Site-Layout Modeling: How Can Artificial Intelligence Help?

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Abstract: Using the site-layout task as an example to compare existing practices and tools used in industry and research environments, this paper puts artificial intelligence (AI) modeling techniques in perspective. The site-layout task is characterized, field practice is described, and a thorough review of available tools for layout product modeling (including physical models and computer-aided design tools) and process modeling (using AI as well as operations research methods) is presented. A rationale is provided for why many such tools have failed to gain widespread use in the construction industry. Comparing the capabilities as well as the data and knowledge needs of computer programs with those of construction practitioners reveals a large discrepancy, which is also apparent when fitting the layout literature in a comprehensive table. This paper argues that AI-based systems can reduce this discrepancy by better matching model capabilities with industry needs, and, therefore, suggests that such models will become valuable decision-support tools for construction management.

Introduction

In the last decade, many models that use artificial intelligence (AI) programming techniques, including knowledge-based systems (KBSs) and expert systems (ESs), have been created. Several have been described in the construction management literature. Despite these systems' existence and continued efforts in developing them, the research community appears to remain ambivalent about AI's success. This is ascribed to three factors: AI's inability to live up to the high expectations and bold claims that were set forth, limited or inadequate reporting on successful developments (industry views the success or failure in developing a KBS as proprietary information), and mismatch between how people address the task versus how models represent it.

AI and ESs might have faced less skepticism had they been named differently. Acknowledging this naming problem, the term ESs is slowly being replaced by the less-threatening and more realistic term KBSs. While their original conceivers ambitiously set out to have computers perform a large number of human tasks within a short time, AI has experienced a fate similar to that of operations research (OR). The term OR was coined in the 1940s to include all modeling related to military operations. It has since come to mean models that represent the behavior of systems by means of numerical equations and constraints, to which mathematical techniques are applied to find solutions. Similarly, many of the AI systems built to date fall in a

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category of models that use declarative, categorized, and mostly nonnumeric predicates to represent a system, and the mathematics of logic to infer new facts or answers to the questions posed. This is the type of AI system that we are considering here. As research advances, our community is gaining a broader understanding of the tasks AI can address, and a new term will have to emerge to describe tasks that the technology developed under the name of AI cannot address.

It is worth noting that some researchers see the challenge of AI as modeling ill-understood problems that cannot yet be modeled. Accordingly, they exclude declarative logic systems, such as ESs, from the real AI, as these are now quite well understood. Their position is paradoxical in that they will never be able to implement a true AI system, as such an implementation implies the existence of a model.

Even those who read the literature, however, may not fully understand what is encoded in any given AI system and how it operates. Not only do developers have problems with communicating their systems' operation to users; among themselves they find it difficult to unambiguously describe their systems' architecture, capabilities, and application range. Much AI research remains enigmatic and few formal comparisons put in perspective what was really implemented at a level above the inference engine versus knowledge base or rule-based versus frame-based descriptions. Making code available to other researchers is one step forward, but few have the time to plow through others' codes or have the hardware to run it. A better way to convey the knowledge embodied in AI systems is to use knowledge-level descriptions, that is, descriptions of the structure, function, and behavior of systems that are much more abstract and only loosely related to the implemented code (Newell 1981; Balkany et al. 1991). When systems are characterized in this way, they can more easily be compared. This description method is only slowly getting formally established and gaining acceptance.

This paper addresses the third factor, namely that site-layout field practice and modeling capabilities have often been mismatched. AI-based systems could improve this match and, thus, become invaluable decision-support tools for construction management.

Site-Layout Task Description

Site layout consists of identifying the facilties needed to support construction operations, determining their size and shape, and positioning them within the boundaries of the available on-site or remote areas. Examples of temporary facilities are office and tool trailers, parking lots, brass alleys, change houses, warehouses, batch plants, maintenance areas, 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.

What temporary facilities are needed depends on many factors, including project type, scale, design, project location, and organization of construction work (Popescu 1978, 1980a, 1980b, 1981, 1986; Neil 1980, 1982; Handa and Lang 1987, 1988, 1989; Tommelein 1989). Some factors determine what facilities will be needed and how large they should be; others affect the facilities' location on site. While some selection and sizing decisions can be made before layout commences, the sizing and location tasks generally interact with one another. If not enough space is available on site, the size of facilities may be reduced to make them fit while still meeting their functional requirements. If space is abundant, facilities tend to expand in area although they may be restricted in number.

Space availability during construction is governed by the construction schedule, construction methods, and contractors' mobilization and demobilization of materials, equipment, and personnel on site. As a project reaches peak construction, the site is more congested and the corresponding layout is tighter. Even when space is abundant, there will be a high demand for prime space (prime space typically is the space immediately surrounding the facility under construction) as travel distances increase for accessing the facility from more remote locations.

Good site layouts meet multiple objectives. Some high-level objectives are to promote safe and efficient operations and to maintain good employee morale. Some low-level objectives, more easy to gauge, are to minimize travel distance and time for movement of personnel and materials, to decrease material handling time while increasing productive time, and to avoid obstructing material and equipment movement (Chandler 1978; Neil 1980; Parsons and Pachuta 1980; Popescu 1980a). More often than not, these objectives cannot be met simultaneously. For example, reducing travel time may conflict with decreasing congestion. Managers who set out to meet several objectives must prioritize them—a nontrivial and highly subjective task—and apply their priorities in constructing a layout—a task for which no generally agreed upon method exists either.

Because so many factors ought to be considered in laying out a site and conflicting objectives must be traded off, it is obvious that the preferences of the person responsible for the layout's design will greatly impact the decision-making process, and that one person's final layout will be different from someone else's. Empirical evidence suggest that:

1. The role played by the person doing the layout affects the layout. Handa and Lang (1987) found qualitative differences in layouts generated by general contractors, construction managers, and developers. This suggests that if one person were to assume each of these different roles, different layouts would be created because the objectives associated with each role vary.
2. A person's level of involvement with the project affects the layout. Whereas subcontractors are concerned with the detailed layout and internal organization of the area assigned to them, the general contractor or construction manager must consider contractor areas relative to one another and focus on major access roads, shared utilities, and so on.
3. The personal relationships between individuals making layout decisions and their authority within the organization affect the layout.
4. Even a single individual may choose one of several alternative strategies. According to Rad and James' (1983) survey, constructors commit themselves either to locating labor-oriented facilities (e.g., sanitary facilities, craft change houses, job offices) closest to the work site, followed by material-oriented facilities or, alternatively, to placing material-oriented structures (e.g., warehouses, storage areas, and lay-down areas) closest to the

work site. That choice of strategy may depend on the type of project. For example, companies working on nuclear power plants opt for the second strategy because quality assurance requirements impose strict inventory control.

While many implicit constraints and objectives complicate layout construction, evaluating and criticizing existing layouts is not any easier. The few formal guidelines that are available suggest that before visiting a site, managers make a list of the expected facilities and planning elements (Dressel 1963; Handa and Lang 1988), assign a maximum score to each facility for its ideal organization, group facilities by type, and give each type a weighting factor. During their site visit, managers should assign minus points to each facility based on its deviation from the ideal in terms of practicality, operability, and organization of the layout. Minus points combined with the weights then result in a measure of overall quality of the layout. Sadly enough, this approach is curative, not preventive. A bad layout is often recognized only when it is too late to avoid it, when the sole remedy is to replan during construction and compensate for unanticipated problems.

Substantial amounts of money can be tied up in temporary facilities. Popescu (1981) estimated that the cost of temporary facilities on power plants amounts to 10–12% of the direct cost of the project. (Note that Popescu's definition of temporary facilities is likely to be different from the definition presented in this paper.) As the cost for temporary facilities increases, one may expect that the potential payoff for better laying out the site increases, especially on larger and more remote projects. According to Handa and Lang (1989), a major purchaser of construction stated that for every dollar committed to preplanning, a savings of between \$4 and \$8 is realized by the completion of the job. Layout is, of course, only one cost item of preplanning. Yet because layout is a tightly intertwined part of the construction management process, it is hard to attribute project savings or avoided costs directly to it, and because layout costs are typically charged to project overhead, no one will eagerly pay for them. This makes it difficult to convince management that layout is an essential and indispensable planning task.

The allocation of space to temporary facilities on site is a routine, but not an easy, construction management task. In fact, so many factors need to be taken into account in coming up with a good layout plan—making it a complex task—and so many people are involved in realizing or changing the layout in the field—making it difficult to adhere to the planned layout—that managers do not want to devote too much of their time to it. For the required effort, they perceive that only marginal benefits can be gained by performing this task better. Site layout tends to be considered secondary to planning, scheduling, resource allocation or leveling, and budgeting. Time-cost trade-offs, for example, seldom consider space availability. Yet, it is obvious that a site's layout affects worker travel time, material movement costs, activity interference, and, thus, productivity. The availability of site space is key to deciding on alternative construction methods, choosing between prefabrication or in situ construction, and making other management choices. Better layouts do pay off, if only managers could afford the time and effort needed for creating them. To reduce such efforts, simplifications must be introduced to make the layout task cognitively as well as computationally tractable. This is the case in practical situations as well as in theoretical approaches for modeling site layout.

Field Practice

If a layout is planned at all, this is typically done by a project engineer or superintendent. A field manager is chosen because such a person can take full responsibility for implementation of the layout plan. Since site layout is only one of the tasks addressed in construction management and consideration of all the factors affecting the selection, dimensioning, and location of temporary facilities is not humanly tractable, field managers have adapted their layout approach to deal with this situation.

1. They postpone addressing layout issues until a project's design and milestone construction schedule have been determined, so information contained therein can be treated as input to the layout process. Site layout is often a preplanning task, following substantial completion of design drawings, after civil works (e.g., clearing and grading of the site or excavating and installing foundations for the project) have already commenced, but before construction of the project gets too far along. The field manager then has access to project specifications, schedules, site arrangement drawings showing the permanent facilities, contract documents, and other information about the construction processes, methods, and resources to construct the site layout. Such a sequential treatment of the design, scheduling, and layout tasks is practical, but obviously prevents constructibility feedback from being given by the layout designer to the architect/engineers and other construction managers. More integrated approaches are feasible and are used, for example, on turn-key projects.
2. Field managers extract the main variables from those considered less relevant, so that the problem can be formulated concisely. As the construction schedule dictates which facilities will be needed on site for certain time intervals, longer-term facilities can be laid out before shorter-term facilities. We designate by long-term facilities those that are on site for almost the entire duration of construction of a project and that rarely change location (examples are management offices and parking lots). Medium-term facilities are on site for a major construction phase and also rarely move (examples are major lay-down areas for a subcontractor). Short-term facilities are on site for comparatively short time spans or change location frequently (examples are staging areas as well as spaces occupied by construction equipment). Prime space is usually left open until being assigned for staging facilities or equipment shortly before their use. Expensive, hard-to-move, and time-critical facilities or equipment are positioned first.
3. Field managers divide the global problem into more tractable subproblems and initially ignore possible interactions between variables or subproblems to reduce complexity further. Managers divide available space up into smaller areas, and delegate the task of laying out contractor areas to the contractors themselves. They group and arrange facilities separately, before positioning the group into the overall arrangement. Typical examples of isolated subproblems are rigging studies (Rodriguez-Ramos and Francis 1983; Furusaka and Gray 1984; Gray and Little 1985; Warszawski 1990; Bohinsky and Fails 1991), consisting of the careful selection and positioning of major pieces of equipment engaged in critical construction activities such as making major lifts. The high cost of such activities and their potential for delaying project completion warrant careful analysis.
4. Field managers reason about the decisions to make; once made, they

are rarely changed during further problem solving. This approach is called early commitment. Once they commit major facilities to a location, they do not modify or even question these locations when positioning facilities considered less important.

5. Field managers use tools like pencil and paper, icons and templates, scale models, and mathematical models to help visualize, inspect, and evaluate the layout during its development. They sketch in the process of generating the arrangement, before drawing the final plan, and move around templates to test whether particular arrangements will fit. They rely on trial and error and use partial layouts from previous job sites for constructing layouts that meet a project and its site's requirements.

Layout designers typically summarize the result of their effort on a single site arrangement drawing. They use this drawing throughout construction of the project but rarely update it as construction progresses. Because so many changes take place over time, updating to keep track of all facilities, especially those that move around on site, is too much work for not much return. This single drawing, however, contains information regarding facilities on site at successive time intervals; it is really a superimposition of several drawings, each pertaining to a different period. For example, the drawing may be a marked-up site-arrangement blueprint showing the permanent facilities at project completion and at the same time showing major excavations needed for installing building foundations. It may show how areas, excavated at one time and backfilled later, are subsequently used for material lay-down areas during yet another phase of construction. Any person who is to interpret such a drawing needs good spatial and temporal conceptualization skills. Visual aids and more formal layout models can facilitate these visualization and interpretation tasks.

Formal Models

Two types of models assist field managers with laying out construction sites. Product models display a layout and its parts. Process models represent or implement methods to generate a layout.

Product Models

Physical or graphical models make it easy on viewers to visualize components of the problem input or the solution output. Examples of models of facilities delineating or occupying physical space are icons, drawings, sketches, templates, and two- or three-dimensional scale models.

Drawings are common visual aids in construction, easy to create and distribute with minimal tools. Templates, like drawings, are easy to generate at low cost. Unlike drawings that become part of the project records, they are not valuable enough to be retained after serving the purpose for which they were made. Templates are mostly used in the trial-and-error process of fitting pieces together in order to achieve satisfying layouts. This approach is very popular, probably because the person who is moving templates around has the feeling of being literally in close contact with the objects to be located. Realizing their popularity and usefulness, Rad (1982) implemented templates representing temporary facilities in an interactive computer program allowing its users to select them and move them around.

Saved site arrangement drawings showing temporary facilities or anecdotal descriptions of layouts used on actual sites [e.g., Tatum and Harris

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(1981) and Weidemier (1986)] would be useful if more of them were available. Projects and layouts could then be classified in case bases and statistically correlated. At present, however, such layout descriptions cannot be reused for new projects as they fail to provide enough background knowledge on the context in which the layout applied. Moreover, one cannot gauge to what degree the subsumed knowledge is typical for the described or new layout.

Although visual aids help a person explore possible alternate solutions, they do not give any guidance toward which alternatives to pursue. Nor do they help a user remember which arrangements were previously generated unless pictures of the evolving layout are taken. The problem-solver's method for reaching a solution is not captured by these models at all, because physical models lack the behavior necessary to achieve this.

Three-dimensional scale models have an advantage over other physical models in that they represent to scale more spatial relations between the modeled parts. According to Henderson's (1976) survey, few of industry's standard-scale three-dimensional models are used to study the layout of temporary facilities, however. But three-dimensional models form impressive displays and are particularly well-suited for modeling permanent facilities such as complex industrial projects where electrical conduit, heating, ventilation, and air-conditioning (HVAC) ductwork, and other piping may interfere. Designers and construction engineers, who conceptualize what the final constructed product looks like, study the model and determine how its components might be assembled to fit. Because they are made of distinct parts, physical models lend themselves well to modeling construction as an assembly task.

Tangible three-dimensional models are often so expensive that only one of a specific kind is made. If more than one kind of physical model is developed, consistency maintenance becomes a serious problem when each model is modified independently. Consequently, only a limited audience can be allowed to access and modify them. The party that has access is not always the one who can best use the models, however. Architects and designers like to hold on to their models until design is completed, thus, preventing construction from using them when they are most needed to plan their work. Moreover, because such models are fragile, they must be protected (for example from being taken apart and reassembled in construction sequencing studies) and, thus, cannot be exploited to their full potential.

In the last 10 years, physical product models have been phased out and replaced by computer-aided design- (CAD-) based wire frame and solid models. Computer modeling techniques have overcome many limitations of physical models and are nowadays widely used in major construction and engineering companies for permanent layout, siting, and construction sequencing studies. Examples of the many well-known CAD packages are Bechtel's WalkThru (*3D* 1988; Cleveland 1990), Black & Veatch's POWRTRAK, and Stone & Webster's integrated system (Zabilski and Hall 1989; Reinschmidt and Zabilski 1990) that ties together three-dimensional graphics packages and engineering data bases. The writers suggest that they also be used for the material, temporary facilities, and equipment layout on site.

Product models need not be limited to graphical or spatial representation. They can be augmented with technical annotations, or, conversely, technical prototype plant descriptions can be accompanied by spatial representations.

Such knowledge is often available in larger construction companies where several projects of the same type have been engineered and constructed [e.g., *Reference* (1978)] and experience could be compiled. Prototype knowledge can then be refined to suit new design requirements. To the writers' knowledge and surprise, few such parametric models have been computerized and even fewer contain knowledge related to the layout of temporary facilities.

Construction field practitioners use graphical and physical models for layout generation because these are easily recognizable and manipulable representations. They seldom use process models.

Process Models

Process models represent a method that is applied to input data in order to generate a solution. The data representation need not be pictorial.

Some process models are descriptive (Handa and Lang 1987, 1988, 1989; Rad and James 1983; Neil 1980; Popescu 1980a). They list what types of steps or facilities a layout designer should consider in constructing a layout, but they are incomplete in that they do not mention exactly which steps need to be taken or in what order they should be taken. Although this is useful, it is insufficient: novices cannot be taught or computer programs implemented with this knowledge and be successful in constructing layouts.

Other process models fully prescribe methods for generating layouts. Depending upon which factors are taken into account, one can distinguish location from layout problems. Location problems abstract the objects to be positioned to points, thus, ignoring their dimensions because they are negligible compared to the distances in between objects. Insufficient space is generally not an issue in location problems, because these kinds of arrangements are very loosely packed, or individual objects (e.g., tower cranes) are singled out at the expense of others. Optimal generation methods were found appropriate to deal with single facility location problems. For example, in construction site layout, the location of a concrete batch plant, a single crane, or a haul road may be computed by such a method (Gates and Scarpa 1978; Maher and Stark 1981; Rodriguez-Ramos 1982; Rodriguez-Ramos and Francis 1983; Stark and Mayer 1983). Warszawski (1973) and Warszawski and Peer (1973) applied optimization and suboptimization methods for locating facilities such as a concrete mixing plant and a center for cutting and bending reinforced steel among facilities with known position on site.

Layout problems represent the objects to be positioned by their area molded in a (usually standardized) shape. For example, a layout problem may consist of locating and fitting rectangular objects close or adjacent to each other, or tightly packing them within a contour. Traditional methods for dealing with layout problems are reviewed in Francis and White's (1974) standard work on layout and location methods and Tompkins and White's (1984) book on facilities planning. A review of available computer systems is given by Driscoll and Sangi (1986) and a thorough mathematical characterization of layout process models in done by Kusiak and Heragu (1987).

In its typical mathematical formulation as a quadratic assignment problem, laying out facilities is NP-complete, which means that no algorithm exists that can guarantee to solve any kind of layout problem in polynomial time (Garey and Johnson 1979). In spite of specialized models that address particular subclasses of the general layout problem, there are only a few algorithms that promise to optimize, and they do so only for fairly unusual

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situations. Most models are, therefore, heuristic. They use a spatial representation tailored to suit procedural transformations of layouts. The space and objects to be laid out tend to be two-dimensional, although there are exceptions (Johnson 1982; Bozer et al. 1991). Objects are composed of unit areas or have a rectangular shape; again, there are exceptions (Eastman 1972, 1973, 1975; Pfeffercorn 1975; Rad 1982), and some models even allow objects to change in shape during problem solving.

The two best-known heuristic methods for solving layout problems are improvement and construction (Moore 1980). A third method involves graph representations.

Improvement methods start from an initial, complete layout, generate alternate layouts by swapping places of objects, rate the alternate layouts according to some evaluation function [e.g., Moore (1971)] and proceed with the alternate layout until no more improvement is attained. The earliest models were developed by Muther (1961); Armour and Buffa (1963); and Buffa et al. (1964); an improvement model was applied in construction by Rodriguez-Ramos (1982). Although distinguishing good from better solutions, methods that monotonically improve layouts (i.e., hill-climbing methods) do not guarantee that the best solution will ever be reached. The iteration may end at a local optimum depending on the initial layout and the generation of alternates. A possible way to overcome local optima is to allow for an occasional decrease in value of the evaluation function, which is done in simulated annealing for instance (Kirkpatrick et al. 1983; Meller and Bozer 1991). Alternative heuristic methods relax constraints during problem solving or choose not to meet all constraints.

Construction methods select object(s) for placement (for example, based on decreasing size), place the candidate(s) according to a placement criterion (e.g., desired closeness, minimum material movement, or transportation cost), and repeat these steps until all objects are positioned. Probably the best-known traditional implementations of construction procedures are CORELAP (Lee and Moore 1967) and ALDEP (Seehof and Evans 1967). These programs fall within the class of OR methods. Other implementations for layout fall within the class of AI methods that are often termed knowledge-based systems. AI methods were investigated in the early 1970s by Eastman and others (Eastman 1975). Benefitting from advances in ES and KBS technology, it continues to be of high interest today. Work on knowledge-based facilities layout by Yoshida et al. (1986), Andre and Porcheron (1986), Baykan and Fox (1987), and Flemming et al. (1989), and on construction site layout by Hamiani (1987), Hamiani and Popescu (1988), and the present work on SightPlan (Tommelein et al. 1987a, 1987b, 1991; Tommelein 1989) attest to this continued interest.

A third method, based on graph theory, starts by representing adjacency relations in a bubble diagram and applies heuristics to transform this graph into a two-dimensional layout [e.g., Whitehead and Elders (1965), Foulds and Robinson (1963); Foulds et al. (1985); Foulds (1983); Roth and Hashimshony (1988)]. The main difficulties in this approach are obtaining the planarity of the graph so that the existence of a layout can be guaranteed, and expressing more than only adjacency in the graph. This method is taught to architecture students for facility design, but has not been used for construction site layout.

Though tested on construction applications, OR-type process models are seldom used in practice (K. F. Reinschmidt, personal communication, Dec. 1986). 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 facilities change over time as construction progresses. In summary, OR-type process models were unsuitable for construction site layout 15 years ago, and no substantial advances have been made since for newer models to be more suitable.

This enumeration of references and types of models is necessarily incomplete as new models using different assumptions are constantly emerging, but further extending this review falls outside of the scope of this paper.

STATE OF THE ART IN LAYOUT MODELING: SUMMARY OF LITERATURE

Fig. 1 categorizes selected pieces from the literature on field practice and theoretical layout methods, based on two criteria. First, the topics of publications vary by degree of specialization. Accordingly, the corresponding problem-solving methods are more or less domain-specific. Papers that describe a particular power plant are shown at the top level of the chart, those that reflect company practice are shown at the second level, those that explain more general approaches applicable to any kind of construction site layout problem are shown at the third level, and those that describe work pertaining to any kind of layout are shown at the bottom level. The spectrum includes papers describing case studies (Tatum and Harris 1981; Weidemier

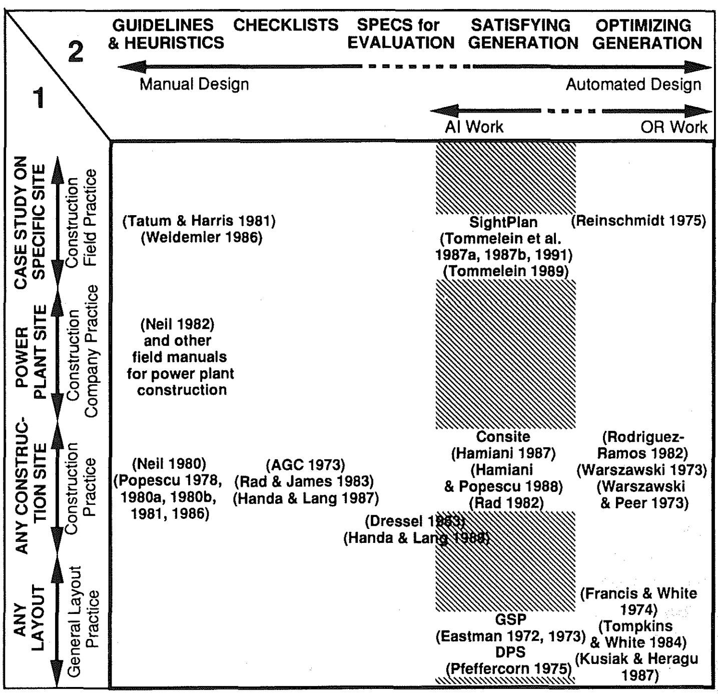

FIG. 1. Literature on Site Layout Charted by (1) How General or Domain-Specific Described Work Is, versus (2) Whether Described Method Applies to Manual or Computerized Layout Generation

1986), manuals for field construction operations (Neil 1982), teaching guidelines (Neil 1980; Popescu 1980a), articles recommending layout practice and pointing out issues that need to be addressed (Popescu 1978, 1980b, 1981, 1986), and papers and books that describe generic layout methods (Eastman 1975; Francis and White 1974; Tompkins and White 1984; Kusiak and Heragu 1987).

Second, some methods lend themselves better to automated computation than others do. Fig. 1 shows our qualitative assessment of this. In the left column are abstract guidelines, heuristics, or recommendations for people who lay out sites. In the center column are papers that specifically address facilities requirements and manual layout evaluation. In the right column are descriptions of methods to be implemented on computer. AI work, using symbolic, logic-based mathematics to mimic human behavior, is distinguished from OR work, using numerical mathematics to prescribe satisfying or optimal solutions. Yet, the two types of work cannot unequivocally be separated, as both include so-called heuristic methods that could be classified either way. This spectrum spans project studies and field manuals describing concerns in site layout (Tatum and Harris 1981; Neil 1982), checklists to help select temporary facilities (*Associated* 1973; Handa and Lang 1987; Rad and James 1983), criteria to assist field managers in evaluating site conditions (Dressel 1963; Handa and Lang 1988), approaches to stepwise construct layouts (Hamiani 1987), and optimization routines (Warszawski 1973; Warszawski and Peer 1973; Rodriguez-Ramos 1982).

The cross-hatched rectangle in Fig. 1 marks the gap between field practice (shown to the left) versus formal optimization methods (right), and domain-specific (top) versus generic layout methods (bottom). Possible reasons why optimization models have not gained recognition and use 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.
2. A substantial amount of data is needed as input to these models. That information is not readily accessible to field practitioners.
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 one is held responsible for a model's results, one 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 get insight into the process, not do they allow the practitioner's intervention to make intuitive changes in order to lead to an acceptable solution; so practitioners oppose to their use.
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 on simplifying and interpreting may outweigh the value of the results.

The tradeoff between domain-specific versus generic layout methods has been characterized by Feigenbaum (1977) as the knowledge-is-power paradigm. By encoding large amounts of domain-specific knowledge in 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.

Many of these are well-known shortcomings of formal optimization models and computer implementations (Vollman and Buffa 1966; Francis and White 1974; Scriabin and Vergin 1975; Hollnagel et al. 1986). Because of these, field managers prefer using simple and well-understood models to lay out sites, over more abstract but potentially more powerful, provably sound, and complete models. With the limitations of existing models in mind, the AI modeling philosophy is brought into the modeling arena.

AI Modeling Philosophy

Numerical optimization for solving layout problems has focused researchers' interest on well-defined, isolated problems, often of limited scope that proved to be solvable. Early on, it was recognized that many practical problems either were too complex to be modeled in such a way, optimization methods were not computationally feasible, or optimization criteria were found to be unsatisfactory. Consequently, people resorted to heuristic methods and took satisfaction with suboptimal solutions to their carefully tailored problems.

Accepting satisfaction instead of optimality of solutions, one need not restrict oneself to addressing only narrowly tailored problems, and instead can look at broader problems to start with. This is a premise for AI researchers who build models for integration [e.g., Fenves et al. (1988) and Howard et al. (1989)] or synthesis problems (e.g., plan generation) that have not been addressed before. This notion also sheds a different light on the reasons for optimization model failure, and, accordingly, the following guidelines for developing alternative models are presented.

1. Build systems that help select appropriate models.
2. Build full-fledged and reusable knowledge bases to capture large amounts of domain-specific knowledge and make such knowledge bases available throughtout and across organizations.
3. Make models transparent, so that people can closely observe the problem-solving process. Make models interactive, so that people can make desired changes. Make the models' processes interruptible, so that changes can be imposed from the outside and taken into account by the system at run time.
4. Build general frameworks that can handle many tasks and internally take care of the problem formulation, or build interpreters to clarify system output.

These types of systems cover much of the research in AI conducted today, but the following discussion pertains specifically to the capabilities of AI-based layout models. Examples from Fig. 1, Eastman's General Space Planner (GSP), Pfeffercorn's Design Problem Solver (DPS), Hamiani's Consite, and Tommelein's SightPlan, are used as illustrations. All of these systems are AI systems because they attempt—more or less truthfully—to mimic the layout task performed by human designers. [Another view on AI is cast by Fisher's (1984) FADES system, addressing a task that is one step removed from designing layouts. FADES mimics a person who needs to select one of the available OR models for layout design. It helps its users prepare data, select the appropriate layout algorithm based on problem characteristics, and interpret results. FADES functions as a pre- and postprocessor of data. It does not make the layout process transparent as it calls upon existing algorithms to perform the layout, but it does address items (1) and (4) listed previously.] The contributions of AI to layout product and process modeling are discussed next.

First, large amounts of knowledge or data are typically made available in AI systems or in data bases linked to AI systems. These may be encoded as knowledge bases (SightPlan, Consite), classifying facilities that appear on construction sites, constraints between them, and typical sizes of such facilities; or detailed descriptions (such as case bases) of layouts used on past project sites. Describing facilities by using natural language such as English instead of cryptic variables makes AI systems more easy to browse and understand even by novice users. English-like descriptions can then be incorporated in natural-language explanations describing a system's state at run time. Moreover, knowledge can include details that are quite domain-specific. Together with a sound classification system and fast query routines, such knowledge-intensive systems then make problem solving easier and produce tailored solutions. With progress being made, AI systems have gradually become more domain-specific (they move upward in Fig. 1) and more powerful in their modeling capabilities.

Second, AI systems typically articulate individual objects and constraints between objects and constructively assemble solutions, much like people do (GSP, DPS, Consite, SightPlan). This enables them to reason about which objects to select and constraints to apply, relax, or ignore, and when to take applied constraints into account. If the system were developed to do so, it could even generate its own constraints in order to proceed with problem solving, or relax them when no satisfactory layout can be found. Conversely, conflicting constraints could be signalled to the user. People, initially using trial-and-error for selecting objects and constraints, eventually learn which choices are more likely to succeed than others, and develop strategies for problem solving. Strategic information can also make AI systems more effective in finding solutions. Whereas many of the traditional construction or improvement systems apply one selection heuristic throughout the solution generation process, systems need not be so limited. AI systems (including SightPlan) can use heuristics that strategically change over time during problem solving, a feature that clearly reflects human opportunism. In addition to describing selection priorities, strategies may also describe how the system can back out of dead-end partial solutions, or what intermediate partial solutions (possibly all) to conserve before proceeding further.

Finally, AI systems generally rely on one of two methods to somehow guarantee the quality of their solutions. Developers of constructive systems may assume that their programmed strategy is a good one (Consite, SightPlan), and consequently, that the generated solution is a good one as well, even if that is difficult to prove. Alternatively (or in addition), they may implement evaluation functions to assess the quality of or compare intermediate solutions (DPS). Similar to accommodating flexible strategies, AI-based systems could use flexible evaluation functions. For example, determining the best positions of key facilities may require a more detailed analysis and evaluation than do secondary facilities. In either case, assessing the quality of solutions is not a trivial issue. Especially when AI systems use flexible heuristics, solutions are unlikely to be provably optimal. It then is of the essence to thoroughly validate the expertise that is embodied in such strategies or evaluation functions.

Example systems for layout construction were used to illustrate that AI systems' capabilities clearly extend in flexibility and knowledge content beyond those of traditional OR systems, but, as pointed out earlier, AI and OR systems cannot unequivocally be separated. It is impossible to generally discredit one in favor of the other. Insisting on differentiating AI systems from others is pointless, but it must be recognized that thinking in AI terms opened new directions for computer-model developers to pursue by introducing the notions of mimicking human problem-solving activities, approaching problems in the way people do, and using strategies like people do. In fact, many AI researchers, extremely ambitious at first, have since come to the conclusion that the best computer systems use all three: AI knowledge, OR routines, as well as interactive user input. With additional display graphics, new systems can easily integrate process and product modeling, and one may expect forthcoming integrated systems to outperform all existing ones.

Summary

This paper characterized construction site layout and stressed the task's complexity. It described what tools are available and used in the construction industry to model the construction layout process and product. The discrepancy between tool availability and tool use was ascribed to (1) the difficulty of identifying the appropriate tool to suit a new situation; (2) the need for large amounts of input data for tools to be usable; (3) the opaqueness of most tools; and (4) the difficulty of realistically interpreting the solutions to highly tailored problems. Fig. 1 illustrated that AI is an integral part of a continuous spectrum of existing models. By means of example implementations, it was demonstrated that the AI approach opened up new ways of building computer models while bringing models and practice closer together. In particular, model developers could make computers mimic layout designer's actions, and add flexibility and functionality to existing models, in order to develop programs that are potentially more easy to understand and use. AI modeling techniques clearly fill a gap among other modeling tools available today. Research should therefore be continued in this area. At the same time, as many descriptions of AI systems are deficient, the AI community must try to overcome this hurdle.

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