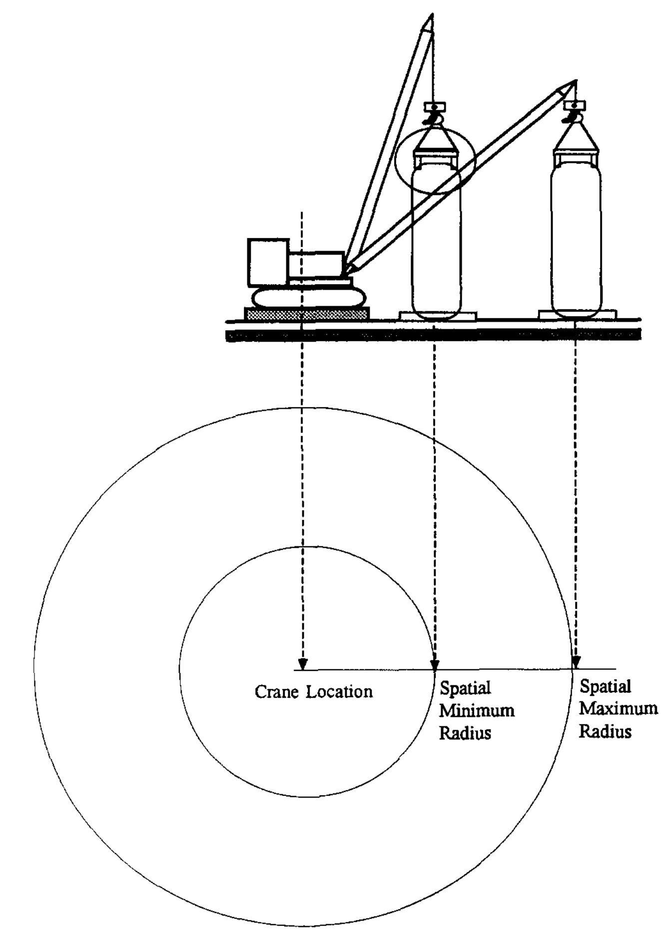


**FIG. 4. Constrained Work Envelope Based on Spatial Interference Conditions**

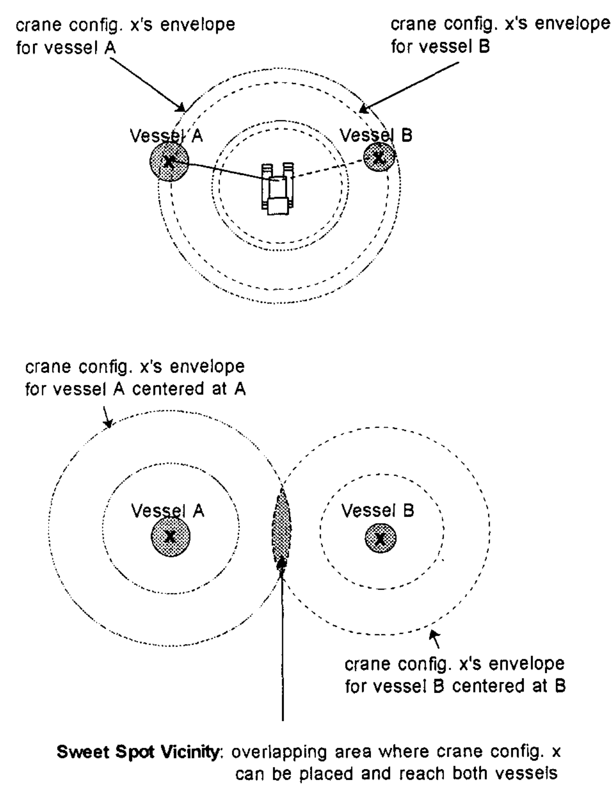


**FIG. 5. Work Envelope Overlapping Concept**

lopes overlap. That is, it is possible to place the crane in the overlapping area to reach both locations. For example, there is a link between vessel 1 and vessel 2, so it is possible to lift them with one single crane placement if the crane is placed within the overlapping area between envelope 1 and envelope



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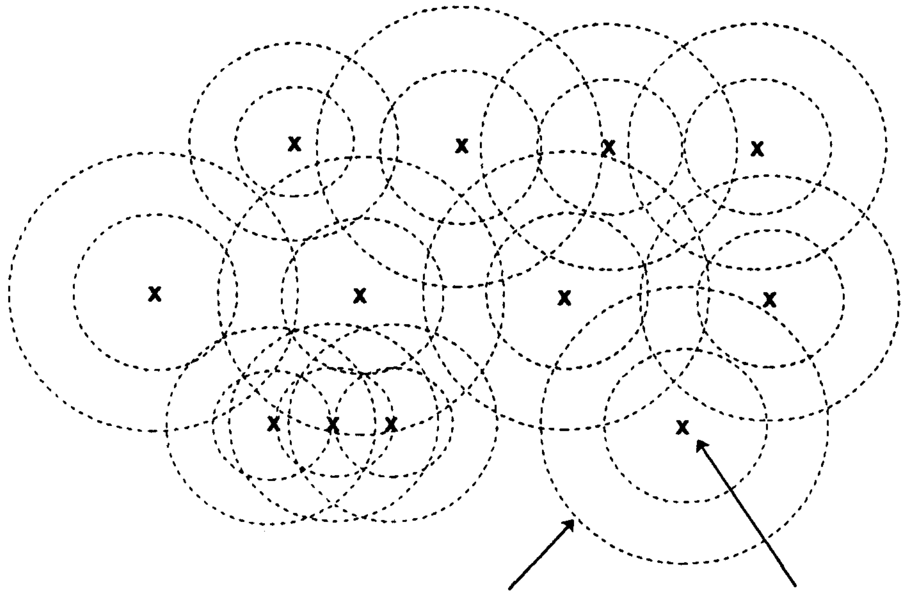
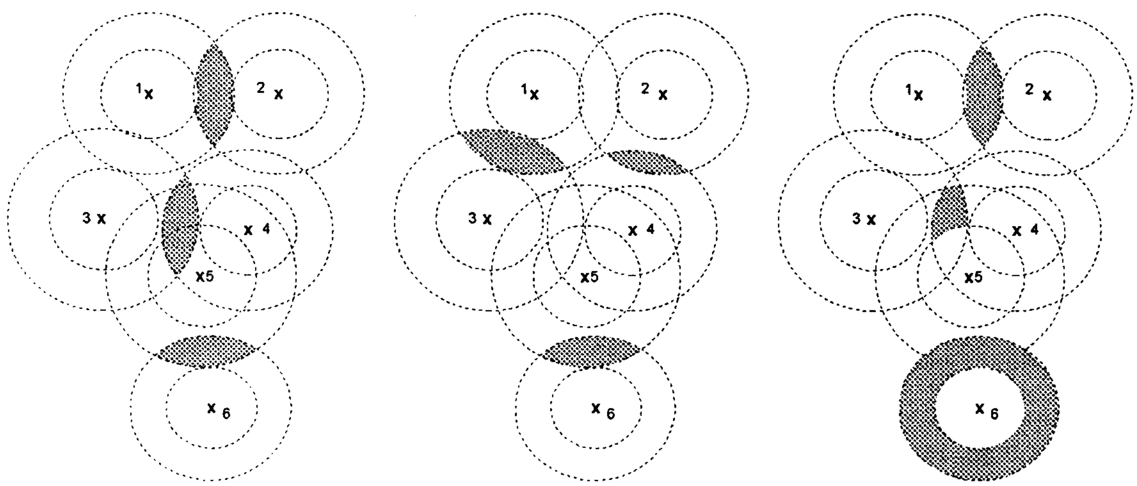



FIG. 6. Complicated Multiple Lift Scenario




**(a)** *Alternative I:*
Overlap(1, 2)
Overlap(3, 4)
Overlap(5, 6)

**(b)** *Alternative I:*
Overlap(1, 3)
Overlap(2, 4)
Overlap(5, 6)

**(c)** *Alternative I:*
Overlap(1, 2)
Overlap(3, 4, 5)
Envelope(6)

FIG. 7. Alternative Layouts for Two Placements

2. The black dot within vessel 3, vessel 4, and vessel 5 denotes that an overlapping area exists between these three respective envelopes.

The algorithm has two parts: (1) derive and store all the feasible crane (individual and overlapping) areas; and (2) calculate the minimum number of relocations and find all the alternative crane layouts. The first part of the algorithm, to derive and store all the feasible crane locations, is accomplished by using an iteration loop to test whether the envelopes intersect. Before an envelope is included in the iteration loop, any obstructive area within the envelope is subtracted from the envelope. This procedure ensures the areas being processed are obstacle free. The loop will come to an end when no overlapping area is generated. Graphical Boolean functions, intersection and difference, are employed to make this implementation possible. Fourteen different crane areas are possible in the illustrated example. The second part is to minimize the number of the placements from the information derived from the first part, and find all the alternatives. For this purpose, the planning problem is modeled as a binary integer programming problem. For the example in Fig. 8, the model is built by the software as follows:

Objective function

$$\text{minimize } Z = X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_{12} + X_{13} + X_{24} + X_{34} + X_{35} + X_{45} + X_{56} + X_{345} \quad (1)$$

Subject to

$$\text{Constraint: } 111{,}111 - X_1 - 10X_2 - 100X_3 - 1{,}000X_4 - 10{,}000X_5 - 100{,}000X_6 - 11X_{12} - 101X_{13} - 1{,}010X_{24} - 1{,}100X_{34} - 10{,}100X_{35} - 11{,}000X_{45} - 110{,}000X_{56} - 11{,}100X_{345} = 0$$



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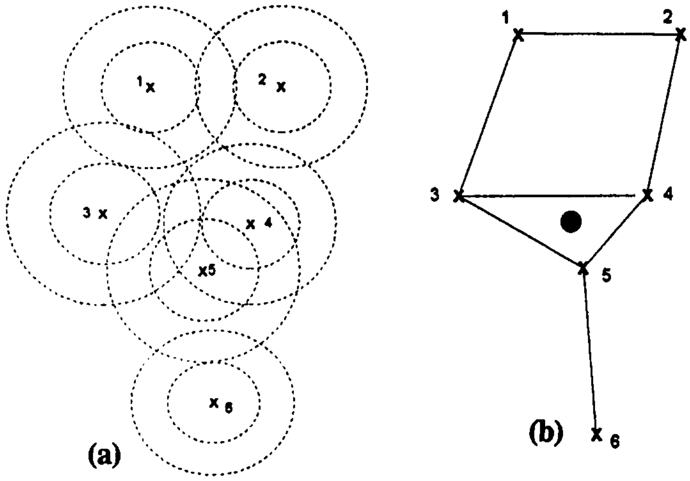



**FIG. 8. Multiple Lift Example**

All variables are equal to 0 or 1, where $X_1$ = whether a crane is placed within envelope 1; $X_{12}$ = whether a crane is placed within the overlapping area between envelope 1 and 2; and $X_{345}$ = whether a crane is placed within the overlapping area between envelope 3, 4, and 5, and so on.

This model can be easily solved using a numerical approach which examines all the possible solutions. This algorithm thus obtains the minimum number of crane relocations and all the alternatives. Planners then have to further examine crane accessibility, crane assembly, lift path clearance, and schedule impact to test the feasibility of each alternative. This is a reasonable approach for multiple lifts.

## Optimizing Placement

The major safety concern in heavy lifts is the capacity percentage used during operations. For multiple lifts, the following objective function for safety performance is used to evaluate the safety performance for each crane placement:

$$\min Z = \sum_{i=1}^{n} C_i + \rho_x(C_i - X) \text{ for } C_i \geq X \qquad (2)$$

where the first term is the total capacity used for the lifts, and the second term is the penalty for critical lifts; $C_i$ = maximum percentage of crane capacity used for lifting vessel $i$; $X$ = maximum percent of capacity desired to be used (many owners and contractors will require this to be set at 80% of the crane's chart capacity—it represents a desire to lower risk associated with a lift); and $\rho_x$ = penalty parameter for critical lifts exceeding $X$% of crane capacity.

The optimum crane placement location is the one that results in the minimum safety measure. The capacity percentage used for lifting a vessel is relevant to the distance between the vessel and the crane placement location and is calculated from the database using the following pseudocode:

(operating_radius)$_i$=DISTANCE[ (vessel_place_location)$_i$, (*crane_place_location*) ]; max_capacity[ (operating_radius)$_i$=SELECT CAPACITY FROM CRANE_CAPACITY WHERE OPERATING_RADIUS=(operating_radius)$_i$;/*SQL statement to query crane database */$C_i$ = (vessel_weight)$_i$ / max_capacity[ (operating_radius)$_i$]

The crane place location (*crane_place_location*) is the only variable in the calculation. It is constrained by the overlapping operations and is subject to obstruction. Instead of solving the optimization model using numerical or other methods, an interactive procedure is used to allow planners to determine the optimum placement location in each alternative layout.

In each alternative layout, the planner identifies one feasible crane placement area and then the locations to be reached are displayed in the "Monitoring" dialog box (Fig. 9) in the COPE environment. Next, the planner is prompted to identify the desired crane placement location within this feasible area. As the planner moves the cursor, the required radii, reached capacities, and an overall safety performance measure is shown in the dialog box. The optimum crane placement location within this feasible area would be the one with the minimum safety performance measure. The optimum location should be easily located as the planner slides the cursor around the area. After the crane placement in each alternative is optimized, the safety performance measure is recorded for com-

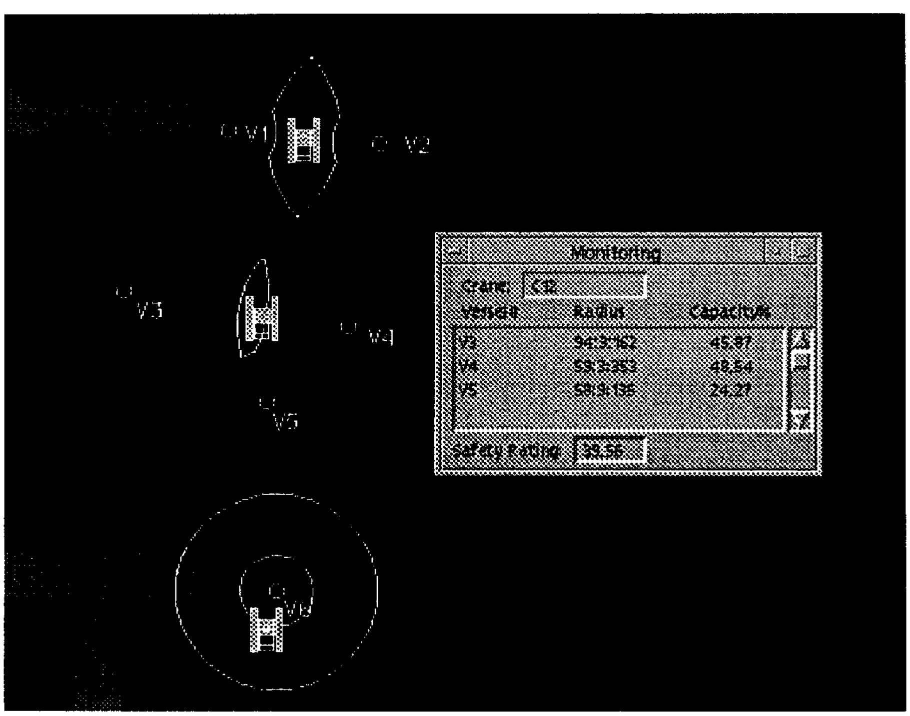
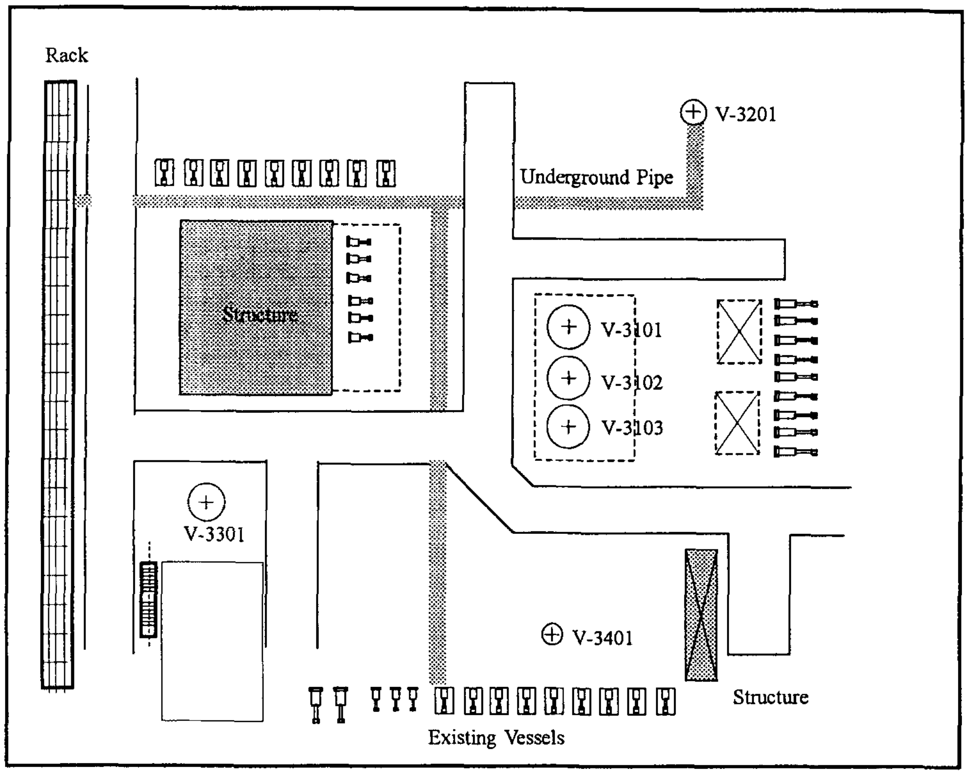



**FIG. 9. Interactive Placement Optimization Procedure**




(a)

| Vessel | Dimensions | Weight | Vessel | Dimensions | Weight |
|---|---|---|---|---|---|
| V-3101<br>V-3102<br>V-3103 | 36.60 m<br>6.10 m | 108.96 T | V-3201 | 21.35 m<br>3.66 m | 68.10 T |
| V-3301 | 15.25 m<br>6.10 m | 59.02 T | V-3401 | 45.75 m<br>3.05 m | 90.80 T |

(b)

**FIG. 10. Multiple Lifts in Amoco Texas City Project**

parison of alternatives. This approach allows the planner to control the process and to make trade-offs prompted by special project circumstances.

## Area Interference and Schedule Impact Analysis

During the preparation and operation of heavy lifts, a large portion of the site area is likely to be blocked because of crane transportation and assembly, vessel transportation, and mat construction. This kind of area sterilization often interferes with the progress of neighboring activities and can cause project delays. Such interference impact is another important factor influencing the decisions on crane location layout. An accurate estimate of interference impacts requires consultation with the persons in charge of these activities. Work area coordination prior to the operations can help relieve the interference in order to minimize the impact. One way to avoid such interference in the planning phase is for planners to specify key areas required for neighboring activities as obstructive areas and then try to set up cranes away from these areas. When it is difficult to avoid interference, an area interference analysis model is proposed here to help planners estimate this interference impact as crane locations are being determined.

Interference impacts can be evaluated using the total estimated dollar impact on neighboring activities directly caused by the lift being planned.

$$I = \sum_{i=1}^{n} u_i \times d_i \quad (3)$$

where $I$ = interference effect (in \$); $n$ = number of activities affected; $u_i$ = estimated daily dollar impact on activity $i$ directly caused by the critical operation being planned (\$/d); and $d_i$ = duration of interference on activity $i$ (days).

## CASE STUDY: MULTIPLE LIFT ALTERNATIVES EVALUATION (MODELED AFTER AMOCO TEXAS CITY PROJECT)

Heavy lifts in the Amoco Texas City plant construction project involved installation of six large vessels with different weights and sizes. Fig. 10 lists the vessel configurations and



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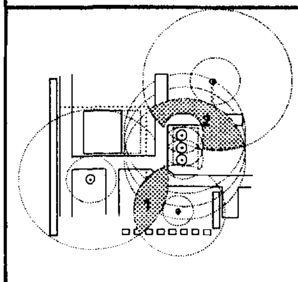
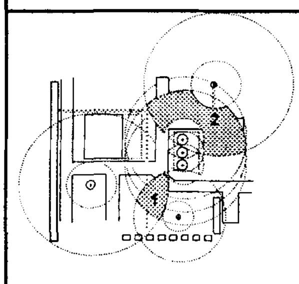
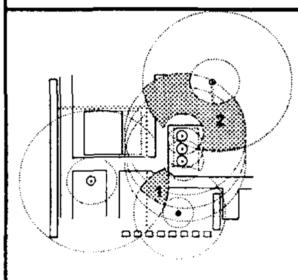
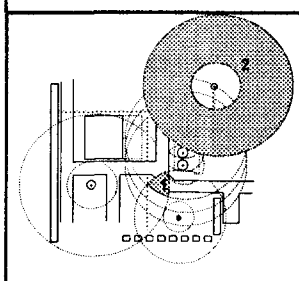
| | Crane Location Layout | Vessel | Operating Radius and Capacity % | Safety Rating (Total %) | Interference Cost ($u_i * d_i$) |
|---|---|---|---|---|---|
| (a) |  | **Location 1:**<br>V-3401,<br>V-3301<br><br>**Location 2:**<br>V-3101,<br>V-3102,<br>V-3103,<br>V-3201 | <br>40.57 m (62%)<br>26.54 m (62%)<br><br><br>17.39 m (63%)<br>19.52 m (67%)<br>21.96 m (73%)<br>25.01 m (73%) | 400 | **Location 1:**<br>0.6K * 30 = 18K<br><br>**Location 2:**<br>0.9K * 40 = 36K<br>----------------------<br>**Total: 54K** |
| (b) |  | **Location 1:**<br>V-3401,<br>V-3301,<br>V-3101<br><br>**Location 2:**<br>V-3102,<br>V-3103,<br>V-3201 | <br>47.89 m (77%)<br>25.32 m (73%)<br>17.39 m (73%)<br><br><br>18.30 m (63%)<br>17.69 m (70%)<br>23.79 m (70%) | 426 | **Location 1:**<br>0.6K * 33 = 19.8K<br><br>**Location 2:**<br>0.9K * 35 = 31.5K<br>----------------------<br>**Total: 51.3K** |
| (c) |  | **Location 1:**<br>V-3401,<br>V-3301,<br>V-3101,<br>V-3102<br><br>**Location 2:**<br>V-3103,<br>V-3201 | <br>48.90 m (73%)<br>35.38 m (70%)<br>18.91 m (75%)<br>17.39 m (73%)<br><br><br>21.96 m (63%)<br>31.11 m (63%) | 417 | **Location 1:**<br>0.6K * 40 = 24K<br><br>**Location 2:**<br>0.9K. * 30 = 27K<br>----------------------<br>**Total: 51K** |
| (d) |  | **Location 1:**<br>V-3401,<br>V-3301,<br>V-3101,<br>V-3102,<br>V-3103<br><br>**Location 2:**<br>V-3201 | <br>49.41 m (77%)<br>36.91 m (73%)<br>17.39 m (73%)<br>19.52 m (67%)<br>21.96 m (73%)<br><br><br>12.2 m (32%) | 395 | **Location 1:**<br>0.6K * 45 = 27K<br><br>**Location 2:**<br>0 K* 40 = 0K<br>----------------------<br>**Total: 27K** |

**FIG. 11. Alternative Evaluation—Customized Ringer**

shows the site layout. Two initial equipment options are proposed for the installation: a large customized ringer with a 73.20-m reach and a 363.2-t capacity, and a smaller lift crane with a 36.6-m reach and a 139.10-t capacity.

The ringer is first evaluated. Based on the overlapping relationship of the vessel place locations, the linear programming model was formed and solved. Two is the minimum number of crane locations for the ringer to reach all six vessel locations. Four alternative layouts are possible. After the placement optimization procedure, each alternative is assessed a safety rating. Fig. 11 lists the alternatives and safety rating results. From a safety point of view, the fourth alternative [Fig. 11(d)] appears to have a slight edge over the others.

In this case, area interference becomes an important factor when deciding the final layout. During the crane setup period, underground piping work is also undergoing construction around the center group of vessels. If the crane is set up near the underground piping area, piping productivity would be lost because of the obstruction. When placing the crane for lifting vessels in the lower left side (V-3401, V-3301, V-3101, V-3102, V-3103), interference is bound to occur since the area is tight. However, in Fig. 11(d), the crane placement for vessel

**TABLE 1. Lift Cost—Customized Ringer**

| Category<br>(1) | Cost values<br>($)<br>(2) |
|---|---|
| Equipment cost | |
| Rent | 100 K |
| Fuel/labors | 6 K |
| Transportation cost | 50 K |
| Setup and assembly cost | 40 K |
| Insurance | 1.2 K |
| Foundation | 20 K |
| Others | 15 K |
| Direct total | 232.2 K |
| Interference total | 27 K |
| [Grand total] | 259.2 K |

Note: The cost is estimated based on a three-month lift period. These numbers are typical but may vary from areas.

V-3201 can be located in the upper area, which is away from the piping area so that interference could be avoided at this placement. The interference cost for each alternative is also estimated in Table 1. Daily penalty costs used in the interfer-



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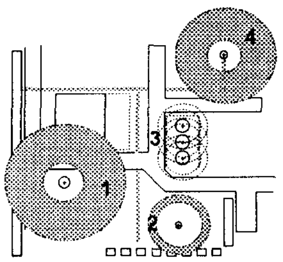
| Crane Location Layout | Vessel | Operating Radius and Capacity % | Safety Rating (Total %) | Interference Cost ($u_i * d_i$) |
|---|---|---|---|---|
|  | **Location 1:**<br>V-3301 | <br>15.01 m (32%) | | **Location 1:**<br>0.6K * 20 = 12K |
| | **Location 2:**<br>V-3401, | <br>25.26 m (63%) | | **Location 2:**<br>0.6K * 20 = 12K |
| | **Location 3:**<br>V-3101,<br>V-3102,<br>V-3103 | <br>21.96 m (77%)<br>19.52 m (67%)<br>21.96 m (77%) | 349 | **Location 3:**<br>0.6K * 30 = 18K |
| | **Location 4:**<br>V-3201, | <br>21.96 m (33%) | | **Location 4:**<br>0K * 20 = 0 |
| | | | | **Total: 42K** |

**FIG. 12. Performance Evaluation—Smaller Lift Crane**

**TABLE 2. Lift Cost Estimate—Smaller Lift Crane**

| Category (1) | Cost values ($) (2) |
|---|---|
| Equipment cost | |
| Rent | 70 K |
| Fuel/labors | 5 K |
| Transportation cost | 40 K |
| Setup and assembly cost | 75 K |
| Insurance | 1 K |
| Foundation | 35 K |
| Others | 30 K |
| Direct total | 261 K |
| Interference total | 42 K |
| [Grand total] | 303 K |

Note: The cost is estimated based on a three-month lift period. These numbers are typical but may vary in areas.

ence calculations for this example are hypothetical but typical of those observed for a project of this scope. On combining the safety and interference analysis, the initial selection is the fourth alternative [Fig. 11(d)]. The direct cost for using this ringer is estimated in Table 1.

Another equipment option is to use a smaller lift crane while reducing the chance of overlapping (Fig. 12). Four placements are required after the location analysis. Area interference cost is estimated at a total of $42 K. At locations 1, 2, and 4, the crane has only one vessel to erect, so the crane can be placed at the minimum radius to enhance safety. This is reflected in the overall safety rating which is at 349. However, because of more relocations required, the total lift cost is increased. Table 2 is the lift cost estimate and the total lift cost is estimated at $303 K, compared to the customized ringer option's $259.2 K. Since both equipment options are feasible for the lift, the planners' initial decision may be the smaller lift crane option. However, with further analysis, the customized ringer option turns out to be more economic due to the ringer's long reach to multiple vessels to reduce relocation.

## CONCLUSIONS

Heavy lift planning has been recognized as an important aspect for industrial construction. Current computer-aided heavy lift planning systems focus on computer-aided drafting and 3D simulation capabilities for planning heavy lifts with one single load. When more than one vessel is involved in a lift (which is called a multiple lift in this paper), the planning problem becomes more complicated and can have great impact on a project. This paper discusses the considerations for planning multiple lifts, models the planning problem, and then provides a feasible approach to solve this problem. The algorithms developed in this paper can be implemented within current heavy lift planning systems to extend their capability to plan for multiple heavy lifts.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