Computer-Aided Planning for Heavy Lifts

By W. C. Hornaday[1] and C. T. Haas,[2] Associate Members, ASCE,
J. T. O'Connor,[3] Member, ASCE, and J. Wen[4]

Abstract: This article presents research into automating some lift planning practices common to industrial construction contractors and owners. A detailed investigation of heavy-lift planning methods was conducted through a series of interviews and lift studies with expert lift planners. This investigation documented a wide variety of manual and computer-aided lift planning methods to perform similar types of planning tasks. Based on the information collected from these interviews and lift studies, a structured systems model was developed of the typical heavy-lift planning process. This structured model is used as an architecture for the development of computer software to aid key planning tasks. An examination of major planning tasks indicates that significant reductions in direct planning costs and indirect construction heavy-lift costs are possible through the implementation of computer-aided planning procedures. Computer-aided procedures would also improve the overall quality of lift planning practices through the automation of tasks which are difficult to perform and are critical to heavy-lift planning accuracy.

Introduction

In industrial construction, it is becoming more common to reduce plant equipment fabrication costs by fabricating larger portions of equipment at specialized off-site locations (Fitzsimmons 1991). This equipment includes pressure vessels, reactor columns, and equipment skids loaded with heavy steel walls or framing systems, internal piping, and trays, which collectively can weigh up to 900 t (1,000 tons). The lifting costs to erect these large, heavy objects in place grow excessively as the lifting capacity of the crane increases. Heavy lifts using standard crane configurations can have total planning and execution costs ranging from \$50,000 to \$300,000. Five percent to 10% of the lift cost is consumed by planning activities while the majority of the total cost is attributed to the lifting equipment itself (Hornaday 1991).

An estimated \$25 million–\$50 million is spent annually by U.S. industrial owners, designers, and contractors on the planning of \$500 million worth of heavy crane lifts (Hornaday 1991). The cost of the lift is dependent on the lift planner's experience and skill in selecting equipment and preparing lift plans that are optimum for given sets of conditions. The number of lift specialists with the experience required to effectively plan critical lifts is dwindling, while the number of heavy lifts being performed each year is increasing (C. W. McCoy, vice president, Dow Chemical; heavy-lift survey interview; July 11, 1991). The activities of the lift planner are highly specialized and well rewarded by contractors.

The heavy reliance of industrial constructors on a small pool of highly specialized planners to plan a growing number of lifts of increasing mag-

[1]Appl. Const. Res., 902 Meriden, Bldg. B, Austin, TX 78703; formerly, Res. Asst., Univ. of Texas, Dept. of Civ. Engrg., 5.2 ECJ Hall, Austin, TX 78712-1076.
[2]Asst. Prof., Dept. of Civ. Engrg., 5.2 ECJ Hall, Univ. of Texas, Austin, TX.
[3]Assoc. Prof., Dept. of Civ. Engrg., 5.2 ECJ Hall, Univ. of Texas, Austin, TX.
[4]Res. Asst., Dept. of Civ. Engrg., 5.2 ECJ Hall, Univ. of Texas, Austin, TX.
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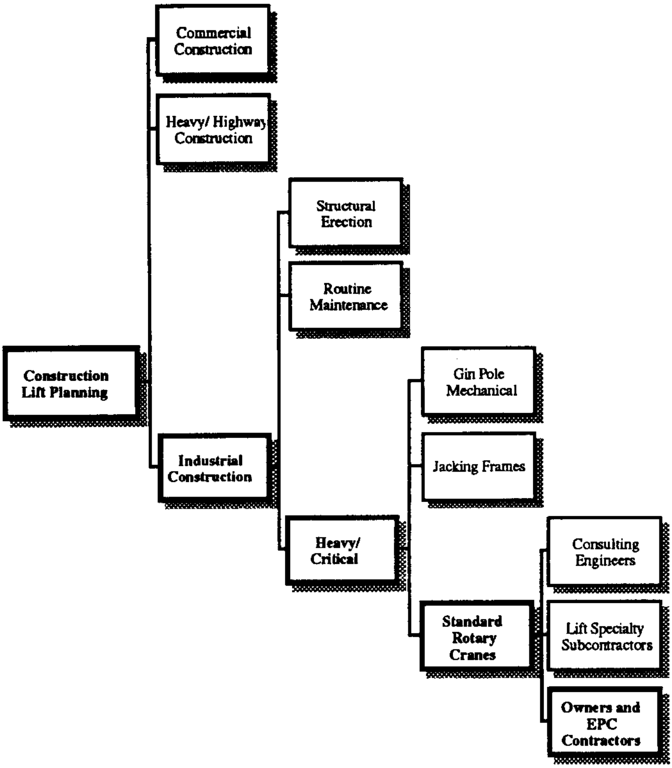

FIG. 1. Scope of Construction Lift Planning Studied

nitude is a costly and risky practice. Optimum use of available crane equipment might not always take place with limited planning resources. Construction contractors are also increasing their risk by relying on a few key planners for the success of lifts in which accidents can cost millions of dollars. The research discussed here was motivated by the need to both improve the effectiveness and lower the total cost of heavy-lift planning. It is expected that improved lift planning will also lower the risks and costs associated with the lift itself.

The scope of this paper is limited to the planning of heavy or critical lifts performed on industrial construction projects using standard crane configurations. Industry lift planners define a heavy lift as a lift of over 22–40 t (25–50 tons), depending on the company. But as lifting equipment has improved, the heavy-lift cutoff has increased. As a result many lift planners identify lifts as critical, yet make no distinction of the lift's nominal weight or heaviness. A critical lift is defined by lift planners as either a lift over an area of concern such as an operating process area, or a lift that exceeds a certain percentage of a crane's capacity. This critical definition allows planners to devote their effort to the least reliable types of lifts. This paper encompasses both types of definitions of lifts and defines the lifts studied merely as lifts requiring detailed planning. The detailed planned lift, as a matter of convention, will be referred to as a *heavy lift* throughout this

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document. This type of lift makes up less than 30% of industrial crane lifts, but requires the majority of planning effort from lift specialists.

Some of the very heavy lifts over 400 t (500 tons) use specially designed lifting or jacking systems. The majority of heavy lifts, though, are performed using standard crane configurations. Primarily this study is focused on the use of single cranes that have the capacity to lift the object alone but often use tailing cranes or "J-rails" for uprighting objects (Shapiro et al. 1991). Lifts requiring the lifting capacities of multiple cranes were not examined in detail in this study, but many of the basic planning functions identified for single main crane lifts are applicable to multiple crane or multiple lift object planning. Fig. 1 illustrates the segment of the lift planning industry discussed.

This paper presents an overview of current industry practices, followed by a formalized model of the heavy-lift planning process. The potential impact of computer-aided lift planning methods is illustrated through an examination of a common planning task. Using the planning model as an architecture, a complete computer-aided planning system is proposed. Progress to date on the implementation of this system is described as well as current research and development activities.

BACKGROUND

Methods of heavy-lift planning and execution in industry have many common elements that are independent of the project or organization involved. But as the heavy-lift industry is introduced to new technology, these planning methods are undergoing changes. The first major change has been the result of the steady introduction of cranes with ever-larger lifting capacities. A heavy lift around 1960 was defined as up to 22 t (25 tons), while today rotary cranes are performing lifts 10 times that magnitude or more (Donnie Gosch Sr., heavy-lift planner, Brown & Root, Inc., Houston, Tex.; heavy-lift survey interviews; April 10, 1991, June 11, 1991). A second major change is also evolving. New computing technologies, including computer-aided design (CAD), geographic information systems (GIS), and artificial intelligence (AI) tools are beginning to initiate significant changes in the way planning is done (Varghese 1992).

Industrial heavy-lift planning is performed in three basic stages:

1. Preliminary planning begins 12–24 months before the actual lift date. Its purpose is to examine feasibility and establish the scope of the lift plan. The planner uses preliminary vessel dimensions to make approximate estimates and consults preliminary site plans to establish lift requirements. The results include an estimate of lift cost, an analysis of preliminary feasibility, an outline for the detailed lift plan, and sometimes a short list of potentially feasible cranes.
2. Detailed planning begins when the vessel information and the construction schedule are accurate enough to commit to a schedule for a lift date and equipment rentals. Based on a fixed set of site conditions and vessel data, the planner determines, for example, what specific crane configurations can perform the lift and where the equipment should be located. The planner must also design the vessel rigging and the crane mat.
3. Final planning involves evaluation of the detailed plans and final selection. Detailed lift plans are usually developed for at least two models of cranes to allow for the competitive procurement of lift equipment (Donnie

Gosch Jr., heavy-lift planner, Brown & Root, Inc., Houston, Tex.; heavy-lift survey interviews; April 10, 1991, June 11, 1991). After a level of acceptable risk has been determined, the selection of the lift plan is based primarily on cost. The selection and evaluation phase is often a cooperative effort between the construction contractor and the facility owner because of the risk and high public profile of the heavy-lift execution.

Delays in the execution of detailed lift plans can have a number of causes. The vessel delivery date, for instance, cannot be accurately determined to within less than one week at almost any time during its fabrication. Many planners will not commit to a detailed lift plan until the vessel has actually entered the site due to the numerous fabrication and transportation problems that can delay a scheduled lift (Frankie Spates, lift planner, Dow Chemical, Freeport, Tex.; heavy-lift survey interview; July 11, 1991). The detailed planning period is therefore often very constrained. A structured analysis of heavy-lift planning proves useful for understanding how complex and conflicting planning factors are dealt with in this constrained time frame.

STRUCTURED ANALYSIS OF HEAVY-LIFT PLANNING

Industrial heavy-lift planning can be modeled as a function with inputs, outputs, controls, mechanisms, and an internal process ("IDEF1" 1981). Heavy-lift planning takes as basic inputs the site, characteristics of the lift object (vessel), and crane data. From this information a number of plan outputs are produced (Fig. 2). The process is controlled by the lift planner based on structural, spatial, and schedule constraints. Lift plan outputs increase in detail as the lift plan evolves from preliminary planning, to detailed planning, to final evaluation and selection. Cost and reliability are of constant concern throughout this process. Those employed to execute

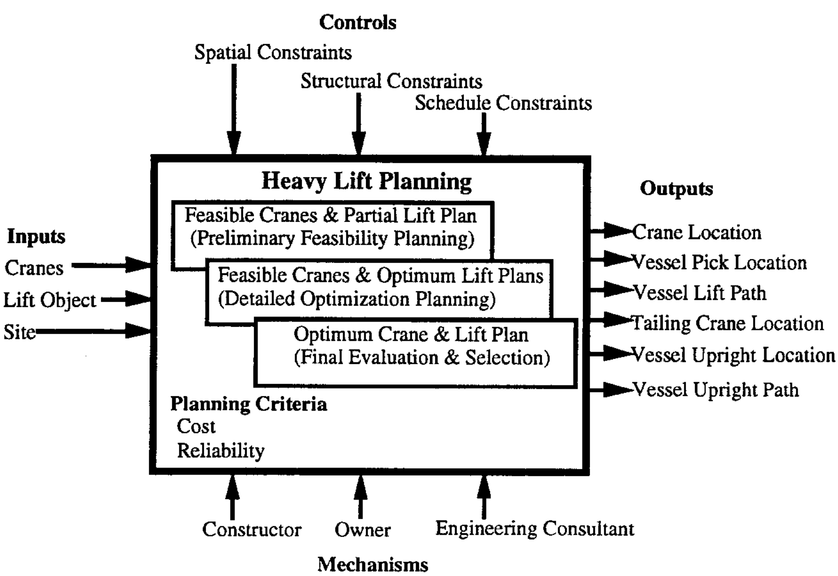

FIG. 2. Heavy-Lift Planning Functional Model

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the planning functions include the construction lift planner, owner representative, and engineering consultants.

Lift Plan Inputs

The inputs to the lift plan correspond to the physical breakdown of the lift: the object, site, and crane. The characteristics of the cranes are organized in substantial manuals of information on each piece of lifting equipment. Architectural and engineering drawings typically represent the site data. The lift object or vessel is described by manufacturer shop drawings.

The lift object (vessel) can be described by three basic categories of characteristics. The dimensions and shape of the vessel represent the information used to evaluate spatial constraints (Dharwadkar 1991). The location and magnitude of the weight of the vessel determine the lifting capacity required to perform the heavy lift. The fabrication and delivery schedule of the vessel establishes the work window in which the lift will be performed.

The second input to heavy-lift planning is the site. The site can also be described by several basic characteristics. The spatial layout and dimensions of the site are typically represented by drawings for lift planners. The structural stability of the site is represented quantitatively by engineering sheets for specific areas of interest. The state of the site's spatial and structural conditions is also represented as it changes with time by the project construction and plant operations schedule.

The crane can be represented by five primary categories of characteristics. The crane's physical dimensions define its spatial operating requirements. The structural design and weight characteristics define the forces and stresses that the crane can endure for a lift. The crane is also characterized by its cost and availability. Subjectively, the crane is also characterized by its reliability and service record.

Lift Plan Outputs

The lift planner structures the planning process around six basic spatial outputs for each of a number of crane configurations. A single crane configuration may include boom length, counter weight, boom size, jib type, and boom tip type. Through each stage of the planning process, the number of crane configurations are reduced while the lift plan outputs are refined. In preliminary planning, approximate regions of feasible locations for the lift plan spatial outputs are determined. In detailed planning, these regions are more accurately determined and the location of each lift plan output is optimized for each crane configuration. The objective is to choose outputs that minimize the structural and spatial requirements of the crane to directly improve the reliability and performance of the lift. The six outputs for the uprighting and lifting of a single critical lift are:

- Main crane location: The main crane location is the plan location of the center pin and the elevation of the top of the crane mat.
- Tailing crane location/path: The tailing crane location and/or path is defined similarly as its center pin location as it uprights the vessel or lift object.
- Vessel upright location: The vessel upright location is the main crane hook location at which the vessel is uprighted for a lift.
- Vessel upright path and vessel lift path: The upright path and lift path are the paths traveled by the main crane hook during uprighting and lifting.

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- Vessel pick location: The vessel pick location is the uprighted point at which the main lifting crane first carries the full weight of the vessel.
- Vessel place location: The place location is usually not variable and is defined as the crane hoist hook location where the vessel rests at the end of the lift.

Lift Planning Mechanisms

The mechanisms of the lift planning function are primarily the responsibility of the lift planner and the facility owner. For example, one large-plant owner supplies construction contractors with preliminary lift plans. More typically, the owner requires detailed lift plans from the construction contractor. The lift planner and the owner in turn receive information from technical consultants such as crane manufacturers, structural engineers, and other lift planning experts. While numerous parties supply information to the lift planner and the owner, the end responsibility for the execution of the lift plan falls with the lift planner, an individual or subcontractor who is usually employed by the contractor.

Lift Plan Controls

Heavy-lift planning is controlled by spatial, structural, and schedule constraints. Spatial constraints take into consideration the work volume or space on the site required for the crane to move the vessel through the lift path. The lift planner cannot check the interference of every point on the vessel, crane, or site with each other. The lift planner therefore uses experience to identify the points on the lift components that are most likely to interfere with each other. Fig. 3 is a small matrix of the common interference conditions that a lift planner checks for clearance requirements. For example, one of the most common conditions limiting a lift is the interference of the crane boom body with the vessel head.

Due to the uncertainty of the dimensions of the crane, vessel, and site

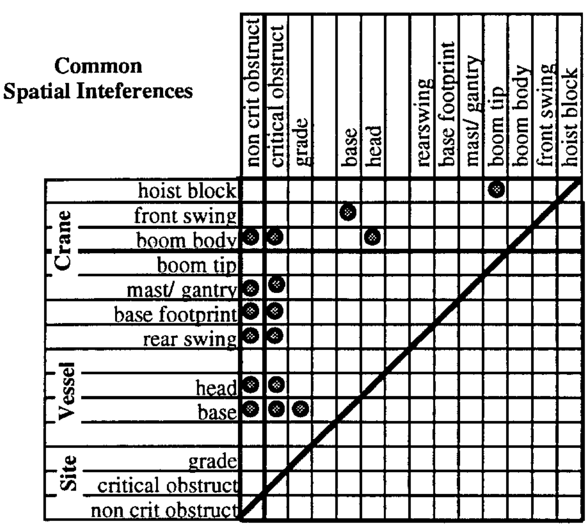

FIG. 3. Typical Heavy-Lift Interference Points

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during dynamic lift conditions, the lift planner defines the tolerances required at these interference points. This tolerance given by the lift planner varies depending on the subjective analysis of the likelihood of an interference condition. The crane has unquantified variances such as boom flexure, foundation settlement, and general mechanical slip. The vessel has variances due to sway and hoist line elasticity during the lifting operations. The shear size of the crane components justifies the planner's assumption that there is uncertainty in the control of the lift. A critical lift clearance allowance is that between the crane boom body and the top of the lift object. A typical minimum clearance for this critical point is 60–90 cm (24–36 in.).

The structural constraints on the lift plan require determination of the required strength of the vessel, site, and crane, as well as allowable loads plus a safety factor. The weights of the lift components make up the static forces acting on the lift. The safety factor to account for dynamic conditions and uncertainties is typically set by the owner in consultation with the lift planner, and is generally based on perception of risk. The lift planner and consulting engineers often have difficulty evaluating the true capacity of the lift when different structural guidelines apply to different components of the lift. The issue of the effectiveness of multiple structural safety factors on the reliability of the heavy lift has been addressed in a previous lift study (Duer 1989).

As the lift date approaches, the schedule begins to impose more fixed constraints. The pick location for the vessel may be constrained by the date that a certain construction activity must take place. Interfering structures may be erected before or after a lift. In addition, physical precedences exist such as the requirement for construction of a vessel foundation and pad before placement. The schedule describes the time variance of spatial and structural constraints as well as the objectives of the project managers.

Evaluating Lift Plans

The complete lift plan is optimized with the simultaneous objectives of cost, reliability, safety, and performance. Interdependencies abound. For example, the cost of a crane greatly increases as its structural capacity increases.

The weight of each of these objectives or evaluation criteria varies, but the method by which each criteria is applied to the lift plan is fairly uniform throughout the industry.

In terms of reliability or safety, the lift planner's objective is to minimize the chances of catastrophic accidents and general lift failures. Catastrophic-type accidents are failures involving the loss of life or extreme damage to hazardous processes such as chlorine gas removal. Lift failures are defined as structural failures or spatial interferences causing damage. The clearest indicator of reliability of a lift is the percentage of the crane capacity used. This is established by the fact that most lift failures are caused by the overturning of cranes, or by exceeding the structural stable capacity of the crane.

Primary lift cost components are the crane lease rate, crane transportation/setup, engine mat/foundation construction cost, and the cost impact on area construction activities. Ideally, the lift planner evaluates these components together and selects the best lift plan, but typically the lift planner minimizes the cost of the lift through the selection of the most economical crane based on fixed object and site information. In the early planning stages, though, lift planners are able to better reduce the total lift cost by evaluating the site constraints on the lift along with the lift conditions (Donnie Gosch Sr., heavy-lift planner, Brown & Root, Inc., Houston, Tex.; heavy-lift survey interviews; April 10, 1991, June 11, 1991). For example, a single crane foundation can be used for the execution of several heavy lifts in an area. This requires the coordination of construction plans to ensure that area structures are constructed in a sequence that allows access to multiple place points from a single crane location.

Performance criteria are also used by lift planners to optimize lift plans. One performance factor is the use history of the crane. The history of the crane impacts both the structural and spatial reliability of the equipment and potential maintenance and servicing costs. Automated measurement devices have recently been introduced to allow the lift history of the crane be economically recorded.

DEVELOPMENTS IN COMPUTER-AIDED PROCEDURES AND THEIR IMPACT ON LIFT PLANNING METHODS

A presentation of research findings for a common lift planning task serves to illustrate the impact of computers on the overall lift planning process. The sample planning task is the identification of the minimum radius at which a single crane can lift an object. Since the structural reliability of the lift increases significantly as the lift radius decreases, a primary objective of all heavy lifts is to perform the lift as close to this minimum radius as possible. The interference of the lift object with the crane base or boom determines the minimum radius on the majority of heavy lifts performed with rotary cranes. Occasionally, stability with respect to the crane's counterweights will also affect the minimum radius.

The method of performing this task for six engineering/procurement/construction (EPC) contractors is presented in this section (Hornaday 1992). The purpose of this section is to provide insight into planning methods of industrial constructors, not to rank or compare. Some of the contractors studied specifically requested that company references in lift planning materials not be disclosed. Thus, the planning methods and the drawings shown in this section are not specifically referenced.

Three of the six EPC contractors and owners studied currently use manual lift planning procedures. In determining the minimum crane radius, an elevation view of the vessel is hand-drafted by the lift planner. Then, for each crane configuration under study, the lift planner drafts an elevation view of the crane body and boom. The process of determining whether the boom clears the vessel height is performed iteratively. For a single crane configuration and vessel pair, lift planners take about 8 man-hours to accurately calculate and document the minimum crane radius.

Lift planners may use shortcuts to improve the efficiency of this planning task. One planner keeps a notebook of sketches of common crane models drawn to scale. Common rigging attachments are also filed in a second notebook. Using a photocopier, portions of the drawings are constructed using cut-and-paste methods. Other planners who draw out the individual components of the crane take shortcuts by only drawing the critical dimensions needed. In Fig. 4, a lift planner sketched only the critical crane dimensions like the boom length and rotation center line.

The remaining three of the six planners use computers to aid in the planning of heavy lifts (Hornaday 1992). Different levels of technology were observed.

The first documented use of computers for heavy-lift planning was a

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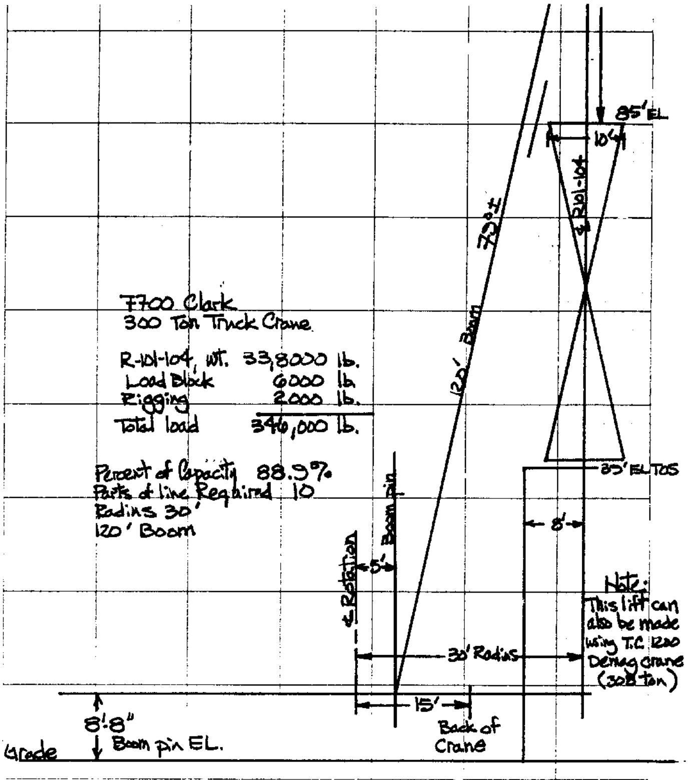

FIG. 4. Drafted Elevation Working Drawing of Crane Lift

planner's use of AutoCAD in 1982. Various common crane components, such as boom sections, types of rigging, and crane bases, were saved to scale in files. Once the vessel was drafted on the computer from shop drawings, the lift planner would insert common crane components to construct the lift plan. This planner still uses AutoCAD to store common crane components and to document the heavy-lift plan. Once all of the vessel information is entered into a drawing file, the calculation and documentation of a crane configuration's minimum crane radius for that vessel takes about one man-hour.

Another integration of the computer encountered was the use of site range scanning technology to quickly construct standard DXF (drawing exchange format) drawings of existing vessels to be lifted. The owner company performs mostly maintenance construction of existing plant equipment.

In this case, the lift planner uses AutoCAD to store graphic representations of crane components. The transfer of vessel dimensions is performed via the DXF files produced by the scanner. The calculation of the minimum crane radius takes about an hour once the vessel information is transferred into AutoCAD. The primary automation advantage is the reduction of the time-consuming process of field measurement of existing vessels.

Another EPC contractor has invested a significant sum of money in the development of a computer-aided heavy-lift planning system running on graphics workstation computers. This system is used to automate the calculation and documentation of common lift planning procedures. This planning system uses applications developed with MicroStation® for a graphic display of lift configurations and for graphic interactive user interfaces (Alexander 1992). Many of the common planning tasks are performed in the

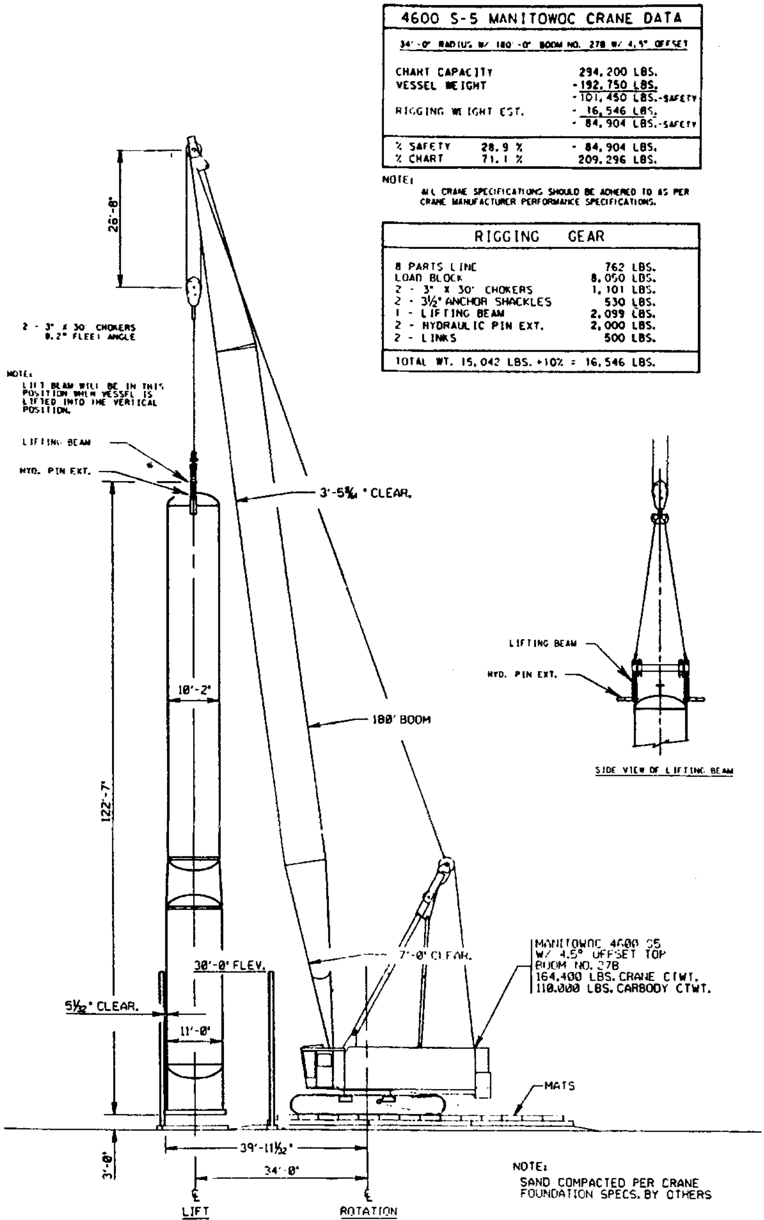

FIG. 5. Lift Elevation Drawing Documenting Minimum Radius Position

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background by in-house programs developed in the language C++, an object-oriented language. To calculate the minimum radius of a crane configuration, the user constructs or imports a drawing of the vessel. Lifting constraints such as required clearances and type of rigging are selected. The user then specifies a trial radius and the crane configuration is graphically constructed in seconds. The experienced lift planner, after a few trial radii, constructs the crane's minimum radius configuration in about 1 min. A sample illustration of a crane configuration and vessel pair produced by this system is presented in Fig. 5.

Excluding the cost and time to develop and implement computer planning aids, the task of calculating a crane and vessel pair's minimum radius was reduced from an eight-hour work day to 1 min. This task is only a component of the total heavy-lift planning process. However, significant improvements to the process can be realized through the improvement of individual tasks.

INTEGRATED COMPUTER-AIDED HEAVY-LIFT PLANNING SYSTEM

The opportunities to use computer tools to improve heavy-lift planning are far broader than the previous examples may suggest. Some of the tools and their potential applications are summarized in Table 1. The challenge is integrating these tools into a useful computer-aided heavy-lift planning system. The system should enhance and amplify the planner's capabilities, but not replace the planner, who is ultimately responsible for the final lift plan.

A computer-aided heavy-lift planning system could conceivably reduce by one-half the total number of hours spent on lift planning activities. It should also result in better lift plans and reduced lift costs.

In the next section the requirements of such a system are discussed. Then, the writers' progress toward implementation is described. This progress is representative of the related efforts of several private groups within the heavy-lift industry. The writers' research seeks to integrate and advance these efforts.

System Requirements

A computer-aided lift planning system must recognize the practical requirements of the heavy-lift industry. Industry lift planners must be able to transition from current practices to automated methods or automated methods will not be accepted.

TABLE 1. Technologies for Computer-Aided Planning

Technology (1)	Use for computer-aided heavy-lift–planning (2)
Computer-aided design (CAD)	Model crane, vessel, and site geometry; interference checking
Geographic information system	Model site layout and subsurface conditions
Graphical user interface	Enhance user productivity
Relational data base management system	Store, maintain, and organize graphical and nongraphical data
Robotics path planning	Provide algorithms for spatial reasoning and path planning
Computer graphics simulation/animation	Visualize lift for review and execution instruction

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The owner requires management control information from the lift planner relating to the cost, reliability, and schedule of the lift. Since lift cost is typically excessive relative to other construction operations, owners require a detailed breakdown of where resources are being consumed in the lift (Larry Londot, lift planner, The M. W. Kellogg Co., Houston, Tex.; heavy-lift survey interview; June 13, 1991). A second requirement by the owner is a verification of the lift's reliability. Owners currently review lift plans for the most critical lifting conditions based on knowledge of past accidents (Frankie Spates, lift planner, Dow Chemical, Freeport, Tex.; heavy-lift survey interview, July 11, 1991). As a result, the lift plan requires documentation of critical parameters such as close clearances and structural capacity utilization. Another control function is the assurance of schedule progress. Lift planners are usually required to provide the owner with work plans and evidence of schedule progress (Marshall Wheeler, erection field engineer, Becon Construction, Co. Inc., Kingsport, Tenn.; heavy-lift survey interview; May 28, 1991). These three management control functions are a required component of a complete lift planning system that serves the owner and the lift planner. The system should produce appropriate reports and output for these functions.

A primary requirement made by lift planners is the need to integrate planning methods with the information received from outside sources. Even with CAD modeling of the crane, vessel, and site, planners often have to reconstruct aspects of the lift plan. This would not be required if information from different sources could be integrated more easily (Donnie Gosch Jr., heavy-lift planner, Brown & Root, Inc., Houston, Tex.; heavy-lift survey interviews; April 10, 1991, June 11, 1991). A second requirement of lift planners is the ability to better model structural planning tasks. Currently these tasks are performed by external consulting engineers at substantial cost and time (Donnie Gosch Sr., heavy-lift planner, Brown & Root, Inc., Houston, Tex.; heavy-lift survey interviews; April 10, 1991, June 11, 1991). A third requirement is better lift scheduling and crane availability tracking. Planners sometimes must delay commitment to crane rentals until the vessel or lift object actually arrives on-site. With crane costs from $10,000 per month, planners are challenged by the task of tracking available equipment to meet changing schedules. A fourth requirement is that a computerized system must facilitate the natural iterative nature of lift planning and not artificially constrain the planner to rigid sequences of procedures.

Implementation

Initial efforts at implementing an integrated computer-aided heavy-lift planning system have resulted in the successful demonstration of a heavy-lift planning simulator called HeLPS1, which runs on a Silicon Graphics IRIS workstation using WALKTHRU. HeLPS1 enables the lift planner to visualize the execution of the heavy lift. The simulation process also enables the real-time monitoring of spatial interferences and the crane's structural capacity (Wolfhope 1991). A sample view of the computer monitor during a lift simulation is pictured in Fig. 6.

Efforts are under way by the writers to develop a more completely integrated computer-aided heavy-lift planning system (called HeLPS2) on a microcomputer platform that will incorporate many of the system requirements discussed previously. Fig. 7 is a functional model of this planning system. The two darker outlined components in the figure represent prototype implementations: (1) The graphic simulation of the lift plan using

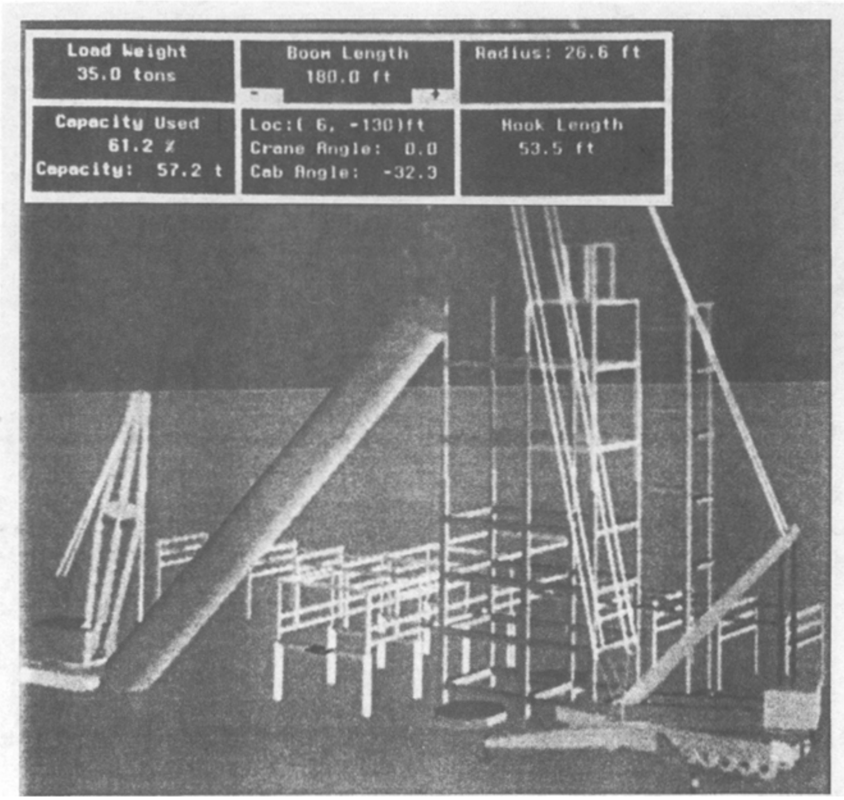

FIG. 6. HeLPS Lift Simulation

HeLPS1; and (2) algorithms for determining minimum lift radius (Hornaday 1992).

The microcomputer-based system will serve as a powerful interactive tool for the heavy-lift planner. It incorporates a personal computer-based CAD software package (MicroStation) and data-base software (Oracle) in order to perform both preliminary planning and detailed planning efficiently. The system is being developed in the MicroStation Development Language (MDL).

It has the ability to query the data base through graphic entities such as crane booms or lifting blocks. The software has been partially implemented, and development is in progress. Its architecture is summarized in Fig. 8. The functional hierarchy of the software modules illustrates the division of the software into a model builder, a data-base manager, and a planning manager (Fig. 9). A more detailed description of the software design is beyond the scope of this paper, but it is presented in a forthcoming paper on the design of the system and its algorithms.

The system implements some limited constraints on planning procedures in its preliminary implementation. The planner sets the spatial clearances that he determines to be reliable. The planner also sets the acceptable percentage of crane capacity ranges.

Each possible configuration of a crane is treated as a separate crane model, therefore each combination of boom length, counter weight, boom size, jib

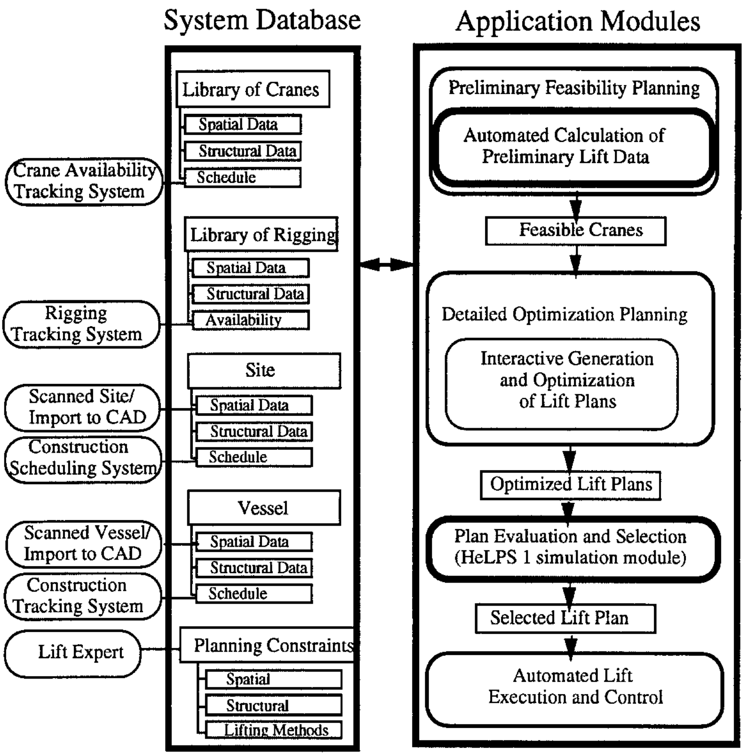

FIG. 7. Computer-Aided Heavy-Lift Planning Process Model (Hornaday 1992)

type, and boom tip type is evaluated separately for feasibility. The vessel is treated as a constant and the site a perfect plane.

A conceptual description (HeLPS2 is not yet fully implemented) of a typical user session can be described as follows.

A site module is activated to display a three-dimensional site layout and a two-dimensional plan view. Site information such as ground conditions, access roads, underground construction is marked in red to aid in the suitable location of the crane. Information compiled for these site entities is accessed by simply clicking a mouse cursor on the graphic images on the screen. For example, double clicking on an underground pipe would reveal a window with planning information like the designed allowable bearing pressure. The planner may next review vessel or lift object data through a vessel module. Clicking the mouse cursor on the vessel opens a window containing dimensions, views, weight, and delivery schedule information.

Based on the vessel information and site conditions, the lift planner can select the crane for a specific lift. A crane module allows the lift planner to evaluate the minimum lift requirements against crane capabilities. The planner may edit this list of feasible crane models. For each crane, several combinations of boom length, counter weights, boom tip type, and jib type can be selected. For each configuration, the computer calculates and automatically displays the possible crane location area on the site layout plan. This area is calculated on the basis of the site conditions, the vessel place

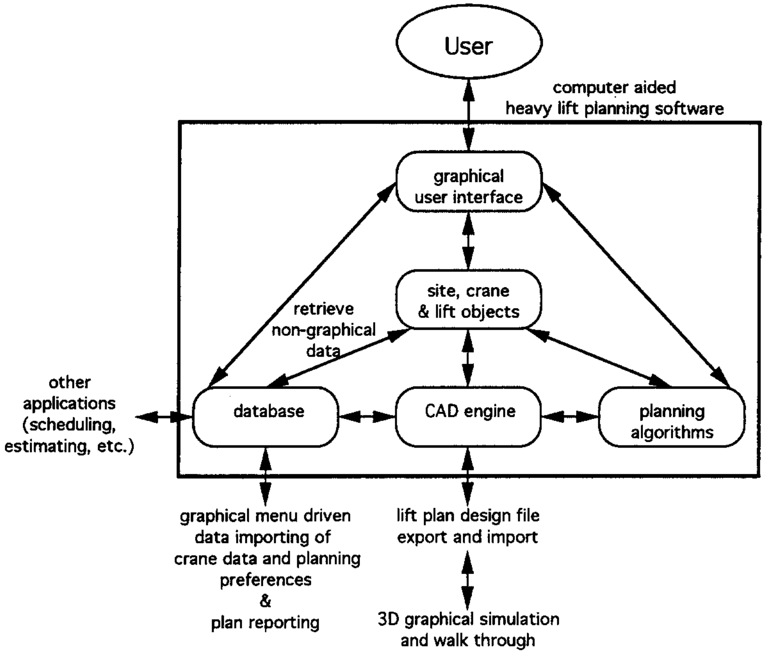

FIG. 8. HeLPS2 System Architecture

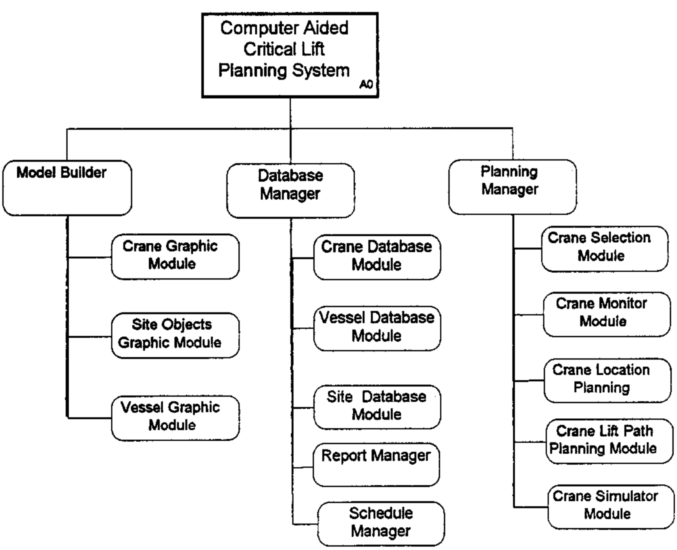

FIG. 9. HeLPS2 Functional Hierarchy

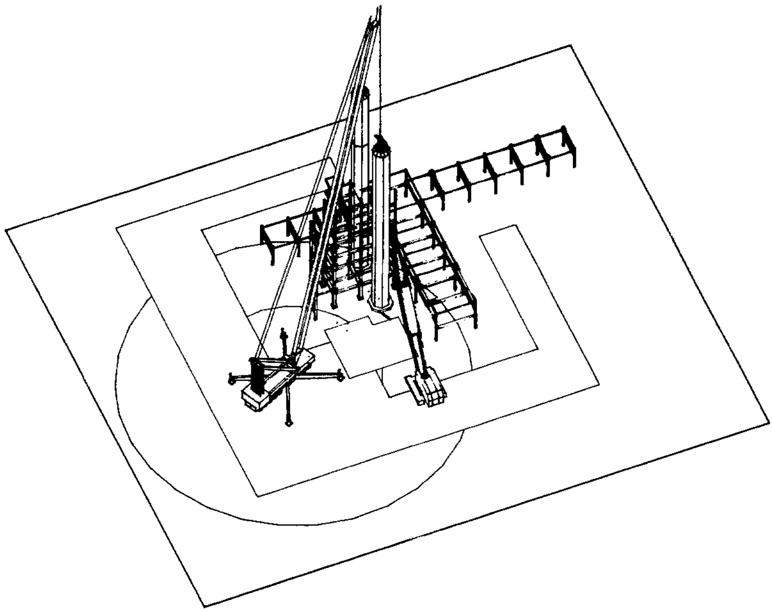

FIG. 10. Detailed Planning Lift Plan View

location, the key dimensions of the selected crane, and the crane minimum and maximum radii.

The planner then selects the crane location based on experience.

The optimal crane location minimizes the furthest radius that must be reached in the execution of the lift plan. He clicks a point at the center of the rotation within the feasible crane position region. The selected crane is then placed on this point, with the minimum and maximum working circles placed about the center as illustrated in Fig. 10. Within the working area of the crane and the feasible vessel pick area, the planner selects the vessel pick location. After the crane location and the vessel pick locations have been selected, the lift path can be generated automatically (Morad et al. 1992) based on the following criteria:

- Perform the lift as close to the minimum radius as possible.
- Prioritize hoisting and swinging motions over crane booming motions.
- Reduce the number of crane operations (the ideal lift path is the simplest one).

The system will also generate cost estimate, clearance, and crane capacity utilization reports. The close integration of a CAD system, data base, and development language make this possible.

FINAL SELECTION, EVALUATION, AND REVIEW USING COMPUTER-AIDED HEAVY-LIFT PLANNING SYSTEM

An optimum lift can be selected based on reliability and cost criteria. The reliability of the lift is related to the spatial clearances, the structural utilization, and the schedule availability. Graphical simulation software such as that implemented in HeLPS1 can be used in the evaluation process for a final three-dimensional check of spatial and structural constraints as well as for visualizing the lift plan. HeLPS2 is intended to also have this ability in the future. Clients are beginning to demand a high-resolution graphical simulation for review prior to final lift plan confirmation. They will also typically demand documentation of the planning clearances that were used to determine the feasible crane and the optimum lift plan. A computer-aided planning system will be able to report this information automatically.

The structural reliability of the lift can be evaluated based on the percentage of the capacity used for each of the structural components of the lift. This information can be reported automatically using the HeLPS1 software. A listing of the lift structural components and their structural utilization allows lift planners to identify the weakest link in the lift plan. A similar listing was used in the evaluation of a lift of a nuclear reactor vessel (Duer 1989).

The primary cost of increased structural reliability is in the crane, so owners often prefer to evaluate the cost of the lift along with the percentage of the crane capacity utilized. This crane capacity utilization is often expressed to lift owners by planners as the lift safety factor (Donnie Gosch Sr., heavy-lift planner, Brown & Root, Inc., Houston, Tex.; heavy-lift survey interviews; April 10, 1991, June 11, 1991).

Computer-aided heavy-lift planning allows the planner to generate several alternative detailed lift plans. Comparing the lift safety factor and the lift cost for each lift plan enables the planner to select an optimal combination of cost and risk, to generate alternatives for procurement within certain cost and safety constraints, and to present the owner with the costs of reducing risk.

CONCLUSIONS

Industrial owners and contractors are expanding the number and size of large prefabricated equipment pieces requiring heavy-lift erection. Other sectors of the construction industry are also moving toward prefabrication and modularized erection methods. This shift in construction methods will expand the number and size of lifts and indirectly increase the need for more reliable and economical heavy-lift planning methods.

Many of the lift planning procedures of industrial contractors can be aided and improved with the use of computers. A model of heavy-lift planning methods common to industrial constructors presented in this paper serves as an architecture to build a computer-aided lift planning aid. A few industrial leaders have already implemented powerful computer-aided lift planning tools. An integrated, microcomputer-based, heavy-lift planning system is being implemented by the authors that will lead to further advances.

The tools described in this paper have the potential to improve upon current planning methods in several ways. Lift planners will be able to evaluate hundreds rather than a few possible crane configurations, thus improving the likelihood that a good plan will be generated. In conclusion, computer-aided lift planning should:

- Improve the reliability and accuracy of lift planning.
- Reduce the cost of planning.

- Reduce the total lift cost through more effective selection of cranes.
- Increase the level of planning from "will it work" to that of "optimization."
- Integrate disparate sources of lift plan information.
- Allow for the simultaneous evaluation of multiple planning components.

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