AN INTERACTIVE PLANNING ENVIRONMENT FOR CRITICAL OPERATIONS

By Kuo-Liang Lin,[1] Student Member, ASCE, and Carl T. Haas,[2] Member, ASCE

ABSTRACT: In this paper, an interactive critical operations planning environment (COPE) is described for planning critical construction operations involving large semistationary equipment such as cranes, concrete pumps, and manipulators. Careful planning is necessary for the use of semistationary equipment; however, formal planning methods and tools are limited. Planning is typically the responsibility of a small pool of experts whose knowledge is largely undocumented. Automating and formalizing aspects of the planning process can improve the productivity and effectiveness of expert or nonexpert critical operations planners. The proposed planning environment uses computer-aided drafting tools and a set of computerized planning primitives to facilitate a very visual planning process. The planning principles implemented include human-computer interaction, constraint enforcement, and performance measurement. Implementation details and initial research results are presented in this paper, which follows previous work. With the developed planning environment and process, a significant amount of planning time can be saved so that more alternatives can be evaluated. A better plan can be determined through comparison of more alternatives. The structured planning process also allows planners to perform more detailed analyses on planning problems. Better decisions can thus be made based on the analyses.

INTRODUCTION

Advancements in construction equipment have precipitated significant changes in construction practice. Cranes, for example, have increased tremendously in size, capacity, and versatility in the last few decades, prompting increasingly larger, heavier, and thus riskier lifts. Concrete pumps with tremendous reaches and sophisticated computer control systems (Benckert 1991) facilitate precise placement plans (Kunigahalli and Russell 1994) for large pours, and large-scale manipulators for handling materials, finishing surfaces, and inspecting structures are emerging as commercial equipment (Haas et al. 1995). The consequences of misuse of this equipment are severe in terms of safety, productivity, and project delay. Improved planning methods for the use of this equipment are therefore required.

The scope of this paper is limited to construction equipment which is large and semistationary. Relocation of such equipment should normally be minimized because it takes considerable time and effort. Examples of this class of equipment include cranes, large concrete pumps, and large-scale manipulators. Equipment in this class has elongated arms used to manipulate, move, and place materials, and to operate on or inspect surfaces and structures. One of the major characteristics of large semistationary equipment is the work envelope, which is the space the equipment can reach about itself. The primary planning aspects of using large semistationary equipment for critical operations include laying out the jobsite to facilitate execution of the activities, examining scheduling impacts, selecting an appropriate equipment combination for a particular job, examining the accessibility of the equipment to the work area and discrete work tasks, placing the equipment at advantageous locations, and detailing operation procedures of the equipment for the job. Planning criteria include feasibility, cost, safety, and efficiency.

Based on the need for efficient planning tools, a number of computerized approaches have been proposed to automate the planning process in related domains (Bennett and Ditlinger 1994; Varghese and O'Connor 1995; C. A. R. 1990). For example, mathematical modeling and expert systems have been used to solve some equipment-placement planning problems by seeing optimal solutions based on predefined criteria and constraints such as time, cost, and coverage (Chalabi and Yandow 1989; Furusaka and Gray 1984). These approaches are most useful where a limited, discretized solution space exists or can be defined. They provide limited support for spatial planning, such as equipment placement, in complex environments that exhibit unique spatial features for each project, or they become inapplicable as additional planning criteria are considered.

Graphical simulation can be an effective way to plan operation procedures in three dimensions. It is a highly flexible approach; however, for many early planning problems, including equipment selection and placement, it can provide too much spatial information and impose severe computational loads. The planner is often burdened by the necessity to use inefficient trial and error approaches, and many people do not think well in three dimensions. Although solutions are being developed for tasks such as automated path planning (Beliveau et al. 1992), and have been implemented as part of the work described here (Chen 1994), three-dimensional (3D) simulation remains most suitable to the later planning stages for critical operations. Similar considerations apply in structural analysis and design.

An interactive planning environment—critical operations planning environment (COPE)—is presented here, which is designed to resolve many of these aforementioned limitations. Fig. 1 describes the planning methodology used in COPE. Interactiveness is the key principle of COPE. COPE models planning data to fully describe planning problems in an easily accessible way. A set of computerized planning primitives (analytical and computational functions) that manipulate planning data is implemented within COPE to help planners develop plans and make decisions. The computerized planning primitives can provide spatial information on the screen, allow interactive analysis of site constraints, suggest feasible location areas, help in determining operation procedures, and provide objective measures of worth. Different planning procedures

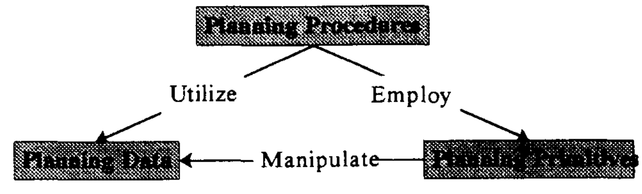


FIG. 1. Planning Methodology

[1]Res. Asst., Dept. of Civ. Engrg., 5.2 ECJ, Univ. of Texas, Austin, TX 78712.

[2]Prof., Dept. of Civ. Engrg., 5.2 ECJ, Univ. of Texas, Austin, TX.

Note. Discussion open until February 1, 1997. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on May 19, 1995. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 122, No. 3, September, 1996. ©ASCE, ISSN 0733-9364/96/0003-0212–0222/$4.00 + $.50 per page. Paper No. 10763.

J. Constr. Eng. Manage., 1996, 122(3): 212-222

employing combinations of planning primitives can be used for different planning situations. COPE is designed to be a preliminary planning tool which facilitates initial cuts through what can be a large and complex solution space. 3D simulation systems should be used for subsequent detailed planning validation and communication.

Literature searches (Hornaday 1992; Shapiro et al. 1991), review of trade magazines, interviews with expert planners (Gosch, personal communication, June 26, 1994; Welsh, personal communication, December 20, 1994; Hsieh and Haas 1993), and detailed analysis of several case studies have provided the information used in identifying planning problems, formalizing the planning process, and developing COPE. It is implemented on a microcomputer, and has been demonstrated in the field using a notebook computer.

PLANNING MODEL

Planning for individual critical construction operations is driven by spatial feasibility, productivity, safety, and schedule impact. Since spatial feasibility is such a significant factor, the issue of which information is best modeled in two dimensions and which is best modeled in three is a central one in developing a critical operations planning environment.

COPE attempts to combine the advantages of both two-dimensional (2D) and 3D approaches. The environment primarily models and presents the planning scenarios in 2D because it simplifies manipulation for the planner, because 2D drawings remain more widely available than 3D drawings, and because many people think more clearly in 2D. However, COPE functions in 3D when analyzing equipment work envelopes and when computing performance measures. Automatic path planning procedures are also implemented in 3D (Chen 1994), and detailed spatial validation of final planning results are expected to be performed in a 3D graphical simulation environment.

Critical operations planning can best be described as an iterative process requiring synthesis, mathematical deduction, analysis, communication, coordination, illustration, and graphical mapping. This iterative process is an art best performed by humans with the aid of computers. COPE, which is an environment designed to support this process, is described in the following section.

Entities and Operations

The key entities to be considered for critical operations planning include tasks, the construction site, equipment, and operation elements. The interaction between these entities forms the core of the planning problems.

An operation completes a task. A task can be defined as the difference between two states of the site: the state before the operation and the state after the operation. The site is the physical environment of the operation. Equipment is used to complete the operation. Operation elements are associated with an operation, and may include concrete in a pumping operation and the lift components in a heavy lift operation. Table 1 describes the key properties of these entities. These entities are implemented as database relations while planning primitives implemented variously as microstation development language (MDL) functions, structured query language (SQL) scripts, and spreadsheet macros are used to manipulate these entities during the planning process.

Process

A generic process for planning critical operations is outlined in Fig. 2. This process can be used for planning critical operations involving various large equipment such as cranes, concrete pumps, and large-scale manipulators. The process includes six major steps: scenario construction, identification of alternatives, work area analysis, equipment placement, task planning, and performance measurement. It is possible for a planner to move sequentially through these stages; however, an iterative path is more likely. Scenario construction is the initiation of the planning process, in which the planner models and describes the operation and the planning problem. In the identification of alternatives stage, the planner identifies several equipment configuration alternatives which may be able to handle the operation. In the work area analysis stage, the planner analyzes the spatial relationships between planning elements to determine feasible equipment work areas for each alternative. In the equipment placement stage, the equipment is placed in desirable locations within feasible areas. For each location or combination of locations, detailed operation procedures are generated (task planning), and the planner assesses related performance measures including cost, safety, schedule impact, and efficiency (performance measurement).

By repeatedly selecting options, generating alternatives, and narrowing down the solution space by evaluating performance measures, the planner can determine an optimal or near-optimal plan. This process can be seen as an adaption of common design methodologies and of multiobjective dynamic program-

TABLE 1. Key Properties of Planning Entities

Entity (1)	Key properties (2)
Task	Job location(s), schedule, requirements
Site	Spatial occupancy, clearance, construction schedule, ground strength
Equipment	Capacity, key dimensions, spatial occupancy, work envelope, cost, availability
Operation elements	Dimensions, weight, quantity, work specifications, delivering schedule

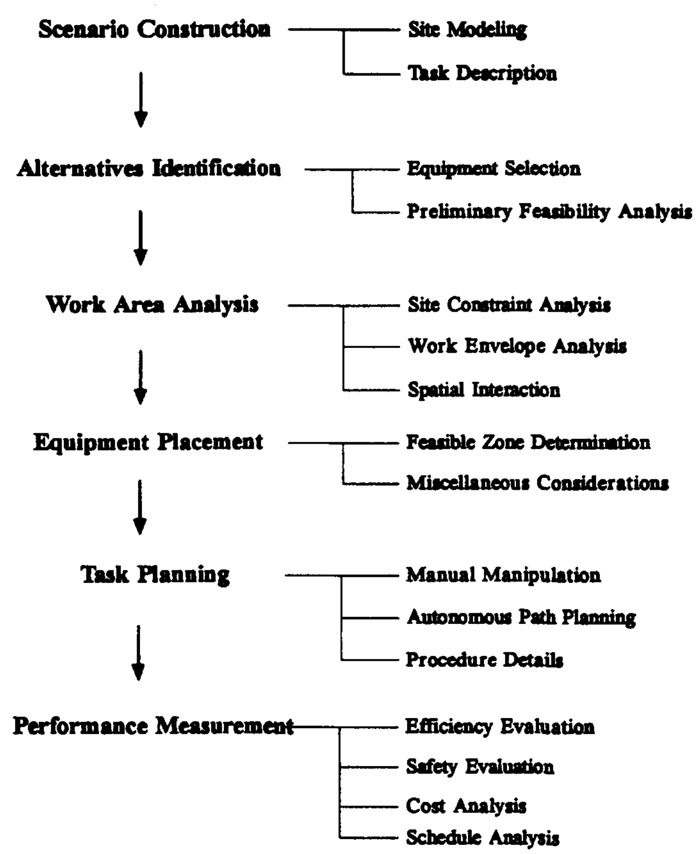


FIG. 2. Critical Operations Planning Process

J. Constr. Eng. Manage., 1996, 122(3): 212-222

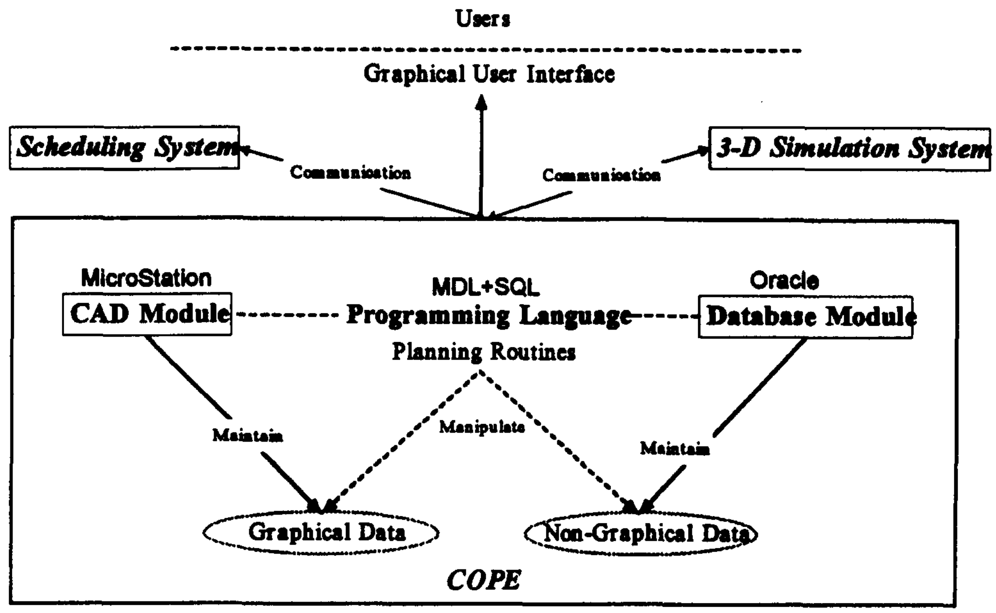


FIG. 3. Planning Environment Architecture

ming to an interactive environment for a specific class of planning problems.

System Requirements

To implement an efficient computer-aided environment incorporating the aforementioned planning process, three basic requirements should be met.

Problem Modeling

The capability to model planning problems is the first requirement. Computer-aided design (CAD) drawings of the site, specifications of the task, and other supportive nongraphical information should be tightly integrated to fully describe planning situations. A comprehensive planning environment should enable planners to model the planning entities and manipulate the information efficiently. A geographic information system (GIS) system or a CAD system with outside database support are possible platforms for implementing this requirement.

Operation Simulation

A comprehensive environment should provide tools for planners to develop operation plans and simulate the output of the plans. To do this, construction knowledge support, such as equipment capability and constraint analysis, should be supplied to enable reasonable outputs. An outside database containing equipment and constraint knowledge can be the knowledge supplier as in COPE. An interactive simulation process and/or an autonomous path finder is required for developing detailed operation procedures.

Evaluation

Evaluation of alternatives is necessary in order to find good or optimal plans. Evaluation, while ultimately based on judgment, can make use of performance measures. Functions for performance measures should be constructed within the environment based on information retrieved from the developed plan. Resulting quantitative values can be assigned to each alternative plan.

IMPLEMENTATION

COPE has been developed based on the preceding model. Three software components are integrated: (1) a CAD platform (MicroStation) to store and maintain graphical elements for planning; (2) a database management system (Oracle) to store and maintain the nongraphical planning information; and (3) a programming language (MDL) to manipulate the graphical elements and the nongraphical information in order to produce the required add-on planning primitive functions. COPE provides a useful way for planners to model and describe the planning scenario as well as implement their planning tactics. Fig. 3 is the planning environment architecture and Fig. 4 is the data flow structure of COPE. The following describes implementation of the planning process using COPE.

Scenario Construction

In the planning process, planners first construct the planning scenario from the available planning information, which usually includes design drawings and task specifications. In COPE, planning scenarios are described in both graphical and nongraphical ways. A 2D MicroStation design drawing models the geometry of the site. Similar to the GIS approach, nongraphical site attributes such as identification, name, type, and height, are stored in a background database table hosted by Oracle and are linked to the corresponding graphical element through the database link provided by MicroStation.

The planner can also model the task to be performed using COPE. Both graphical and nongraphical facilities are used to describe the tasks. For example, if the situation is use of a crane to erect vessel components, the planner identifies vessel placement and storage locations and link them to associated vessel specifications; and if the situation is surface finishing using a large-scale manipulator, the planner identifies the surface to be finished and supplies the specifications for the surface.

Alternative Identification

The next step is to select feasible equipment for the operation. Several alternatives are usually identified at this stage for further evaluation. An equipment library containing equipment with various capabilities is built in the Oracle database. By querying the equipment library, planners can pick the capable equipment based on performance constraints, for example, lift capacity for cranes and pouring rate for concrete pumps. Planners must test the preliminary feasibility of each alternative by examining accessibility and operating clearance.

J. Constr. Eng. Manage., 1996, 122(3): 212-222

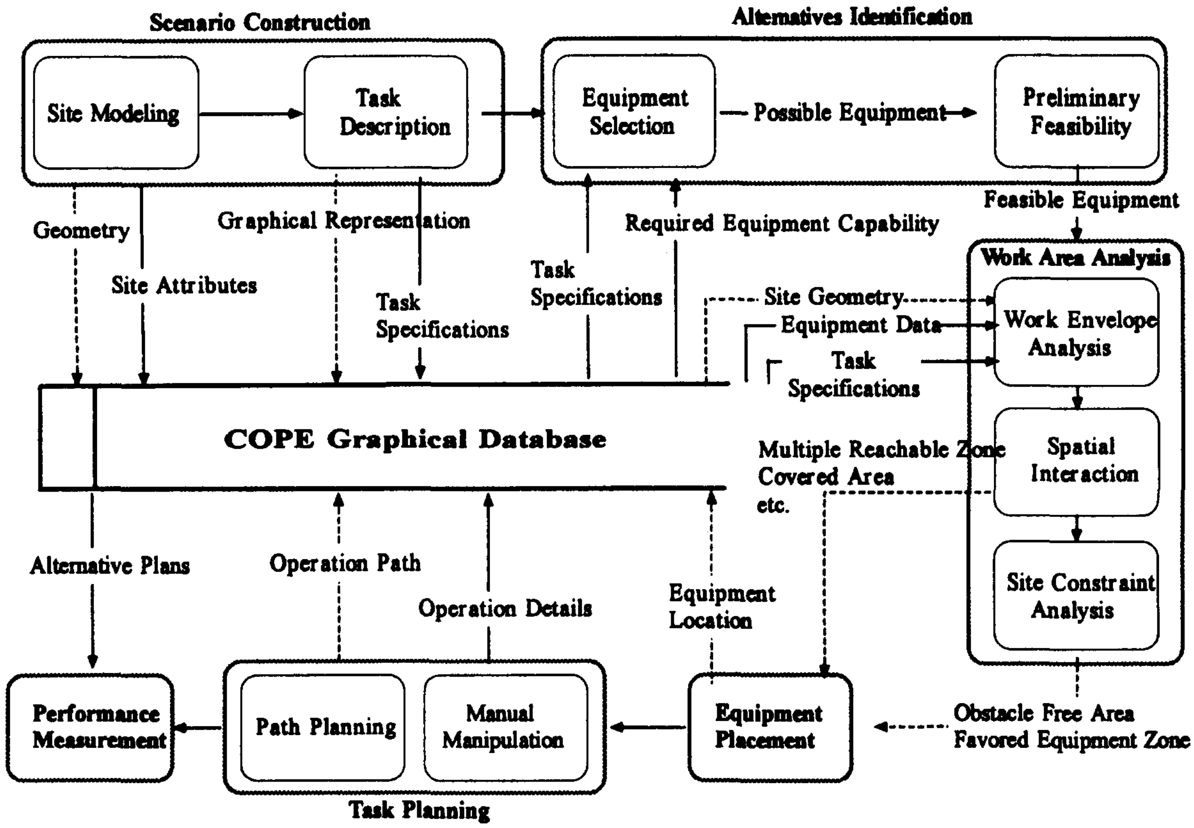


FIG. 4. Data Flow Structure of COPE

TABLE 2. Considerations for Determining Equipment's Work Envelope

Equipment (1)	Degree of freedom (2)	Planning situations (3)	Work envelope consideration (4)
Cranes	Three or four (telescopic)	Critical lift in con1strained area Multiple lift assignments	Cover load place, pick locations Vessel, crane, site interference condition Crane capacity
Concrete pumps	Varies (three to seven)	Concrete pour on building floor	Full area coverage Placing boom length Geometric relationship
Large-scale manipulators	Varies (six to ten)	Pipe installation Surface finishing Inspection	Pick, place locations, elevations Full surface coverage

Several add-on planning primitives are developed using MDL for facilitating these tasks. A simple equipment simulation program allows planners to drive the equipment around the jobsite to test accessibility. The bearing capacity of access routes and clearance in tight areas can be queried for verification.

Another important planning aspect for examining the feasibility of alternatives and determining equipment placement location is the equipment's work envelope, which is the area the equipment can reach based on various constraints during the operation. Table 2 lists the considerations for determining equipment work envelopes. A planning primitive automates the calculation of equipment work envelopes by examining physical and structural constraints, and spatial interference conditions. The primitive retrieves equipment and task information from the database, models the determination of the equipment's work envelope as a nonlinear programming problem, and then solves the problem with a numeric approach to determine the equipment's maximum and minimum radius during the operation for discrete elevations (Lin 1995). Planners can place and move equipment envelopes to determine feasible equipment placement areas, and to examine operating clearances. For critical operations in congested areas, work envelopes can be used to quickly eliminate unreasonable alternatives.

Work Area Analysis

To determine equipment placement location(s), the planner must understand the spatial constraints imposed by the site, equipment, and other planning elements. COPE provides spatial analysis primitives for the planner to explore these relationships. Graphical Boolean operators and graphical query functions are used for implementing these analysis functions (Fig. 5). For example, the obstacle-free area around an equipment placement location can be described as the difference between the work envelope and surrounding obstructive area. When multiple target locations are to be reached, the feasible equipment location area can be described as the intersection of the envelopes centered on each target location. The coverage area can also be represented as the intersection between the equipment's work envelope and the target area at a particular elevation. These primitives effectively handle the most important spatially related factors when determining equipment placement locations. They can be invoked repeatedly, in combination, and in some instances continuously, in order to gain insight into the spatial interactions involved in a particular planning situation.

Equipment Placement

From work area analysis, the planner derives all the feasible equipment placement zones. Before determining final equipment placement locations, the planner can further examine other factors like scheduling significance, job interference, safety, and traffic flow. These considerations are usually evaluated through coordination between project personnel.

J. Constr. Eng. Manage., 1996, 122(3): 212-222

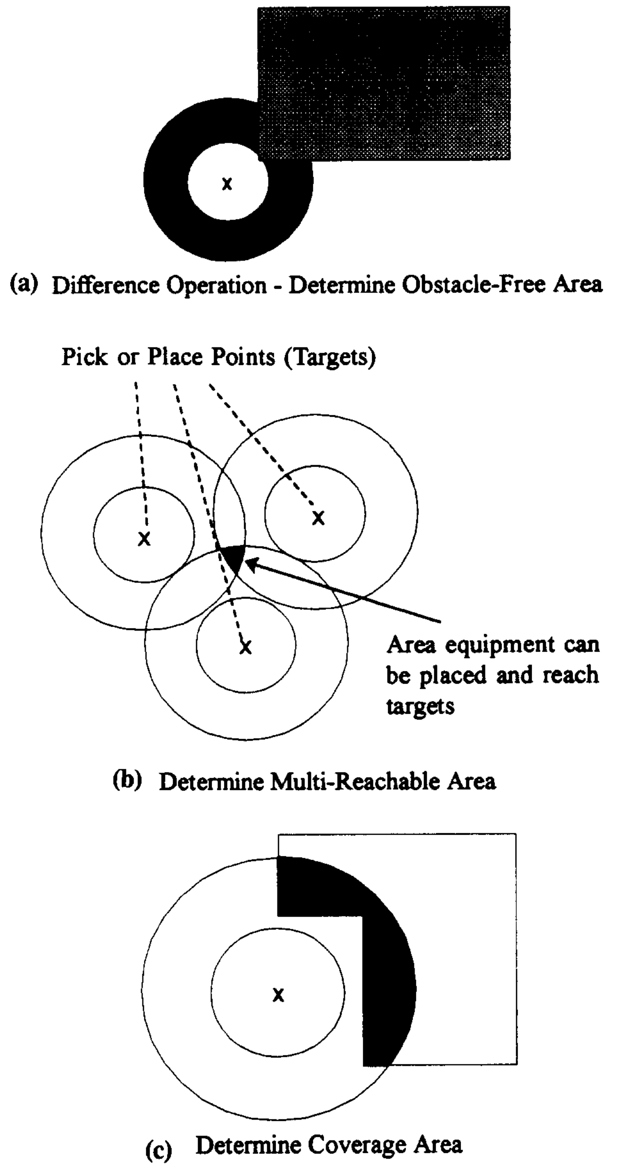


FIG. 5. Graphical Boolean Operators

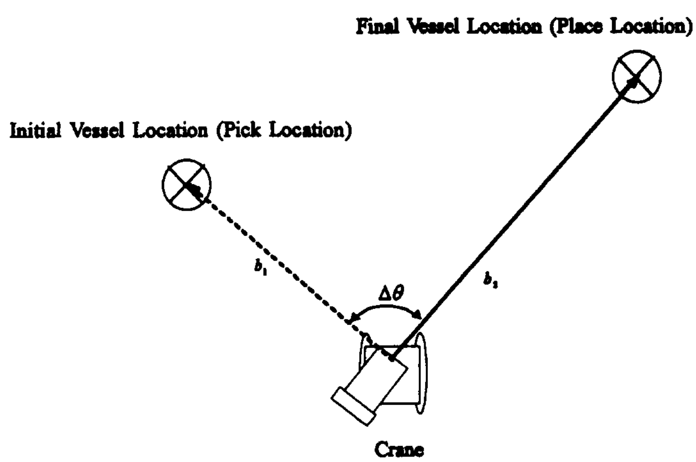


FIG. 6. Initial Vessel Location and Final Vessel Location

COPE's graphical presentation and data management capability can effectively enhance communication between project personnel.

In some complicated operations such as multiple lifts, optimization of equipment placement requires simultaneous consideration of multiple performance criteria, and it is difficult for the planner to make a good decision intuitively. An interactive optimization algorithm is implemented within COPE for multiple lift problems. The algorithm minimizes the number of relocations and at the same time achieves maximum safety within constraints by using safety function values that are based on spatial relationships and lift operation details (Lin 1995).

Task Planning

After deciding equipment placement locations, the planner begins to examine the operation details. COPE's equipment simulation program allows the planner to manipulate the equipment to experiment with operation procedures interactively. An autonomous path planning facility for cranes is also available to find a feasible nonobstructed operation path when the initial state and the goal state of the equipment is specified (Chen 1994). A heuristic, state-based, free path search algorithm is used, which is similar to many in the literature. A

TABLE 3. Summary of COPE Primitives

Primitive (1)	Description (2)
Object modeling	To create graphical representation of planning objects and build the required database linkage
Equipment selection	Database querying function for selecting capable equipment
Site constraint analysis	Graphical querying functions for examining site constraints
Work envelope analysis	To calculate equipment's maximum and minimum radii based on planning constraints
Spatial interaction	Graphical Boolean functions for examining spatial interaction between planning elements
Equipment placement	To place equipment on design drawing and create required database linkage
Manual manipulation	Equipment simulation program with playback capability
Autonomous path planning	To find obstacle-free path between two equipment states
Performance measurement	To assess efficiency, safety, schedule, and cost performance by retrieving planning data from the database and feeding them into spreadsheets

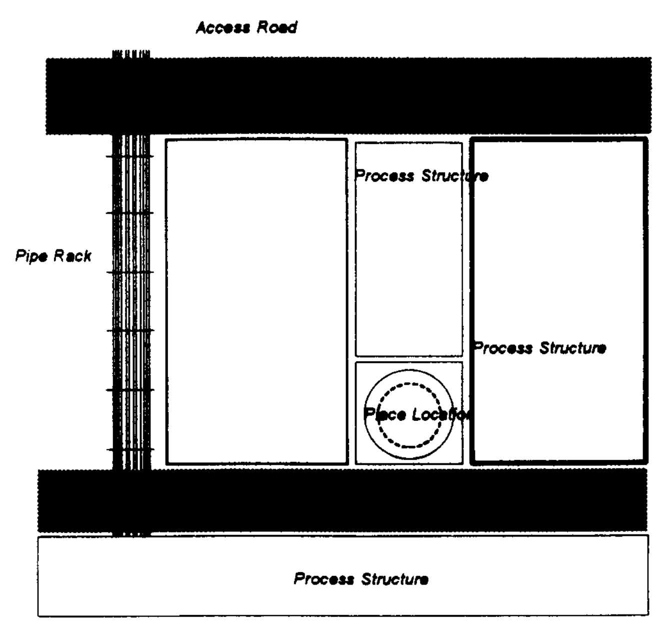
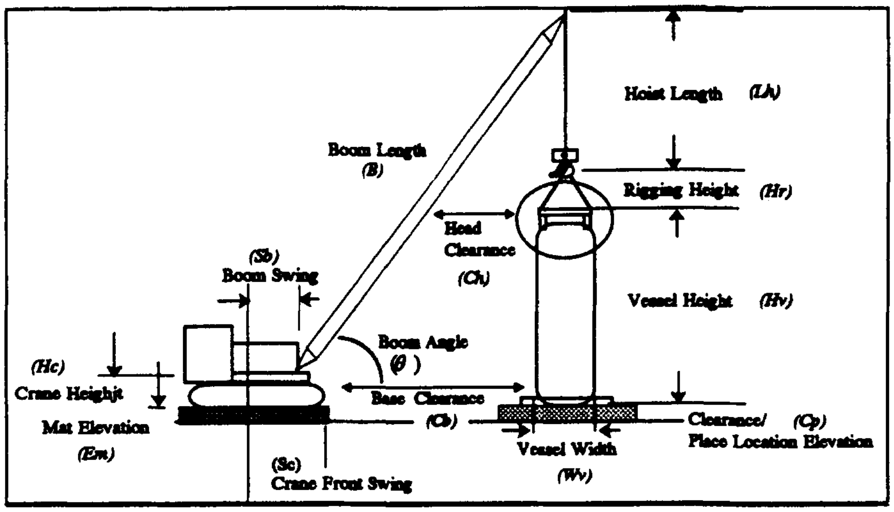


FIG. 7. Dresser-Rand Construction Area Layout

J. Constr. Eng. Manage., 1996, 122(3): 212-222



Spatial Analysis:

(max. and min. radius solved using the quasi-Newton numeric method)

objective function: Max. Min. $Rs = S_b + B \times cos\theta$

subject to

$$H_c + B \times sin\theta = C_p + H_v + H_r + L_h$$
$$L_h >= min\_hoist\_height$$
$$(L_h + H_r) / tan\theta - W_v / 2 >= min\_head\_clearance$$
$$S_b + B \times COS\theta - Sc - W_v / 2 >= min\_base\_clearance$$
$$\theta >= min\_boom\_angle$$
$$\theta <= max\_boom\_angle$$
$$B >= min\_boom\_length$$
$$B <= max\_boom\_length$$

Structural Analysis (Lift Capacity):

(SQL script automatically generated & executed from menu-driven user inputs}

Max. R_c = *select MAX(RADIUS) from CRANE_CA where CRANE_NAME='crane_name' and BOOM_LENGTH=B and CAPACITY > vessel_weight*

FIG. 8. Model for Calculating Crane's Work Envelope

TABLE 4. Alternative Evaluation

Crane (1)	Boom length (m) (2)	Work envelope (m) (3)	Feasibility (4)	Safety (%) (5)	Lift cost (6)
1. 4600S3 (181.60 t auxiliary counterweight)	48.80	(35.38, 22.57)	Yes	40.7	$417,000
2. 4600S3 (181.60 t auxiliary counterweight)	54.90	(39.65, 19.83)	Yes	36.9	$425,000
3. 4100W S1 (55.57 t crane and 83.53 t auxiliary counterweight)	48.80	NA*	No	NA	NA
4. 4100W S1 (55.57 t crane and 83.53 t auxiliary counterweight)	54.90	(22.27, 18.30)	Yes	82.2	$330,000

Note: NA = not applicable.
*Spatially constrained radii are 35.38 m (maximum) and 22.50 m (minimum) while capacity constrained maximum radius is 21.35 m.

primitive is available for recording the procedures and replaying them. A housekeeping primitive associated with the Oracle database system then saves the planning details and feeds them into spreadsheets for later performance evaluation.

Performance Measurement

After all the alternative plans are developed, each plan is assigned a performance score by using evaluation function primitives which retrieve the planning details from the database. Functions exist for efficiency, safety, cost, and scheduling impact. Efficiency is evaluated by the kinematic movements of the equipment required to perform the operation, which correspond to the energy and time spent in the operation. Safety is examined by evaluating structural capacity throughout planned movements and by assessing potential risks. Cost is evaluated by summing up various cost items encountered during transportation, setup, and operation. Schedule impact is a relatively crude dollar-value estimate requiring planner input. With these evaluation primitives, users are able to compare alternative plans and thereby iteratively move toward an optimal operation plan.

Evaluation function primitives implemented for crane operations are described in the following sections to illustrate the application of performance measurement. Similar primitives can be constructed for manipulators and concrete pumps, in which case their relative weights will likely change.

Efficiency Evaluation Function

Equipment efficiency can be used to compare different operation procedures. An efficiency evaluation function based on

J. Constr. Eng. Manage., 1996, 122(3): 212-222

the kinematic movements for a crane lift follows. Fig. 6 illustrates the initial vessel location and the final vessel location of the crane lift.

$$\text{Min } Z = \sum_{i=1}^{n} [\zeta_s(\Delta\theta_i) + \zeta_l(\Delta b_i) + \zeta_t(\Delta d_i) + U_i] \quad (1)$$

where $\Delta\theta_i$ = amount of crane swinging from pick location to place location for vessel i; Δb_i = amount of crane luffing from pick location to place location for vessel i; Δd_i = amount of crane traveling for erecting vessel i; ζ_s, ζ_l, and ζ_t = weighting factors for swinging, luffing, and traveling, respectively, (they are used to compare the efficiency of different crane motions); and U_i = difficulty level of the planned uplift sequence for vessel i.

Safety Evaluation Function

The major safety concern in critical lifts is the capacity percentage used during operation. The following objective function is used to evaluate the safety performance:

$$\text{Min } Z = \sum_{i=1}^{n} C_i + \rho_X(C_i - X) \quad \text{for } C_i \geq X \quad (2)$$

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

Direct Cost

Cost can be divided into the following items:

1. Equipment cost
   - Rent/month × (number of months)
   - Fuel/month × (number of months)
   - Transporation cost
   - Setup and assembly cost
2. Insurance/month × (number of months)

and for cranes

1. Foundation (mat) cost × (number of placements)
2. Cut and fill, and/or compaction cost

Schedule Impact Cost

Schedule impact is primarily caused by the duration of the operation. Secondary impacts are caused by effects on activities related by precedence relationships, shared resource usage, or space conflicts. Magnitude depends on the critical path. While it is conceivable that links could be implemented with a critical path method (CPM) scheduling system, and that algorithms could be developed for automatically estimating primary and secondary impacts, COPE utilizes a more simplified way which depends on direct planner input. For example, a crane's operation duration can be estimated from the breakdown of delivery, setup, operating, and dismantle periods. Secondary impacts can be estimated using the following:

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

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

Table 3 is a summary of the planning primitive functions of COPE.

APPLICATIONS

COPE can be applied to a broad range of critical operations planning situations. Four applications are presented here.

Case 1. Critical Lifts in Congested Areas

In plant extension or renewal projects, replacement of the steam supply system components is one of the most critical activities. The steam supply system components are usually hundreds of tons in weight and tens of meters in height, and the site is often very congested. Detailed planning and preparations are important to ensure the feasibility of the operation. Common equipment used for installing these components include one large main lift crane and one or more tailing cranes.

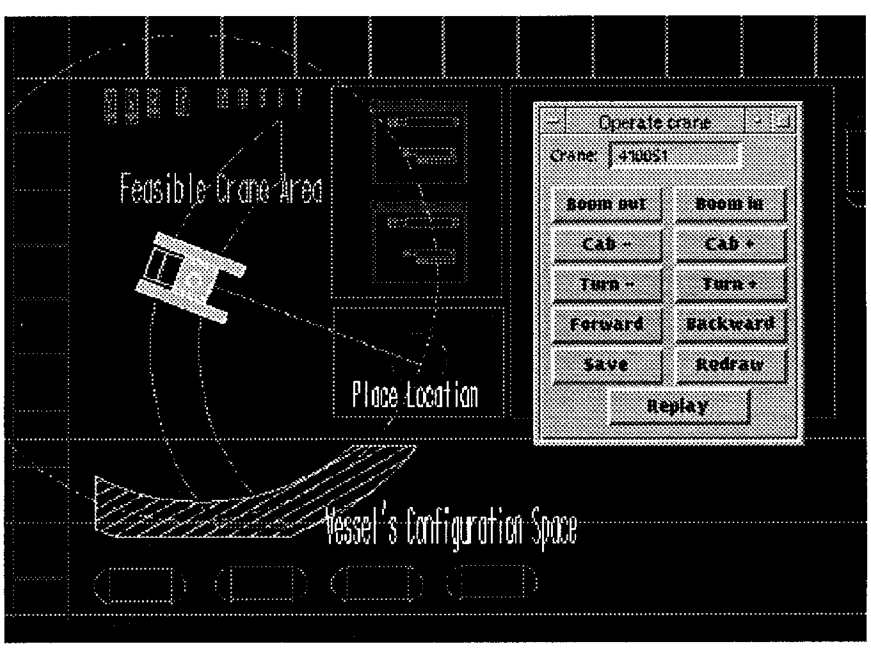


FIG. 9. Determination of Lift Path

J. Constr. Eng. Manage., 1996, 122(3): 212-222

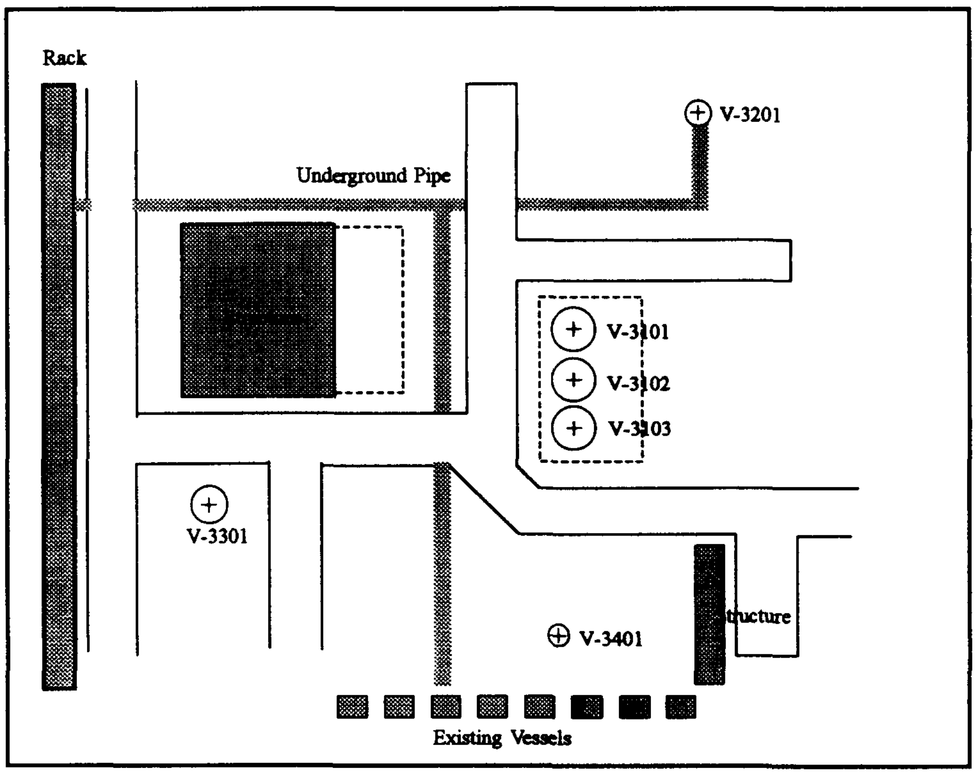
In general, cranes capable of such lifts are bulky in size; thus the spatial feasibility becomes the primary concern. Planning tasks include crane selection, crane placement location, uplifting method, and lift path including vessel pick location. The following case is used to illustrate the use of COPE.

A petrochemical plant near Houston, Texas was being renewed through an upgrading project. One of the major activities in this upgrading project was the replacement of a cylindrical Dresser-Rand compressor with a new, yet similar, compressor. The compressor weighed 131.67 t, measured 9.15 m in height and 4.58 m in diameter, and was located at an elevation of 20.74 m on the second level of a processing substation. This plant, first constructed during the 1960s, is very congested and has a narrow access route. Fig. 7 shows the layout of the construction area.

From the crane database, four different crane configurations are identified as possible alternatives. Crane work envelope analysis is used to test the feasibility of each alternative. Fig. 8 describes the nonlinear programming model for calculating a crane's maximum and minimum radii during the lift. Through feasibility analysis, only three alternatives are qualified. After optimizing crane location for each alternative, a safety indicator is calculated and cost factors are estimated (Table 4). Alternative 4 with a reaching capacity of 82.2% is considered a critical lift and is relatively difficult to perform. If safety is a primary concern, this alternative would be ruled out. Alternatives 1 and 2 are technically feasible while alternative 2 is slightly more reliable but would cost a little more. Fig. 9 shows an obstacle-free area for the vessel pick location (determined with the Boolean operations) and the planning session for determining a feasible lift path. A planner might now choose to simulate alternative 1 and/or 2 in three dimensions for detailed clearance analysis and communication with project participants.

Case 2. Multiple Lifts

Highly spatially constrained lift situations similar to that represented in case 1 are typical in plant expansion or rehabilitation projects. In new plant construction, congestion prob-



(a)

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

(b)

FIG. 10. Multiple Lifts Example

J. Constr. Eng. Manage., 1996, 122(3): 212-222

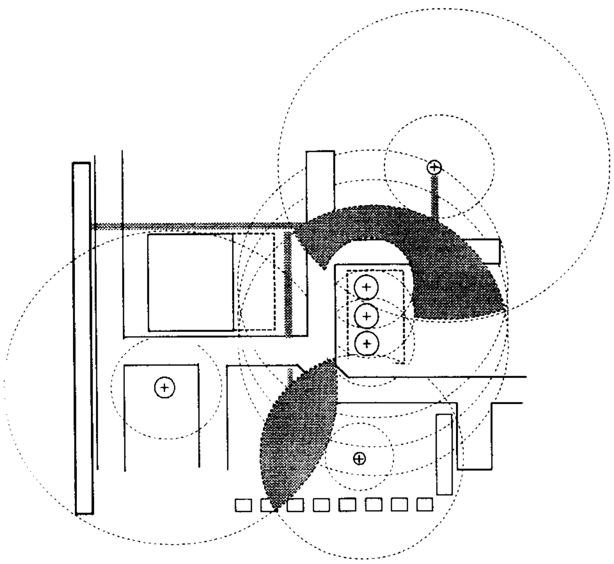


FIG. 11. Possible Crane Placement Alternative

lems are usually avoided by planning better construction sequences. However, another planning problem usually emerges. Multiple vessels are typically erected in new plant construction, so main cranes have to be relocated several times, or multiple cranes are required to complete the erections. Relocation costs include those of time, labor, equipment, and due to construction of extra foundations. Equipment foundation costs are often a major cost item in heavy lifts (Gosch, personal communication, June 26, 1994). Usually, it is possible to select a feasible crane placement location for erecting more than one vessel. Thus, the major planning concern 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 should be used if justified by project schedule constraints or penalties. COPE allows the planner to compare the related trade-offs. Fig. 10 illustrates one of these heavy lift situations with six vessels to be installed (modeled after the Brown & Root, Texas City project).

Using COPE, planners can evaluate different crane configurations as well as different crane placement locations for the lifts. Cost, safety, and efficiency can then be assessed to determine the optimum plan. Fig. 11 shows one of the possible crane placement areas. Since this is a complex and significant planning program, it is dealt with more thoroughly in Lin (1995).

Case 3. Concrete Placement in Building Construction

Concrete placement is a critical operation in building construction. It is labor-intensive, and it can involve large equipment. A typical concrete pump has an extended arm with three to seven degrees of freedom, and a reach up to about 60 m. During pouring, the pump is placed close to the placement area. A pumper positions the arm to the desired location. A hose operator then grips the hose to distribute concrete, and several concrete workers spread concrete with scoops, check slab thickness, and level the concrete. At each pump placement, the pump can cover areas within its work envelope. For a concrete pump to place concrete for a floor slab, it often has to be relocated several times to complete the entire floor, or several pumps are needed. Common steps in planning for concrete placement include scheduling and preparing the pour, determining the required placing boom reach and available equipment, locating the pump(s), and estimating total pouring time.

Using COPE, plans are recreated for a massive concrete pour in the Atlanta Federal Center that is documented in *ENR* (*ENR* 1995) (Fig. 12). The pour area covered a 106.75-m-long, 48.80-m-wide, and 2.135-m-thick monolithic slab which received more than 350 m^3 of concrete (354.66 m^3). Considering the pour area, amount of concrete, high quality requirements, and limited access in some areas, decisions on the number and layout of pumps used becomes complex. COPE can provide an efficient way for planners to try different combinations and layouts of pumps in order to determine a better plan.

Using COPE as a planning environment for this pour, planners would first model the site by specifying the required thickness of concrete at the pour area, and identifying obstructions and inaccessible areas on the site model. Then, planners

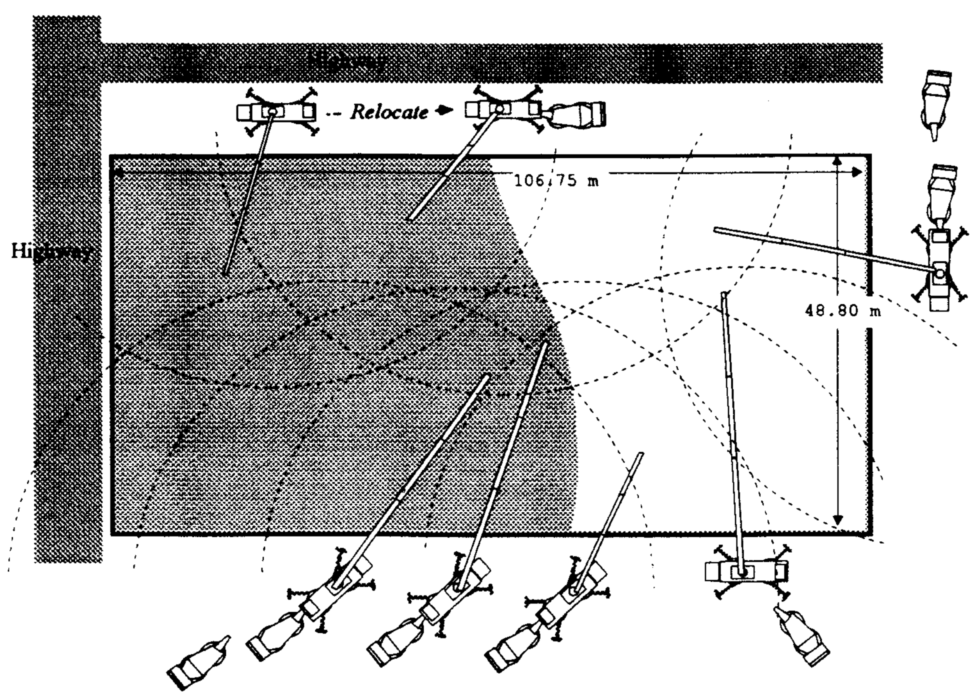
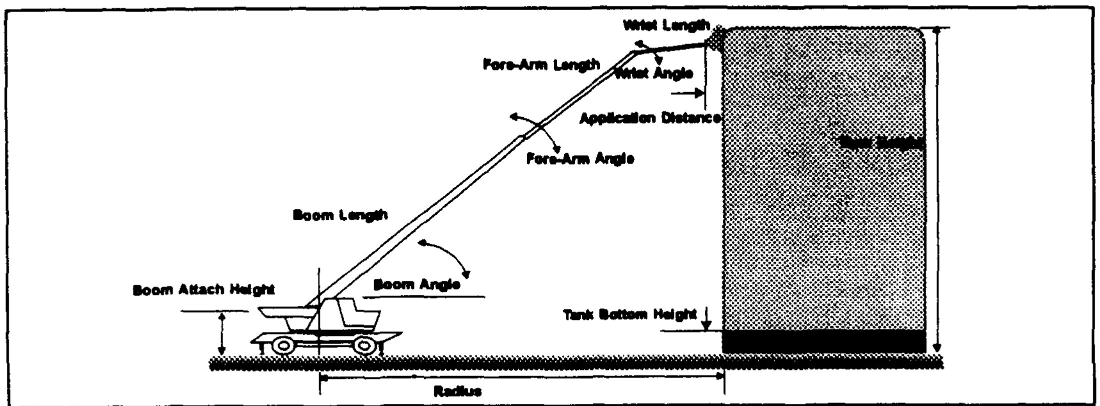


FIG. 12. Concrete Pour at the Atlanta Federal Center

J. Constr. Eng. Manage., 1996, 122(3): 212-222



Task Information:			
Max. Boom Length:	61.00 m	*Max. Wrist Length*	0.61 m
Min. Boom Length:	30.50 m	*Min. Wrist Length*	0.61 m
Max. Boom Angle:	89.00°	*Max. Wrist Angle*	75.00°
Min. Boom Angle:	-12.00°	*Min. Wrist Angle*	-75.00°
Max. Fore-Arm Length:	4.58 m	*Application Distance*	0.12 m
Min. Fore-Arm Length:	1.53 m	*Boom Attach Height*	1.22 m
Max. Fore-Arm Angle:	0.00°	*Tank Height*	45.75 m
Min. Fore-Arm Angle:	-75.00°	*Tank Bottom Height*	1.53 m
Desired Height:	**3.05 m**	to **45.75 m**	

FIG. 13. Task Information for the Surface Finishing Case

TABLE 5. Work Envelope Analysis for Surface Finishing Case

Solution variables (1)	Maximum value (2)	Solution variables (3)	Minimum value (4)
Boom length	61.00 m	Boom length	30.50 m
Boom angle	0.27°	Boom angle	6.86°
Forearm length	4.58 m	Forearm length	1.53 m
Forearm angle	0.00°	Forearm angle	−75.00°
Wrist length	0.61 m	Wrist length	0.61 m
Wrist angle	−0.22°	Wrist angle	68.12°
Maximum radius	66.28 m	Minimum radius	31.58 m

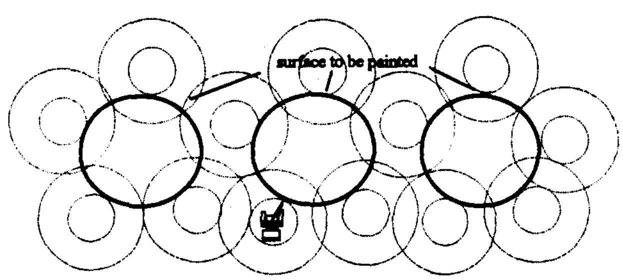


FIG. 14. Interactive Manipulator Placement for the Surface Finishing Case

would select pumps for the pour from the equipment library comprising equipment available in local fleets. Because of the large amount of concrete to be poured in limited time, several pumps are required. By examining the pouring capacity of the available pumps against the required concrete quantity per hour, planners select combinations of available pumps which meet total flow requirements. Planning primitives compute the work envelope for each pump, and planners interactively place the pumps with their envelopes in feasible areas. With the spatial-interaction planning primitives, planners can overlap coverage areas and simultaneously determine the pouring sequences. Planners estimate time and cost of the pour according to the pouring rate and leasing cost of the selected pumps. By further considering ready mixed concrete truck delivery and concrete finishing crew productivity, planners can develop a good complete plan for the pour. COPE provides an effective planning environment.

Case 4. Location Planning for Surface Finishing Manipulators

Potential applications of COPE include planning surface finishing operations which use large-scale manipulators (LSMs). Use of LSMs can improve safety, productivity, and environmental compliance. Several commercialized surface finishing manipulators have been used in the field (Nelco 1993; Sandroid 1993). Although commercial success is not yet proven, development is ongoing and is highly motivated by safety and environmental and productivity concerns (Hsieh and Haas 1993; Haas et al. 1995).

An articulated planning problem is to use the University of Texas (UT) LSM to finish the surface of three large petrochemical tanks. The task information is listed in Fig. 13. Similar to concrete pours, the manipulator has to be placed at several different locations to complete all three tank surface areas. The objective of planning is to locate the manipulator to minimize the number of placements to complete the designated task. The number and location of placement primarily depends on the work envelope of the manipulator, dexterity of the manipulator arm, area and geometry of the object surface to be serviced, and jobsite obstructive conditions. Manipulator kinematics models can be used to calculate maximum cylinder surface sections that can be reached by a particular manipulator with end effector attitude constraints. Such parametrically defined standard sections can be reduced depending on tank height, to simple 2D arcs or to closed manifolds for 2D placement planning. A nonlinear programming model considering various geometric constraints is formed in the work envelope analysis primitive, and the maximum and minimum radii are solved using the quasi-Newton numeric method. Table 5

J. Constr. Eng. Manage., 1996, 122(3): 212-222

shows the solution variables of the manipulator's work envelope. In this example, the number of relocations required can be quickly determined and cost and duration estimates can be performed accordingly (Fig. 14).

CONCLUSIONS AND RECOMMENDATIONS

Based on a systematic analysis of the characteristics of the planning problems for critical operations utilizing large semistationary equipment, a number of fundamental planning procedures and principles were formalized. An interactive computer-aided planning environment (COPE) was described, which implements these planning procedures and principles in the form of primitive planning functions and the model and methods underlying the environment. COPE can improve planner productivity and the value of resulting plans. It implements a relatively simple, practical, and inexpensive approach for planners to model, examine, communicate, and solve planning problems with large semistationary equipment.

The case studies described here illustrated distinct benefits of the procedures and principles developed. Measuring those benefits with more case studies, improving the procedures, and integrating COPE with existing commercial packages would be worthwhile future endeavors. Methods to assign rational weights to the performance measures should also be developed. Current research is addressing these recommendations.

ACKNOWLEDGMENTS

We would like to thank Donnie Gosch Sr. and Donnie Gosch Jr. from Brown & Root, and Mike Welsh from M. W. Kellogg for providing planning information and their personal expertise. We would also like to thank the National Science Foundation for supporting this study.

APPENDIX. REFERENCES

Beliveau, Y. B., Dixit, S. S., Dal, T., and Morad, A. A. (1992). "Multitask motion planning (MTMP) for material handling in construction." *J. Constr. Engrg. and Mgmt.*, ASCE, 119(1), 180–191.

Benckert, I. H. (1991). "Computer controlled concrete distribution." *Proc., 8th Int. Symp. on Automation and Robotics in Constr.*, Fraunhofer-Institute for Manufacturing, Engrg., and Automation, Stuttgart, Germany.

Bennett, C., and Ditlinger, S. (1994). "Bechtel automated lift planning system." *Robotics for challenging environments*, ASCE, New York, N.Y.

C. A. R.: Computer aided rigging manual. (1990). Brown & Root Braun, Houston, Tex.

Chalabi, F., and Yandow, C. (1989). "Crane, an expert system for optimal tower crane selection and placement." *Proc., Constr. Congr. I*, ASCE, New York, N.Y., 290–297.

Chen, L. (1994). "Automated path finding for crane lifts," Master's Rep., Univ. of Texas, Austin, Tex.

"Concrete today: concrete re-invents government center." (1995). *ENR*, 234(18), 48.

Craig, J. J. (1986). *Introduction to robotics.* Addison-Wesley Publishing Co., Reading, Mass.

Furusaka, S., and Gray, C. (1984). "A model for the selection of the optimum crane for construction sites." *Constr. Mgmt. and Economics*, 2, 157–176.

Gatlin, C. E. Jr. (1989). "Benefits of 3D CAD in the construction of power plants." *Proc., 1st Int. Conf. Fossil Plant Constr.*, A. Armor, ed., Electric Power Res. Inst., Palo Alto, Calif.

Gray, C., and Little, J. (1985). "A systematic approach to the selection of an appropriate crane for a construction site." *Constr. Mgmt. and Economics*, 3, 121–144.

Haas, C. T., Dailey, C., Greer, R., Kim, Y. S., and Thomas, G. (1995). "Feasibility study of alternative clinker clearing solutions." *Rep. Draft Prepared for Electrical Power Res. Inst.*, (EPRI), EPRI, Palo Alto, Calif.

Hsieh, T.-Y., and Haas, C. T. (1993). "Performance evaluation model for construction manipulators." *Automation and robotics in construction X*, G. H. Watson, R. L. Tucker, and J. K. Walters, eds., Elsevier, New York, N.Y., 301–308.

Hornaday, W. C. (1992). "Computer aided planning for construction heavy lifts," Master's thesis, University of Texas, Austin, Tex.

Hornaday, W. C., Haas, C. T., O'Connor, J. T., and Wen, J. (1993). "Computer-aided planning for heavy lifts." *J. Constr. Engrg. and Mgmt.*, ASCE, 119(3), 498–515.

Kunigahalli, R., and Russell, J. S. (1994). "Visibility graph approach to detailed path planning in CNC concrete placement." *Automation and robotics in construction XI*, D. A. Chamberlain, ed., Elsevier, New York, N.Y., 141–148.

Lin, K.-L. (1995). "A model for spatial planning of critical construction operations using large semi-stationary equipment," PhD dissertation, Dept. of Civ. Engrg., Univ. of Texas, Austin, Tex.

Mahoney, J. J., and Tatum, C. B. (1994). "Construction site applications of CAD." *J. Constr. Engrg. Mgmt.*, ASCE, 120(3), 617–631.

Nelco Manufacturing. (1993). "Porta shot blast: H-D-VE-100." *Product literature*, Oklahoma City, Okla.

Reinschmidt, K. F., and Zabilski, R. J. (1989). "Application of computer graphics in construction." *Proc., Constr. Congr. I-Excellence in Constr. Proj.*, ASCE, New York, N.Y., 137–142.

Sandroid System. (1993). "The sandroid system." *Product literature*, Boynton Beach, Fla.

Shapiro, H. I., Shapiro, J. P., and Shapiro, L. K. (1991). *Crane and derricks*, 2nd Ed., McGraw-Hill Book Co., Inc., New York, N.Y.

Varghese, K., and O'Connor, J. T. (1995). "Routing large vehicles on industrial construction site." *J. Constr. Engrg. and Mgmt.*, ASCE, 121(1), 1–12.

J. Constr. Eng. Manage., 1996, 122(3): 212-222