SightPlan Model for Site Layout

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Abstract: A model that uses artificial intelligence programming techniques is presented as a new tool for layout designers. This model, named SightPlan, represents the layout process as well as the layout product. A description of the knowledge and problem-solving method is given of the SightPlan system that mimics the actions of a human layout designer. SightPlan lays out temporary facilities, represented as rectangles, on a construction site, represented as a two-dimensional space. An early-commitment strategy and spatial constraint satisfaction techniques are used to find unique positions for facilities among those already in place. An example run in which SightPlan is applied to a case-study project illustrates how the program operates in stand-alone mode. SightPlan demonstrates that knowledge-based systems can successfully address problems not adequately modeled until now and, thus, opens up a new way of thinking about computer-aided decision support for the construction industry. The present system is a prototype, however. Additional work must be done before SightPlan will be ready for field use and useful to field practitioners.

Introduction

The allocation of space to temporary facilities on construction sites has received little attention in modeling due to the complexity of the problem, resulting in a lack of optimization models, and the perceived marginal benefits to be gained from performing this task better. Yet, it is a routine task for many site engineers and project managers, and it is obvious that a site's layout affects worker travel time, activity interference, and, thus, productivity. Better layouts do pay off, if only managers could afford the time and effort needed for designing them.

A characterization of the site-layout problem and a thorough review of field practice and existing models lead to an understanding of the strengths and weaknesses of existing layout tools, so that a better model could be proposed. Model developers can essentially follow one of two approaches. They can learn what people do, model what people do, and develop tools that support people in what they do. Alternatively, they can build tools that approach the problem in a manner different from what people do, and possibly solve the problem in some better way. The first typically is the objective of cognitive scientists; the latter of engineers. In either case, constructing a model is meaningful because it helps identify the important factors, formulate the problem, study the interaction between factors, and understand alternative solutions. In the work that is presented here, the first approach is adopted.

This paper describes a model that mimics how people lay out construction

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sites. Details on the artificial intelligence (AI) programming techniques that were used for coding it as a computer system are given elsewhere (Tommelein 1989, 1992). A site-layout model adopting the engineering approach is contrasted with the present model in Tommelein et al. (1991). The generality of the model is assessed in Tommelein et al. (1992a).

Problem Description

The layout of temporary facilities is a routine construction management task. Once facilities needed to support construction operations are identified and their size and shape determined, they must be positioned within the boundaries of the available on-site or remote areas to meet multiple constraints and objectives related to safe and efficient operations.

Examples of temporary facilities are office and tool trailers, parking lots, warehouses, fabrication yards or buildings, staging areas, and lay-down areas. Such facilities usually remain in place for a period ranging from some days to several months and sometimes years (the duration of a construction activity or a major construction phase) and are, therefore, called temporary facilities. Despite their name, some temporary facilities are not dismantled after project completion and, instead, are reused for maintenance facilities during operation. Conversely, parts of the permanent structure may be built early so that they can be used for construction purposes.

Good site layouts meet multiple, though often conflicting, objectives. For example, reducing travel time may increase congestion. Managers who set out to meet several objectives must therefore prioritize them (a nontrivial and highly subjective task) and apply their priorities in constructing a layout (for which, sadly enough, no generally agreed upon method exists).

Substantial amounts of money can be tied up in temporary facilities, but it is hard to attribute project savings or avoided costs directly to layout decisions. Even so, layout costs are typically charged to project overhead, so no one eagerly pays for them. This makes it difficult to convince management that layout is an essential and indispensable planning task.

Space needs during construction are governed by the construction schedule, construction methods, and contractors' mobilization and demobilization of materials, equipment, and personnel on site. This tight interaction turns site layout into a complex problem. Practitioners dealing with it typically limit its complexity by treating site layout as an isolated problem after many other decisions have been made. Consequently, opportunities to construct good layouts are often passed up and bad layouts are recognized only when problems have arisen.

For the same reason, the present work focuses on the two-dimensional spatial location of temporary facilities on site. This is only part of the site-layout problem. In fact, one may argue that the other parts (including the selection, sizing, and shaping of temporary facilities) cannot reasonably be ignored; but this strong assumption is commonly made in layout modeling.

Existing Models

Practitioners typically sketch the layout of temporary facilities at different points in time on the site-arrangement blueprint. Fig. 1 shows such a site arrangement of the permanent facilities, marked up to show temporary facilities. Practitioners use this single drawing and rarely update it as construction progresses. As many changes are likely to occur, the drawing will become less valuable.

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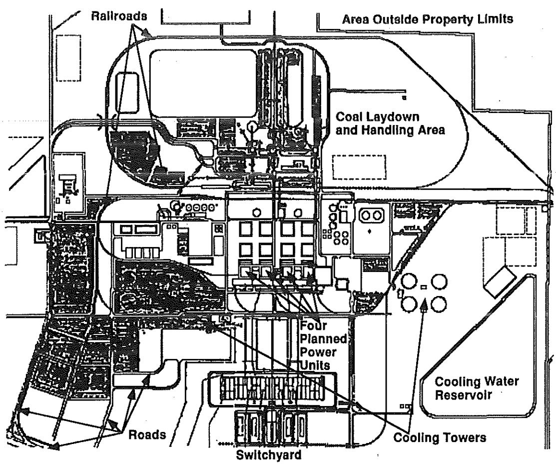

FIG. 1. Site Arrangement of Intermountain Power Project with Highlighted Long-Term Lay-Down Areas

The most popular aids for studying layouts are cut-out templates or other modeling blocks that people can move around to study space needs and assembly sequences (Henderson 1976). Many of the physical models have now been replaced by computer models (Rad 1982; Cleveland 1990; Reinschmidt and Zabilski 1990). Computerized product models have the additional advantage that they need not be limited to spatial representation; instead, they can be annotated and have more general functionality.

Other product models consist of anecdotal descriptions of specific site layouts (Tatum and Harris 1981; Weidemier 1986). These would be useful if more of them were available. At present, however, such descriptions do not provide meaningful, reusable layouts because they fail to elaborate on the specific context in which the layout applied, and one cannot gauge to what degree the subsumed knowledge is typical for the described or a new situation.

In contrast to product models, process models need no human assistance for generating a layout when given the appropriate inputs. Descriptive process models (Dressel 1963; Neil 1980, 1982; Popescu 1980; Rad and James 1983; Handa and Lang 1988, 1989) list facilities that may be needed, what types of steps a practitioner should consider in constructing a layout, while not specifying exactly which steps should be taken or in what order. This partial process specification is useful, yet insufficient to teach novices or program computers to become successful in constructing layouts.

Procedural process models typically involve heuristic construction or improvement methods (Francis and White 1974; Tompkins and White 1984; Kusiak and Heragu 1987). Although tested on construction applications, these operations-research (OR) type models are seldom used in practice (Rodriguez-Ramos 1982; Reinschmidt 1975). This is probably because they require large amounts of data about material flows between facilities and they are unrealistic in assuming steady-state conditions. Such data is difficult to obtain for operations where fixed travel paths may not exist and projects change over time as construction progresses.

There is a large discrepancy between tools and methods used in field

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practice and procedural models. Possible reasons why procedural models have not gained recognition in construction field practice include:

1. Expertise is required for selecting an appropriate model and formulating each layout problem. This expertise is quite different from field practitioners' know-how and may not be available, although knowledge-based systems can address this problem (Fisher 1984).
2. Substantial amounts of data are needed as input to these models. That information is not readily accessible to field practitioners, though it is possible to store vast amounts of generic or specialized data in a declarative system and make it available for multiple uses. In particular, this was advocated by Feigenbaum (1977) who coined the "knowledge is power" paradigm, and its usefulness has been demonstrated many times since. By pouring large amounts of domain-specific knowledge into a (computer) system, one can gain tremendous power and substantially cut the time to search for a solution, especially in cases where no effective, generic problem-solving algorithm is available.
3. Most mathematical models, implemented as black-box systems, follow procedures that are incomprehensible, counterintuitive, or questionable to users. More important, users cannot easily alter such models when the results are different from what they expect. They thus have to resort to a superficial tweaking of input data, that were not satisfactory to start with, to achieve the desired outcome. People resent situations in which they are held responsible for an outcome over which they have no authority. Woods (1986) identified the responsibility/authority double-bind by observing that when people refer to a human specialist, they generally pass on both authority and responsibility. If people are held responsible for a model's results, they should also have control over the selection and use of the model, even when this means that less-than-optimal models are thus preferred. Black-box models do not provide the practitioner with any means to gain insight into the process, nor do they allow the practitioner's intervention to make intuitive changes in order to lead to an acceptable solution, so practitioners oppose their use. The aim of much AI research has been to craft systems that are more transparent and easy to use. Rule-based systems have met this objective only in part. Ongoing research focuses on developing better interfaces and interruptible systems, so that users can interact with computers naturally and be in control.
4. If a user is forced into introducing many simplifications in order to be able to apply a model, it may take substantial effort to interpret the model's results within its broader context. The amount of effort spent may outweigh the value of the results.

Many of these are well-known shortcomings of procedural models and computer implementations (Vollman and Buffa 1966; Scriabin and Vergin 1975; Hollnagel et al. 1986). They explain why field managers prefer using simple, well-understood models to lay out sites over more abstract but potentially more powerful models. Keeping the limitations of existing models in mind, we set out to explore another modeling philosophy.

AI Modeling Philosophy

While existing tools help people construct layouts, they do not help model the human process itself of laying out a site. Modeling this process is desirable for the following reasons:

1. The quality and success of the process could be assessed, so as to allow for improvement, either in terms of the quality or quantity of input data, or in terms of the process itself.
2. Knowledge of the process could be made available to teach novices about site layout or to obtain feedback from managers now left out during the layout process.
3. When the process and all factors of importance are clearly stated, they could be taken into account in related construction-management decision-making.

These observations gave rise to the questions:

1. What are the logical steps that people take while laying out a site?
2. Do people have a systematic approach for laying out a site?
3. If so, is it possible to model this approach?

An AI-based approach to construction site layout was taken by Hamiani (1987), but a more sophisticated model is presented here. The present model, named SightPlan, mimics the layout process that people use and encodes the domain knowledge and heuristics they apply in this process (Tommelein et al. 1987a, 1987b).

SightPlan Model

Task Definition

SightPlan lays out about 25 facilities among approximately the same number of facilities that are in place. Each facility to be positioned is subjected to three constraints on average. As input to the system, all facilities are rectangular and specified by their dimensions or area, or by the facilities that they include as a grouping. In the latter case, it is part of SightPlan's task to dimension the grouping. Because space is abundant, all constraints on facilities' positions can be met, though not necessarily optimally. SightPlan's task is to determine the position(s) in two-dimensional orthogonal space of facilities relative to the site and permanent facilities, where they meet the imposed constraints.

Case Study

SightPlan's knowledge is modeled after two case studies. The Intermountain Power Project (IPP) and the model resulting from a layout protocol analysis are described in this paper. The American 1 Power Project (AM1) was used to validate the IPP model and to extend SightPlan's capabilities. More detail on AM1 is given in Tommelein (1989).

IPP is a coal-fired power plant designed for four units of 750 MW, two of which have been constructed. The plant is located in Delta, Utah on a site of about 1,850 acres (not including the area reserved for evaporation ponds) and provides electricity for Los Angeles, California. The project was planned by the Los Angeles Department of Water and Power (LADWP), the project manager. LADWP hired Black & Veatch architect-engineers (BV) for the design of the plant and contracted with Bechtel Construction (Bechtel) as construction managers. With 1,500 MW, constructed in a time span of six years, and at a construction cost of about $3.5 billion, this project is one of few of this size constructed in the 1980s. For more information on the successful construction of IPP, see (Boltz and Molinski 1987) and (Reinhardt 1987).

The following description is necessarily a simplification of the layout process as it was described by different parties. It captures the work of both the architect-engineers (AE) and the construction managers (CM) on IPP. Each party generated a layout design as needed for its specific task, so the result closely relates to the party's period of involvement and responsibility on the project.

Besides designing the permanent facilities, including power units, support buildings, permanent roads, and railroads, the AE laid out the temporary structures comprising warehouses, office buildings, first-aid facilities, entrance gates, brass alleys, security buildings, and management and labor parking lots. These are the buildings and support facilities needed for almost the entire duration of construction of the project, some of which would later be used for maintenance of the plant in operation. Of course, all structures associated with the construction workers' entrance to the site had to be grouped together. For practical reasons, many of the other long-term temporary facilities were clustered in the same area so that they would not cut up large open spaces on site that might be used by contractors for other purposes.

The AE also made rough estimates of needs for lay-down spaces for construction and anticipated their grouping on site. Accordingly, the AE extended the railroad and road grid to include construction railroads and roads. Upon completion of the design task, the AE produced the site-arrangement drawing, which was submitted together with a milestone schedule to the CM. As it turned out, the owners revised the scope of the project at the beginning of construction and decided to proceed with only two units instead of the planned four.

Part of the CM's task was to decide on the layout of the long-term lay-down areas for approximately 25 major contractors. The CM's lead mechanical coordinator was assigned to do this. Starting with the site-arrangement drawing, the CM identified all areas occupied with permanent facilities, all access roads, and all otherwise unavailable areas on site. From the site arrangement, the CM inferred which area the AE had anticipated for long-term lay down. Since unit 1 would go on-line before completion of unit 2, a section of the site to the southeast of unit 1 was reserved for plant operation and, thus, could not be used for long-term lay down. The area immediately surrounding the power units was kept open as a work area and for short-term lay down (the work area). A temporary railroad extension gave access to the southwest corner of the site, so all lay-down areas for contractor work on power units 1 and 2 would be concentrated in that so-called construction area. Contractors working on coal-handling facilities would be located in the coal storage area. Material lay-down for the cooling towers and circulation water piping would be located near the cooling towers.

For each contractor, the CM specified the needed area, identified access requirements, determined whether or not major pieces of material would need to be moved to and from the lay-down area, and established how critical the contractor's activity was. Based on this information, the CM ranked the areas by overall importance and picked the one ranked first to find an appropriate location for it on site. This meant determining in what area that lay down had to be (i.e., meeting a zoning constraint), determining whether or not the lay down needed to be adjacent to a railroad (adjacency constraint), and making sure that it did not overlap with roads or any of the fixed facilities on site (nonoverlap constraint). Finally, if several alternative positions remained that met these constraints, the CM satisfied the preference of the contractor to be as close as possible to the place of installation of the work in the permanent facility by picking the best (as-close-as-possible constraint, computed based on shortest distance) position from the remaining alternatives. Then, the CM repeated this process with the second contractor's lay down, and so on. The results of this process were finalized by highlighting and labeling areas on the site-arrangement drawing (Fig. 1).

Before the award of contracts, contractors bidding the job were told what area would be available to lay down materials on site, so they could plan their work and further subdivide their assigned areas to specifically accommodate individual needs. The aforementioned description is necessarily a caricature of the layout process applied at the IPP site, but it is what was implemented in SightPlan.

Model Description

SightPlan's model builds upon the blackboard knowledge-based system architecture for cooperative problem solving (Hayes-Roth 1985; Engelmore and Morgan 1988). *Blackboard architecture* refers to the structure and mode of operation of a specific type of computer program. Different implementations of this architecture exist, such as the BB1 architecture that was used for SightPlan (Hewett 1988).

The following analogy applies between the system's operation and the setting of a meeting at which a problem is to be solved. At any one time, different meeting participants (called knowledge sources) may suggest contributions to solve the problem that is stated on the blackboard (a common data structure), but only one participant at a time will get to make a change. To select one of several changes that may have been proposed at once, the moderator (called scheduler) gauges each participant's potential contribution against an explicitly stated problem-solving strategy. After determining the change that best matches the strategy's prescription, the moderator proposes to allow that change to be made. In addition, the user of the system can either agree with the moderator's choice, or disagree and propose an alternate change. The user has the final word on which change gets executed and effectively acts as another participant in the system.

SightPlan uses this mechanism of considering all possible actions at a cycle and selecting the best one in accordance with a strategy to construct layouts. To do so, it needs two types of knowledge. First, it must know which objects are to be positioned and which constraints they must be subjected to. Second, it must have a strategy.

The following project-specific data pertaining to objects and constraints on IPP is input to SightPlan:

- Major permanent facilities on site with their dimensions (rectangular in shape; possibly including some surrounding area) and location.
- Access roads and railroads with their dimensions and location.

- Long-term temporary facilities with their dimensions (location to be determined).
- Long-term lay-down areas with their dimensions (location to be determined).
- Constraints on the location of temporary facilities and lay-down areas relative to the permanent facilities and roads (e.g., constraints describe whether facilities need to be adjacent to a road or railroad, or which permanent facility a lay down must be close to).
- Zones that partition the site in smaller areas (including the work, coal, operations, and construction area).

The early-commitment strategy, learned from the AE and CM in the case study, is also input to SightPlan. This so-called expert strategy is encoded as a skeletal plan that prescribes the types of actions SightPlan ought to take and their sequence for layout of a power plant site. This strategy captures the strategic expertise of a field engineer who knows how to lay out such sites. In essence, it prescribes that one must start by identifying the space occupied by permanent facilities, that temporary facilities on site for the entire duration of construction should be positioned first, followed by shorter-term facilities, and that larger objects should be positioned before smaller ones. Thus, this strategy is not project-specific; it is rather general in that it can be used to lay out other construction sites as well. Fig. 2 illustrates this strategy's skeletal plan.

Table 1 lists some of SightPlan's actions while pursuing the expert strategy on IPP. Column 1 gives the system's execution cycle numbers. Column 2 outlines SightPlan's action corresponding to each cycle. In the remainder

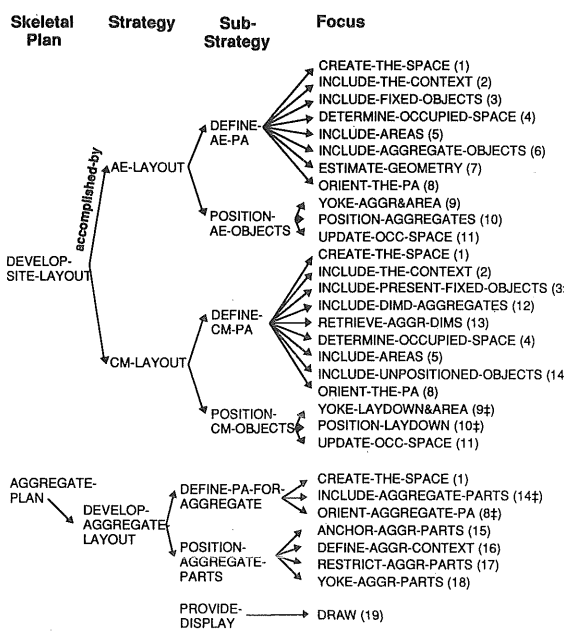

FIG. 2. Skeletal Plan of Expert Strategy Applied to IPP

TABLE 1. Some Cycles from SightPlan's Expert Strategy Applied to IPP

Cycle (1)	Action (2)
	(*a*) Architect-Engineers
14	create pa1
19	include context in pa1
24	include fixed objects in pa1
29–30	include and identify occupied space in pa1
34–37	includes areas in pa1
43	include first aggregate in pa1
44	size aggregate context
45	shape aggregate context
47	include second aggregate in pa1
48	select aggregate layout plan
55	create pa2
60–72	include object in pa2
77	orient pa2
82–136	anchor object in pa2
142	shape context pa2
145	transfer size from aggregate context in pa2 to aggregate in pa1
152	orient pa1
158–165	position first aggregate in pa1
167–175	position second aggregate in pa1
182–194	refine pa2
	(*b*) Construction Managers
14	create pa1
19	include context in pa1
24	include fixed objects in pa1
29	include and identify occupied space in pa1
33–36	include areas in pa1
40	include laydowns in pa1
44	orient pa1
50–136	position objects in zone or outside of zone in pa1
138–188	position objects so that they don't overlap with permanent facilities
190–293	position large objects first, with as close as possible constraints, then update occupied space and proceed with following object

of the paper, discussion is focused on a few specific cycles and actions. For a full description of the expert layout strategy, please refer to (Tommelein 1989).

During knowledge acquisition, we found that the AE and the CM each laid out part of the temporary facilities on IPP. This division of tasks is reflected in the layout strategy: the AE-layout precedes the CM-layout (Fig. 2 and Table 1). Many of the strategic steps of the AE, however, were quite similar to those of the CM. Identical numbers in parentheses following each focus in the skeletal plan reflect this apparent duplication of effort. Yet, the objects involved in the actions of the AE are different from those of the CM. For example, Table 1 reflects the same action for the AE as for the CM at their respective cycle 24 (include fixed objects in partial arrangement [PA]1). Fixed objects for the AE are the permanent power plant facilities; temporary objects for the AE are the warehouses and construction management office buildings that they design and also locate. Fixed objects for the CM, however, are the permanent power plant facilities as well as the warehouses and construction management office buildings located by the AE, whereas temporary objects for the CM are the long-term lay-down areas for contractors. The English-like sentences of the layout steps shown in Table 1 clearly describe SightPlan's actions.

SightPlan in Operation

Screen dumps illustrate how SightPlan constructs a solution. In parentheses are the cycle number and the corresponding action's description.

SightPlan creates a first partial arrangement (14—create PA1) and defines the boundaries of the space to be laid out (19—include context in PA1). The system then includes the fixed objects (24—include fixed objects in PA1) (Fig. 3). It identifies the groupings of objects, called aggregate objects, and includes them (43—include first aggregate in PA1 and 47—include second aggregate in PA1). Because these groupings do not have a shape nor dimensions, SightPlan must first take some steps to determine those, before the aggregates (IPP-construction-facilities and IPP-construction-entrance) can be displayed (Fig. 4). The substrategy that SightPlan calls to shape and size the IPP-construction-entrance groupings is shown as the aggregate-plan in Fig. 2, but discussing its operation is not done here. Interested readers can refer to Tommelein (1989) for more detail.

After that is done, SightPlan can position each of the aggregates in PA1 by sequentially meeting less stringent constraints, as is prescribed by its strategy (158–165—position first aggregate in PA1) (Figs. 4 and 5) (167–175—position second aggregate in PA1) (Fig. 5).

When the AE layout is complete, SightPlan uses the result as input for the CM layout. All facilities shown on the AE layout are now treated as fixed. (Before construction started, the project owners decided to build only two 750-MW units instead of the planned four. These actual units are shown as two black rectangles in Fig. 6, whereas Fig. 5 showed four.)

The CM starts by creating a new partial arrangement (14—create PA1), including the site boundaries within which they have to work (19—include context in PA1) and what they consider to be permanent facilities (24—

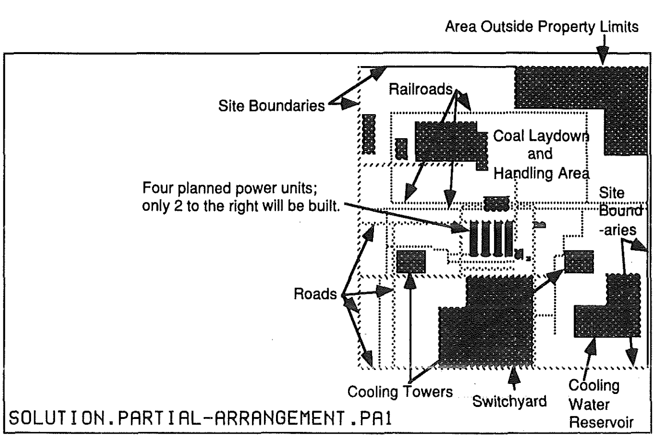

FIG. 3. SightPlan Includes All Permanent Facilities on IPP

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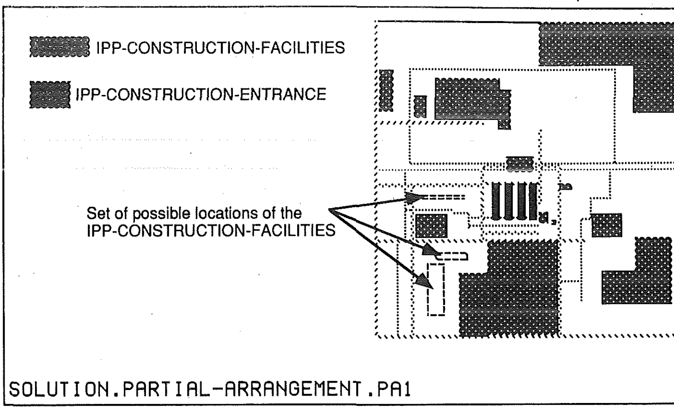

FIG. 4. Two Shaped and Sized Aggregates in PA1. IPP-Construction-Facilities Has Met All Constraints Except Preference Constraint as-Close-as-Possible to Power-Unit-1

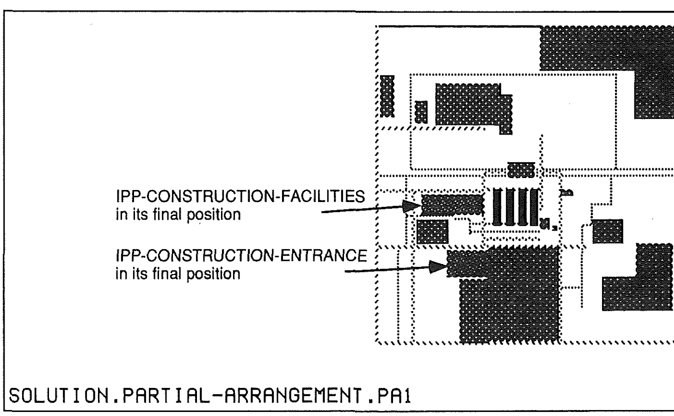

FIG. 5. SightPlan's Solution to AE's Layout Task on IPP

include fixed objects in PA1). SightPlan then zones the site into four areas (33–36—include areas in PA1) (Fig. 6):

1. The work area, immediately surrounding the power units, to be used for short-term lay down.
2. The coal area, where the coal-handling facilities are, to be used to locate all contractors constructing these facilities.
3. The operations area, located to the southeast of unit 1, to remain accessible at unit 1 start-up when unit 2 still is under construction.
4. The construction area, to the southwest of the site, where all contractors involved in construction of units 1 and 2 will be grouped.

SightPlan then includes temporary facilities (40—include laydowns in

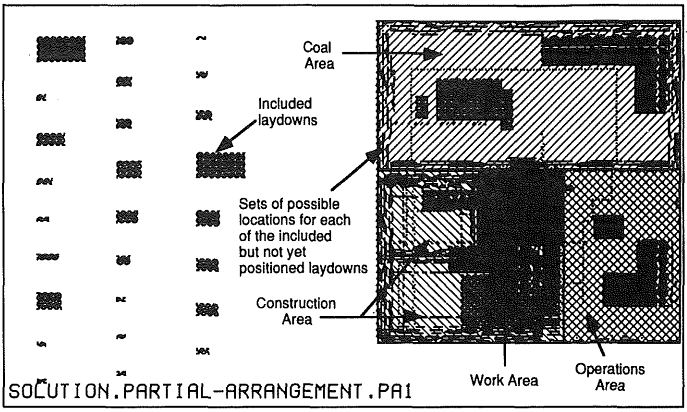

FIG. 6. SightPlan Zones Site in Four CM-Specified Areas and Includes All Lay-Downs in PA1 for Layout by CM

PA1) (Fig. 6) and positions each lay-down area in the appropriate zone (50–136—position objects in zone or outside of zone in PA1) (Fig. 7).

The program can then position each lay-down area by sequentially meeting less stringent constraints, as is determined by the strategy (138–188—position objects so they do not overlap with permanent facilities in PA1 and 190–293—position large objects first in PA1, with as-close-as-possible constraints, then update occupied space and proceed with following object). SightPlan stops when no more executable actions remain (Fig. 8). In this way, it has computed possible locations for each of the facilities that needed to be positioned and has thus satisfactorily completed its task.

Implementation

SightPlan is implemented in Common Lisp using BB1 version 2.1 running on a Texas Instruments Explorer. Its system code is available from the Civil and Environmental Engineering Department at the University of Michigan and from the Center of Integrated Facilities Engineering at Stanford University. A license to the BB1 development environment must be obtained from Stanford's Office of Technology Licensing.

Lessons Learned

SightPlan's Capabilities

The SightPlan model shows that it is feasible for a computer program to mimic the steps taken by a field practitioner for laying out a construction site. The model takes into account more factors than other construction site-layout models have done so far, including objects classified by type, spatial, and temporal characteristics, and constraints expressing requirements or preferences. SightPlan is in that sense a more realistic model than other models are.

SightPlan's operation is easy to follow not only by AI researchers, but also by field practitioners. This was empirically assessed by having the construction manager of IPP observe the program. It only took a short introduction to clarify the operation of the system and our manager could easily comment on the program during its run and critique its actions and the

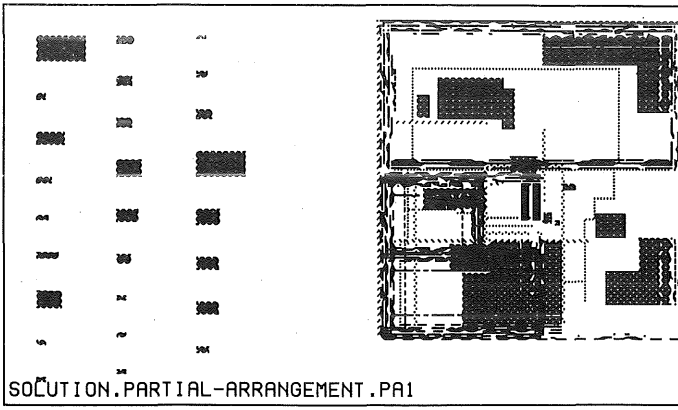

FIG. 7. All Lay-Downs Meet Their Zoning Constraints

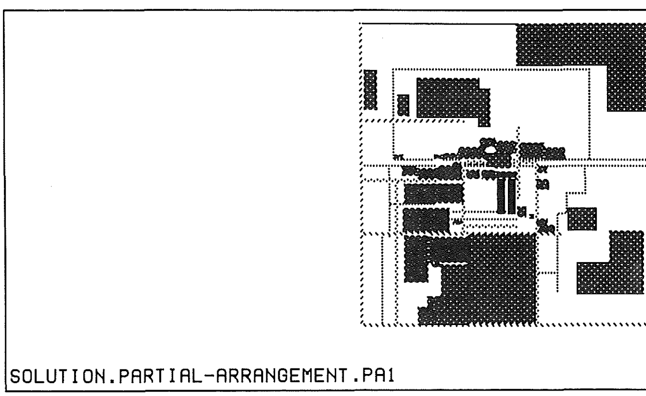

FIG. 8. SightPlan's Solution to CM's Layout Task on IPP

resulting layouts. The following step in assessing the transparency of the system is to have field practitioners use it. SightPlan's current implementation does not easily lend itself to that.

Clearly, SightPlan does not capture all expertise used by practitioners for addressing the layout task, and, in fact, that would be impossible. In particular, human's spatial reasoning, emulated by SightPlan as constraint satisfaction, is arguably modeled satisfactorily. When natural language can remain vague, SightPlan's constraints had to be forced into unambiguous spatial propositions. SightPlan's knowledge is different from that of human practitioners, who rely to a large extent on visual inspection and frequently use graphical and physical models for constructing and evaluating layouts. Early on in this work it became clear that a graphical display would be essential for debugging the program and communicating the layout to other people. Accordingly, the graphical display system was developed, of which screen dumps were used to illustrate this paper.

Beyond mimicry and unlike most other systems, SightPlan explicitly represents the practitioner's layout strategy, so the system knows what it is doing. The major advantage of this is that the strategy exhibits generality, to the extent that it can be reused to construct layouts for new sites. When the objects and constraints related to IPP are replaced by those on a new site, SightPlan's strategy will create a layout for the corresponding new problem. This was confirmed using data from AM1 (Tommelein 1989). Only minor changes were needed for the transferred strategy to be operational. The expert strategy is, thus, a first step towards articulating a strategy that could be applied on different projects and taught to novice practitioners.

The current implementation of SightPlan is nowhere close to outperforming field practitioners. For example, when supplied with all necessary data, IPP's expert took several hours, but less than a day, to lay out the site (more exact data is not available). Faced with the same problem, but likely supplied with less knowledge to take into account, SightPlan constructs its layout for IPP in about three hours. The program is slow, in part because it has not been implemented or optimized for speedy performance. Much intermediate data is kept around for process verification and analysis. While acquiring data is tedious and unavoidable in either automated or manual layout approach, crafting SightPlan's knowledge base takes additional time.

SightPlan's output (Fig. 8) can be compared with the expert's (Fig. 1). The layouts necessary look similar, as SightPlan's constraints reflect those specified by the expert. By virtue of ignoring a number of factors (such as site elevation and underground utilities), SightPlan's layout must be of inferior quality. Assessing the quality of any layout is difficult, however. If an evaluation procedure would be available to replace visual inspection, computer programs could explore more alternatives and potentially find better layouts than people could.

For SightPlan to become field-usable, it must be made both practical and readily available. Field practitioners may want to mirror their expertise in the model, in order to obtain a (perceived) knowledgeable assistant. Automated knowledge-acquisition tools (of which research prototypes exist) could aid them in creating knowledge bases. If SightPlan's strategy is not satisfactory, the user can override it by choosing alternate actions from the SightPlan agenda or using the graphical interface to narrow sets of positions (Tommelein et al. 1991). Learning programs (of which research prototypes exist) could then extract the user's strategy for subsequent automation (Confrey and Hayes-Roth 1990; Gans and Hayes-Roth 1990). Improving availability means reimplementing the system on hardware available on construction sites and optimizing its execution speed. These are both feasible.

Computer-based models for the site-layout process and product have potentially major advantages over other models, though. Computer programs can easily be updated by one or several sources as construction progresses and interface with other programs. The ability to maintain current site data (e.g., to reflect material delivery, construction execution status, and schedule changes) may tremendously improve materials management practice.

SightPlan's Scope

SightPlan's task-specific knowledge solves the carefully bounded layout problem and appears to be largely applicable to the underconstrained problems encountered at IPP and AM1. While it is useful for addressing the task at hand, it is insufficient for addressing other tasks. Additional or different types of knowledge would be required to deal with overconstrained site layouts such as those of downtown building construction sites or to allow reuse of space over time, taking into account the criticality of activities based on the construction schedule.

Field practitioners often recall parts of previous layouts and integrate such case-based knowledge into the solution process. SightPlan starts each solution process from scratch, and does not learn from previously successful (partial) arrangements, i.e, it does not perform case-based reasoning.

The present work focuses on the allocation of space to long-term facilities and ignores shorter-term facilities. This is not to say that short-term facilities are not important. In fact, assigning short-term staging areas is often crucial as delays directly impact the construction schedule. In doing layout, managers leave open critical areas for staging and equipment access. Explicitly, reasoning about the assignment of space over time that is needed to deal with mobile equipment, for example, is beyond SightPlan's current scope.

In summary, SightPlan exhibits the brittleness that most AI programs are blamed for. In fact, most procedural programs exhibit the same type of brittleness. However, SightPlan's implementation architecture has been used to successfully model other tasks. In addition, the opportunism that is innate in the BB1 architecture lends itself well to extending the system with additional knowledge sources to address increasing complexity. Expanding SightPlan's task in an integrated or distributed manner is thus possible.

Although it was stressed that SightPlan would gain power by knowing more about the domain of the task it tackles, its knowledge about power plant construction is not that domain-specific. SightPlan differentiates facilities based on, for example, their dimensions. Dimensions are a characteristic of objects in many domains and appear to be a fundamental concept in the layout task. As with many AI systems, however, SightPlan gains power by using a classification of objects according to their type, which is where the domain specificity is key. For example, all individual contractor lay-down areas belong to the same parent class lay-down areas. SightPlan's strategy uses this classification knowledge by referring to the class, rather than to individuals. In this way, the strategy remains unaffected when individual contractor lay-down areas of one, get replaced by those of another project. SightPlan could, thus, be applied to layout problems in other domains.

Modeling Philosophy

An issue not raised in this paper is whether the expert strategy is necessarily best for a computer system to follow. Clearly, this issue resurfaces every time a knowledge-based expert system is built, and one questions the quality and validity of expertise. One cannot assume that a descriptive knowledge system will lead to desirable results when it is used prescriptively. Thanks to the flexibility of SightPlan's implementation environment, alternate strategies could be tried that might better suit the available computational power. Experimentation led to such a strategy, using postponed commitment (Tommelein et al. 1991). A computer program need not commit to finding a single position of one object at a time before proceeding with the next object because it does not exhibit the same cognitive limitations as people. Instead, computers can easily keep track of sets of alternate positions, gradually constrain those, sample multiple positions after all hard constraints have been met, and generate combinations of satisfactory layouts. The postponed commitment strategy together with a graphical interface for users to change layouts interactively while solutions are constructed delivers proof of concept that we can build powerful decision support tools to assist field practitioners with layout design.

Conclusions

The allocation of space to temporary facilities on construction sites was identified as a task for which no good process and few product models exist. The discrepancy between tool availability and tool use was ascribed to the difficulty of identifying the appropriate tool to suit a new situation, the need for large amounts of input data for tools to be usable, the opaqueness of most tools, and the difficulty of realistically interpreting the solutions to highly tailored problems. To overcome some of these shortcomings and better understand what people do, the SightPlan system was implemented to mimic the actions of field practitioners laying out construction sites. The strengths of this model are that it not only closely approximates the practitioner's layout process and solution layout, making the model easy to follow, but it explicitly represents a strategy that can be reused to lay out other sites. The fully implemented model was tested on only two case studies, so further testing is needed to strengthen and validate claims of generality and practicality.

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