Journal of Intelligent Manufacturing (1994) **5**, 399–409

Knowledge-based facility planning: a review and a framework

P. BANERJEE[1] and S. Y. NOF[2]

[1]*Department of Mechanical Engineering, 3029 Engineering Research Facility, University of Illinois, Chicago, IL 60680-4348, USA*
[2]*School of Industrial Engineering, Purdue University, W. Lafayette, IN 47907, USA*

Received April and accepted September 1993

The knowledge-based facility planning (KBFP) problem is reviewed. The aim of KBFP is to provide a more comprehensive planning package for users so that their expertise can be augmented with proven knowledge, and yield significantly better plans. The categories reviewed include facilities equipment selection, software model selection, and the generative task of creating a facility planning solution. The employed problem representation and problem-solving techniques are reviewed. Finally, the development of an integrated framework for KBFP is discussed.

Keywords: Facilities layout, knowledge-based systems, artificial intelligence

1. Introduction

Computerized facility planning approaches became feasible in the mid-1950s with the emergence of computer systems suitable for operations research (OR)-based planning techniques. These approaches have relied heavily on manual preparation of planning data followed by repeated adjustment of the generated plans. The main objective of the computerized approaches that have emerged since then was to harness computer power to increase the computational and data-handling effectiveness and minimize errors. (See, for instance, Nof, 1980; Driscoll and Sangi, 1986; Teicholz, 1992.) Beginning in the late 1970s, techniques from artificial intelligence have been introduced to lay the foundation for knowledge-based facility planning (KBFP). The aim of KBFP is to provide a more comprehensive planning package for users so that their expertise can be augmented with proven knowledge, and yield significantly better plans. The preliminary impact of knowledge-based technologies in manufacturing and specifically in facility layout has been studied in Yih and Nof (1991).

For the purpose of knowledge-based analysis, the facility planning problem can be functionally divided into two interrelated issues: (1) the technological knowledge-base design problem and (2) the methodological knowledge-base design problem. The technological knowledge-base design problem refers to the selection of facilities equipment (e.g. specification of workstations, material-handling equipment). There are two broad categories of methodological knowledge-base design problems. One is the software model selection problem (e.g. selection of well-defined OR-based algorithmic layout design models) depending upon the specific needs of a facility planning problem. The second category refers to the generative task of creating a facility planning solution. Included in this generative task are the design and manipulation of special information clusters. Both the technological and methodological knowledge-base problems listed above depend upon the specific needs of a particular facility planning project. A major difficulty is that an extensive consultation with a variety of data and knowledge sources is often required, yet this cannot be accomplished efficiently by existing OR approaches.

The knowledge-based solution approaches to the facility planning problem-are reviewed by focusing on their problem representation and problem-solving methods. Following this a framework for a comprehensive problem representation and problem solving approach is discussed utilizing some of the experiences gained from the existing state-of-the-art methods of facility planning.

2. Problem representation

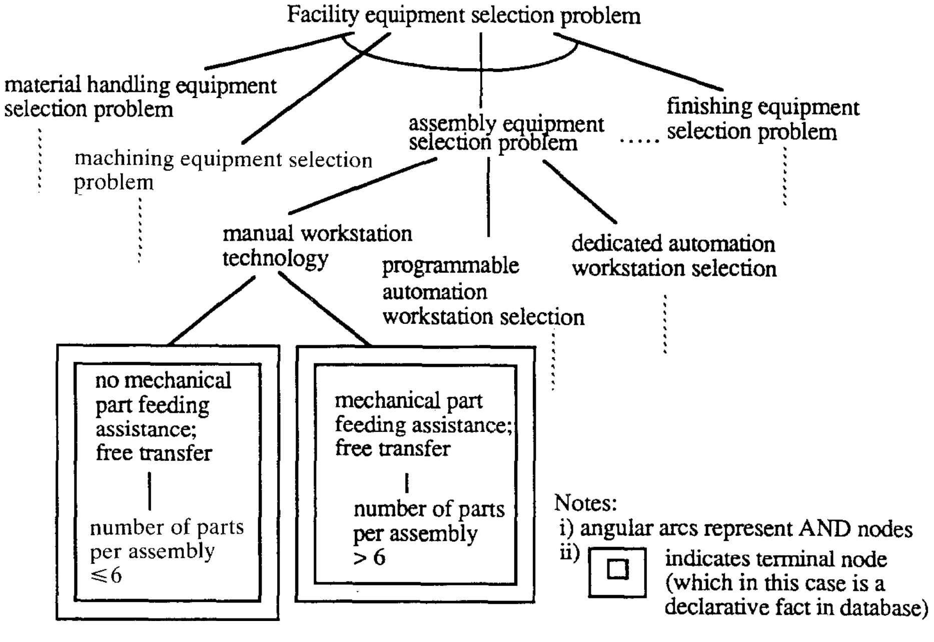
The methods for problem representation have been broadly categorized into two groups: (1) methods based on problem-reduction representation applying the philosophy of AND/OR graphs, under the assumption that the facility planning task can be ultimately broken down into primitive sub-problems referring to the terminal nodes of the AND/OR graph (for which solutions are available); (2) methods based on problem state-space representation, which assumes that it is not efficient to divide the problem into primitive sub-problems, but that the solution can be created through a generative process (mainly through the design of suitable information-clustering structures) after partially dividing the problem.

2.1. *Problem-reduction representation*

In a problem-reduction representation, the overall problem is expressed by a conjunction of several subproblems that may be solved independently of each other involving either an explicit or an implicit use of AND/OR graphs. The central theme is to reduce the facility planning problem into terminal nodes of an AND/OR graph by applying a set of rule clauses. The terminal nodes represent primitive problems for which solutions are available, i.e. it is assumed that the terminal nodes consist either of a database of declarative facts, from which the facts can be retrieved by known methodologies; or that the nodes consist of well-defined OR-based layout solution methodologies which are readily applicable to the appropriately reduced form of the problem. The fundamental assumption of the knowledge-based facility planning search procedures involving problem reduction representation is that the search is limited to reducing the problem into a set of terminal nodes. The commonly encountered terminal nodes are described next.

2.1.1. *Terminal nodes with declarative facts*

2.1.1.1. *Facilities equipment selection:* The existing approaches for the facility equipment selection knowledge-base design have made use of the AND/OR problem-reduction representation with terminal nodes consisting of declarative facts. FADES (facilities design expert systems) (Fisher and Nof, 1987; Yih and Nof, 1991), and its sub-modules: MATHES (material-handling equipment selection expert system), and ASTEC (assembly system technology and equipment consultant) (Fisher, 1986), are examples of technological knowledge-based systems with such problem-reduction representation. For example, consider the graph shown in Fig. 1, which is adapted from Fisher and Nof (1987). The problem is ultimately broken down into terminal nodes of the AND/OR graph by the use of rules like the ones shown in Fig. 2. There are other approaches which have segments belonging to this category (e.g. Gabbert and Brown, 1989; Matson *et al.*, 1992; Trevino and Eom, 1992). In MAHDE (MAterials-Handling DEsign) (Gabbert and Brown, 1989), the terminal nodes consist of device definitions. An example of an inference chain elaborating on the AND/OR graph concept shown in



Notes:
i) angular arcs represent AND nodes
ii) ☐ indicates terminal node (which in this case is a declarative fact in database)

Fig. 1. Simplified AND/OR graph for facility equipment selection problem (adapted from Fisher and Nof, 1987).

IF the number of parts per assembly, NA is less than or equal to six,
AND the number of operators additional to machine supervision on a rotary indexing machine is NR,
AND the annual cost of one assembly operator is WA,
AND the annual cost of one machine supervisor is WS,
THEN use a rotary indexing machine and calculate the total cost of personnel for this machine, WT, as $WT = NR * WA + WS$.

Comment: NR, WA, WS are provided and easily changed by the user. The limit value six used in this rule is also easily changeable.

IF the assembly costs of systems [*ma*, *mm*, *ai*, *af*, *ap*, *ar*, *au*] can be determined to be [$X1$–$X7$], respectively.
THEN sort the costs of the assembly technology alternatives ($X1$–$X7$) in ascending order and report this as the list of candidate technologies and their respective costs, e.g., ([*ar–x*6], [*ap–x*5], . . ., [*mm–x*2])

Fig. 2. Rules for breaking up the AND/OR graph into terminal nodes (taken from Fisher and Nof, 1987).

Fig. 1 is available in EXCITE (Expert Consultant for In-plant Transportation Equipment) (Matson *et al.*, 1992).

A number of conceptual enhancements have been made to the problem-reduction representation to handle uncertainty, increase its flexibility, speed of knowledge acquisition in a situation-dependent domain and enhance its use. In material-handling systems design the designers must anticipate and predict equipment performance in a manufacturing facility that is often not yet constructed. In MAHDE a beta distribution is used to model the uncertain operational knowledge expressed by the experts. The preferential knowledge in MAHDE is based on an extension of multiattribute utility theory in the form of an additive decomposition of a joint utility function under uncertainty.

Approaches such as FADES and KBML (knowledge-based machine layout) (Heragu and Kusiak, 1987, 1990) specify the relationship of the facilities equipment selection and the layout design by rules. For example, FADES has rules for selecting OR-based layout solution methodology depending upon the planning problem context; KBML has rules relating machine layout with the type of material-handling carrier, and vice versa.

2.1.1.2. *Layout design:* The layout design problem has been analyzed with the problem-reduction representation by using a set of production rules and declarative facts by a number of researchers. The approach described in Kumara *et al.* (1988) does not use an implicit expression for the multiobjective layout problem as has been traditionally used e.g. interdepartmental relationships captured as a set of closeness desirability weights (e.g. A, E, I, O, U, X). The interdepartmental, department-site, and intersite relationship weights are explicitly incorporated in the rule clauses and declarative facts, e.g. there are explicit expressions for adjacency, non-adjacency, compressed air requirement, water requirement, heat, noise, material flow, etc. The concept of pareto optimality is used by designing a set of hard (specific values) and soft (a value range) constraints. The results generated by this system, IFLAPS (intelligent facilities layout and planning system) are compared to the results generated by CRAFT and CORELAP on a per criteria basis and the solutions are labeled as inferior or non-inferior.

KBML (Heragu and Kusiak, 1987, 1990) is a rule-based machine layout design methodology with declarative facts and production rules pertaining to factors such as flow, machine clearance, distance and relationship, machine dimensions. All these factors are expressed as matrices. The production rule design is conceptually similar to a combination of FADES-like rules (facilities requirement selection and layout design algorithm selection) and IFLAPS-like rules (explicitly specifying interdepartmental, department-site, and intersite relationship factors).

In Malakooti and Tsurushima (1989) a knowledge-based methodology is described for assigning relative priorities to the following entities for a multiobjective layout design methodology: (1) rules; (2) adjacency; (3) department assignment; (4) site assignment. Any of these entities can take precedence over another entity depending on the priority. Along the same lines as in IFLAPS, the rules give explicit expression to a variety of factors, e.g. electrical power requirement, compressed air requirement. Priorities are also assigned within each entity, e.g. some rules take precedence over other rules, some adjacencies and assignments take precedence over other adjacencies and assignments respectively. All priorities are interactively assigned.

2.1.2. *Terminal nodes consisting of OR methodologies*

There are methodologies in which the terminal nodes represent pointers to well-defined OR-based facility planning techniques. For instance, Fig. 3 illustrates an AND/OR graph in FADES with pointers to various layout design algorithms (linear assignment algorithm,

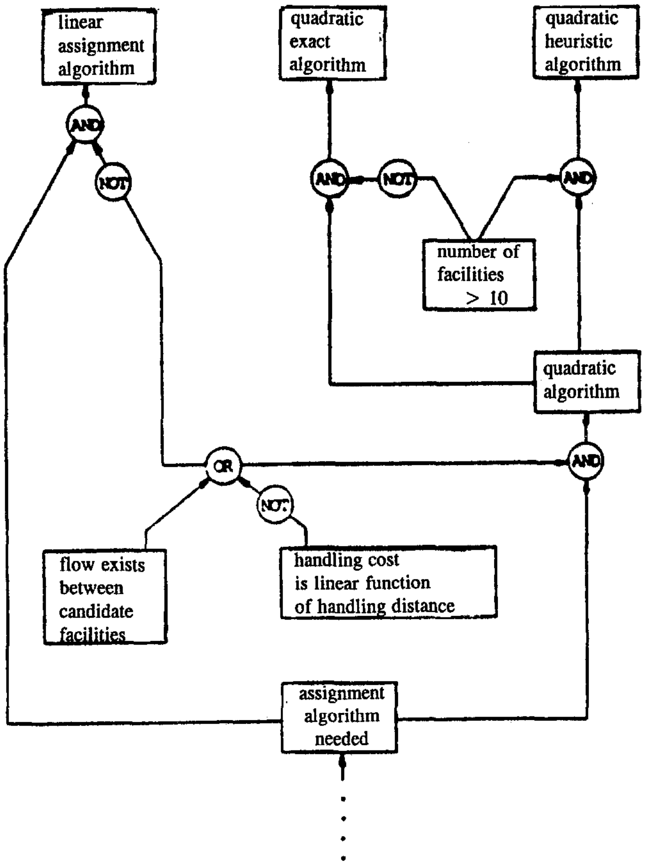


Fig. 3. Example of AND/OR graph with terminal nodes indicating well-defined layout design algorithms (taken from Fisher, 1986).

quadratic exact algorithm and quadratic heuristic algorithm). In KBML (Heragu and Kusiak, 1987) the terminal nodes represent pointers to six algorithms: two variations of linear mixed integer model, two variations of quadratic assignment model, and two variations of quadratic set-covering model.

2.2. *State-space representation*

A state space employs a rich representation structure that qualitatively stores a lot of information. Because of the storage of information by qualitative compaction a state-space representation not only includes an expression for the current partial solution state but also includes an expression for explicitly specifying the remaining solution states reachable from the current solution state (Pearl, 1984). It is this latter expression that expedites the computation of the heuristic estimates towards a satisfactory solution. A state-space representation was originally coined by Newell and Simon (1972) to model efficiently a human being's reasoning about situations. The state-space representation has been mainly applied to the layout design part of the overall facility planning problem. The application of state-space representation is explained by two examples.

The first example is taken from a system entitled QLAARP (Qualitative Layout Analysis using Automated Recognition of Patterns (Banerjee *et al.*, 1992). Figure 4 shows a facility layout comprising of cells and material flow paths. Qualitative layout anomalies are also indicated in the figure. These anomalies indicate focal points in the layout solution space that are potential candidates for further layout improvement. Improvement is measured by the layout score w.r.t. an objective function. The objective function in the case illustrated in Fig. 4 is the sum of products of flow amount and travel distances along the material flow paths).

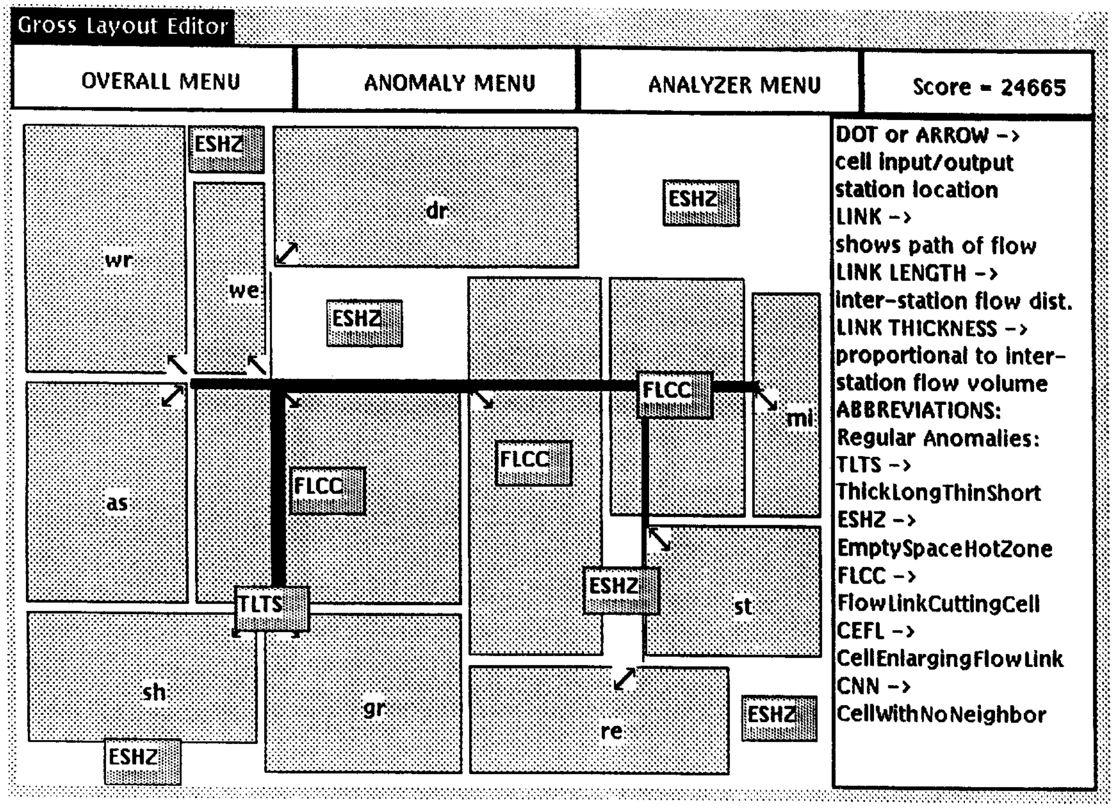
One of the fundamental theses of state-space representation is an expression for the current partial solution state, as well as an expression for the remaining solution states reachable from the current solution state. Figure 5 shows the remaining solution states reachable from the current solution state in the form of sensitivity information based on the linear optimization of the objective function. The actual layout states are not shown in Fig. 5, only the scores are indicated. However, the layout states are stored in an object entitled 'potential solution states' in a condensed form after every linear optimization from the current solution state.

The storage of the useful information by the design of special information-clustering objects (such as potential solution states) improves the efficiency of the process because the information is stored in a readily usable form. Following the specification and analysis of the solution states that are reachable from the current solution state, a decision is made about the next solution state(s) depending upon a predefined control strategy. This issue is discussed below in more detail in the problem-solving section.

Another approach using state-space representation in facility planning is illustrated (taken from Flemming *et al.*, 1988). To evaluate a state s, the tuple $\langle c(s), d(s), e(s) \rangle$ is used, where $c(s)$ is the number of constraints, $d(s)$ is the number of strong criteria, and $e(s)$ is the number of weak criteria violated by s. The example illustrates the layout of residential kitchens. The following objects are chosen and placed in the following order: sink, work area (an imaginary area such that the placement of this object ensures that all the other objects are accessible from it), refrigerator, range and work counter. Figure 6 shows the intermediate states reached from a given state in this approach.

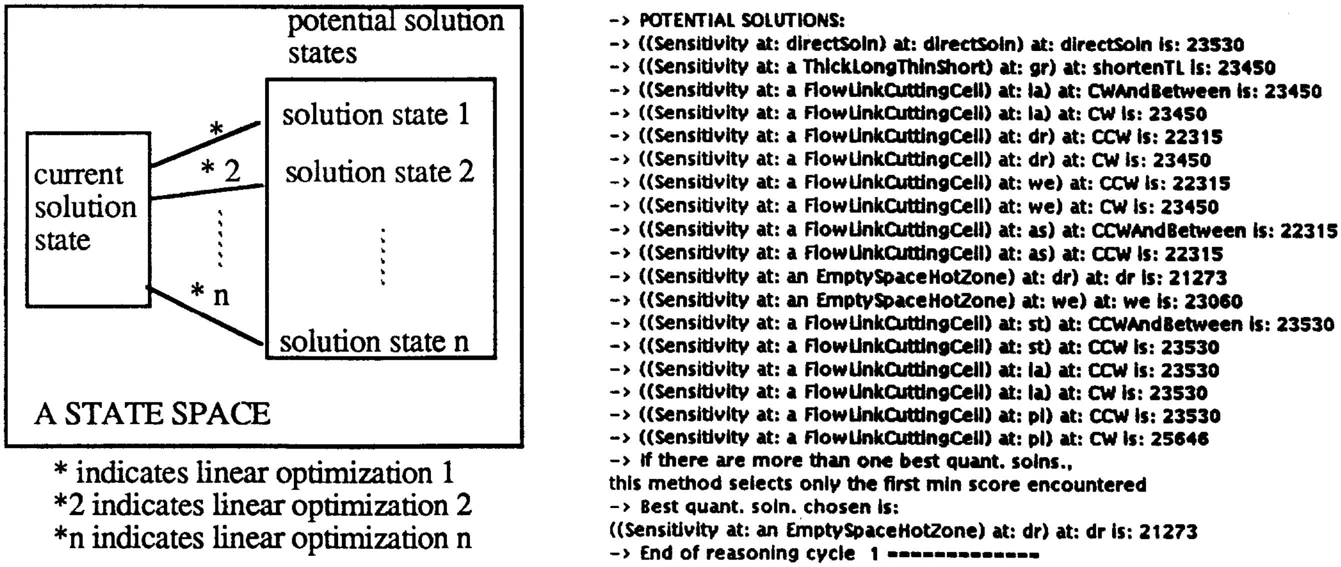
3. Problem-solving approaches

The problem-solving approaches for facility planning are introduced by a comparative review of OR and knowledge-based problem solving.



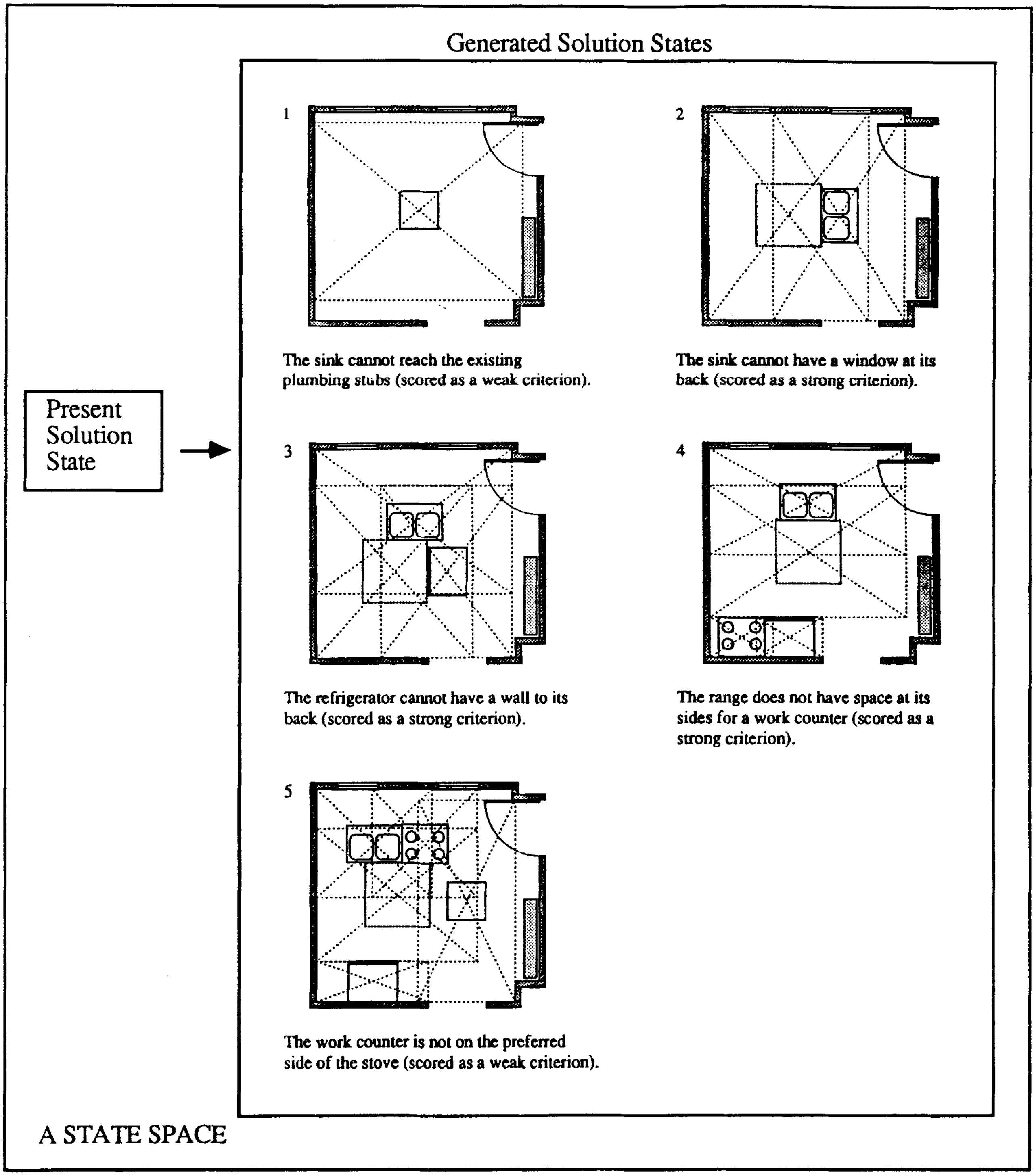
DOT or ARROW ->
cell input/output
station location
LINK ->
shows path of flow
LINK LENGTH ->
inter-station flow dist.
LINK THICKNESS ->
proportional to inter-
station flow volume
ABBREVIATIONS:
Regular Anomalies:
TLTS ->
ThickLongThinShort
ESHZ ->
EmptySpaceHotZone
FLCC ->
FlowLinkCuttingCell
CEFL ->
CellEnlargingFlowLink
CNN ->
CellWithNoNeighbor

Fig. 4. A layout with cells, material flow paths and qualitative anomalies (taken from Banerjee *et al.*, 1992).



```
-> POTENTIAL SOLUTIONS:
-> ((Sensitivity at: directSoln) at: directSoln) at: directSoln is: 23530
-> ((Sensitivity at: a ThickLongThinShort) at: gr) at: shortenTL is: 23450
-> ((Sensitivity at: a FlowLinkCuttingCell) at: la) at: CWAndBetween is: 23450
-> ((Sensitivity at: a FlowLinkCuttingCell) at: la) at: CW is: 23450
-> ((Sensitivity at: a FlowLinkCuttingCell) at: dr) at: CCW is: 22315
-> ((Sensitivity at: a FlowLinkCuttingCell) at: dr) at: CW is: 23450
-> ((Sensitivity at: a FlowLinkCuttingCell) at: we) at: CCW is: 22315
-> ((Sensitivity at: a FlowLinkCuttingCell) at: we) at: CW is: 23450
-> ((Sensitivity at: a FlowLinkCuttingCell) at: as) at: CCWAndBetween is: 22315
-> ((Sensitivity at: a FlowLinkCuttingCell) at: as) at: CCW is: 22315
-> ((Sensitivity at: an EmptySpaceHotZone) at: dr) at: dr is: 21273
-> ((Sensitivity at: an EmptySpaceHotZone) at: we) at: we is: 23060
-> ((Sensitivity at: a FlowLinkCuttingCell) at: st) at: CCWAndBetween is: 23530
-> ((Sensitivity at: a FlowLinkCuttingCell) at: st) at: CCW is: 23530
-> ((Sensitivity at: a FlowLinkCuttingCell) at: la) at: CCW is: 23530
-> ((Sensitivity at: a FlowLinkCuttingCell) at: la) at: CW is: 23530
-> ((Sensitivity at: a FlowLinkCuttingCell) at: pl) at: CCW is: 23530
-> ((Sensitivity at: a FlowLinkCuttingCell) at: pl) at: CW is: 25646
-> If there are more than one best quant. solns.,
this method selects only the first min score encountered
-> Best quant. soln. chosen is:
((Sensitivity at: an EmptySpaceHotZone) at: dr) at: dr is: 21273
-> End of reasoning cycle 1 ------------
```

Fig. 5. (a) A state space representation of facility layout design used in QLAARP (Banerjee *et al.*, 1992). (b) Scores of potential states reached from current solution state (as indicated in Fig. 4).



1 The sink cannot reach the existing plumbing stubs (scored as a weak criterion).

2 The sink cannot have a window at its back (scored as a strong criterion).

3 The refrigerator cannot have a wall to its back (scored as a strong criterion).

4 The range does not have space at its sides for a work counter (scored as a strong criterion).

5 The work counter is not on the preferred side of the stove (scored as a weak criterion).

Fig. 6. Second example of state-space representation in facility layout design (adapted from Flemming *et al.*, 1988).

Two of the main differences between knowledge-based facility planning methodologies and OR-based facility optimization methodologies are the definition of the problem domain and the problem-solving (also referred to as 'search', or 'control') process. The OR-based facility planning methodologies such as the quadratic assignment programming (QAP) approaches, the linear programming (LP) approaches and the quadratic set-covering approaches use standard search procedures which are quite exhaustive (for a recent review of OR approaches, see Kusiak and Heragu, 1987). Because of such standard algorithmic search procedures, the facility planning problem definition is molded to fit the requirements of the search. Such molding of the problem definition makes the problem domain too restrictive for most practical applications.

On the other hand, knowledge-based facility planning methodologies attempt to broaden the problem domain by symbolically making use of domain-specific items of knowledge (such as rules) and special data structures for organization of knowledge (such as frames, objects). The search process relies on an *ad hoc* combination of distinct items of problem-solving knowledge, without assigning any reason for rejecting many intermediate points in the solution space. Often, the provision for exploring the intermediate points in the solution space does not even exist. Hence, the problem solving is not as structured as in OR-based methodologies.

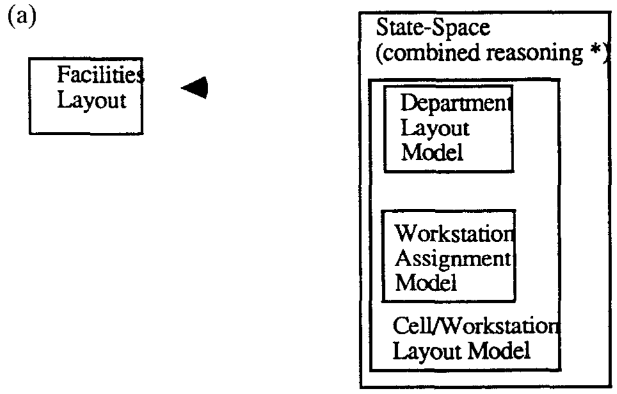
The search strategy for the knowledge-based facility planning approaches with the problem-reduction representation is based on a combination of a data-driven, forward chaining strategy and a goal-driven, backward chaining strategy for reducing the problem into a set of terminal nodes with declarative facts or well-defined solution approaches. The control strategy for forward chaining is primarily interactive, e.g. in the system described in Malakooti and Tsurushima (1989); the designer has the option to accept or reject backtracking, in FADES and IFLAPS the user can specify the criteria to be considered. Forward chaining using the OPS83 rule-based programming language is used in EXCITE to aid the user in searching through the knowledge base. In MAHDE, forward chaining is used to assign instances of devices from the bottom level of a materials-handling equipment hierarchy to device definitions in a materials-handling system design information hierarchy. The goal-driven, backward chaining is carried out by a depth-first search using a Prolog-like control structure in FADES, IFLAPS and in Malakooti and Tsurushima (1989).

The control strategy for the facility planning with state-space representation is based on local criteria for determining and selecting one or more best solution states from the alternatives generated from among the current state. For instance, the control strategy employed in QLAARP is the selection of the solution states with least flow travel score from among the potential solution states. Candidate solution states with scores indicating a deterioration relative to the present solution state beyond a certain threshold are not considered. QLAARP also illustrates the concept of opportunistic reasoning at a conceptual level because it addresses the layout anomalies as they appear during the solution states. In the system described in Flemming *et al.* (1988) the selected control strategy is a branch-and-bound, expanding those and only those intermediate states which are at least as good as any other state(s) generated before (independent of its depth in the search tree). The evaluation of a state(s) is based on the tuple $\langle c(s), d(s), e(s)\rangle$ described in the last section, which ranks the states based on the criteria violated.

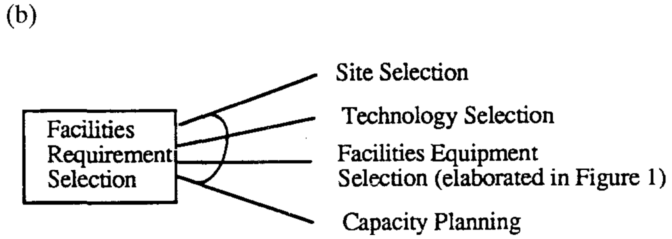
Knowledge-based facility planning involves managing a large set of production rules and declarative facts. Other information-clustering structures have been designed in addition to the production rule structure, e.g. a frame structure has been used for clustering declarative facts in FADES and MAHDE, a syntactic pattern recognition method has been used in IFLAPS, an object-based architecture has been used in QLAARP. Wherever applicable, such information-clustering structures can improve the efficiency of the search process by savings in identifying and grouping related information together and not having to search for such information at multiple database or working memory locations. For example, objects can combine the properties of procedure and data and store the combined knowledge, locally, thereby offering a very high-level programming environment through many such object-based abstract data types. This leads to a highly modular and decentralized storage of knowledge. Additionally, by making use of built-in interactive interface objects (such as use of model-view-controller triad, Banerjee, 1992) the planner can easily build a user interface in an object-oriented environment. The model contains the data about the object, the view maintains its display information, and the controller has all its user interaction primitives. Applying this principle, an interactive layout design environment is illustrated in Montreuil and Banerjee (1988). Use of such a concept has also been reported in Trevino and Eom (1992).

4. Scope of methodological and technological knowledge bases

A version of a methodological knowledge base has been proposed in Montreuil (1990) by encompassing decisions on space, cell, building, flow and relationships, life cycle dynamics, hierarchy, logical design, operational dynamics, and multi-agents. From a knowledge representation perspective, treatment of life cycle dynamics requires supporting multiple time-phased cell sets, building(s),



* This particular representation is adopted because the subproblems: department layout model and workstation assignment model are quite interrelated and it may be efficient to perform combined reasoning within a state-space than separate the two subproblems in a problem reduction representation



It may be more efficient to divide this portion of the problem into independent subproblems by a problem reduction representation

Fig. 7. (a) Example of methodological reasoning. (b) Example of technological reasoning.

flow sets, relationship sets and layouts as well as the notion of probabilistic future requirements and of prospective scenarios with associated probability trees.

A logical design of a modifiable manufacturing systems organization encompasses two broad strategies: (1) plan excess capacity so that the same facility with different units at a time can be used; and (2) provide enough space and scope for rearrangement of the same basic configuration by adding, removing or repositioning components (Nof, 1984). The multi-agent concept in methodological knowledge-base design has been incorporated in Banerjee *et al.*

Technological knowledge bases are clearly differentiated by their focus on particular technological areas. Facilities can be designed for fabrication, assembly, service, maintenance and other applications. For various applications, alternative strategies of production and of manufacturing exist. For instance, flow-shop versus an assembly line, or cellular facility; highly automated, or manual, and so on. In Fisher and Nof (1987), knowledge-based analysis is utilized to compare alternative assembly automation technologies based mainly on cost effectiveness. In each case, the knowledge sources used must be different and include technological data as well as technology-related rules of selection and design.

5. Conclusion: framework and perspective

A framework and perspective for knowledge-based facility planning is provided by incorporating existing knowledge representation and manipulation techniques with new concepts. Many of the design issues which could not be effectively addressed in the past can now be addressed by new knowledge representation and manipulation techniques.

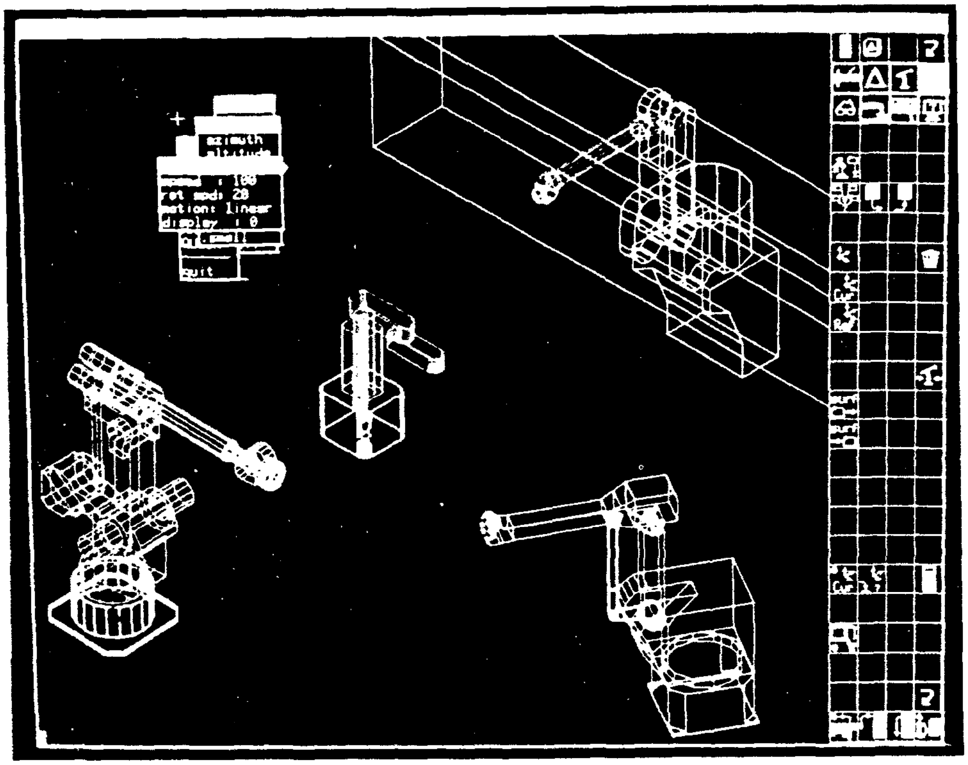
5.1. *Role of existing knowledge representation and manipulation techniques*

It appears that the technological reasoning of the facilities planning problem is more conveniently represented by the problem-reduction representation, whereas the methodological reasoning is more conveniently represented by the state-space representation. Since the facilities planning problem is a mixture of technological and methodological reasoning, and sometimes these are inseparable, pockets of problem-reduction representation and state-space representation are envisioned. The state-space representation is more suited for highly interrelated subproblems (Fig. 7a) whereas the problem reduction representation is more suited for working on subproblems which do not have a single sequence for addressing, i.e. the subproblems are highly independent (Fig. 7b).

A significant portion of the methodological knowledge in facilities planning is algorithmic. An algorithmic control is suitable when there is a fixed sequence of steps with very little variation, e.g. the sequence of steps in classical approaches like CRAFT and CORELAP falls in this category.

Among the recent approaches in methodological reasoning most of the steps are algorithmic with the exception of the overall control, e.g. in QLAARP, the layout anomaly identification, anomaly rectification attempts—these steps are all algorithmic. Only the situation recognition, i.e. deciding which anomalies are important and which should be rectified first, is non-algorithmic.

The technological knowledge has to gather information from a variety of sources and a major portion is non-algorithmic. As shown in Figs 1 and 7a, the technological reasoning problem of facilities requirement selection needs to be partitioned into independent subproblems by a problem-reduction representation for ease of management. For the example shown in Fig. 7a, the site selection and facilities technology selection are primarily non-algorithmic, whereas the capacity planning



motion: linear
display : 0

Fig. 8. GMF's OLPW-200 Sun-based workstation enables users to perform workcell feasibility studies, create complete robot programs in GMF's KAREL language, and perform simulations of the robotic workcell in action at a three-dimensional color graphics terminal (courtesy of GMF Robotics Corp.).

can be algorithmic by using a stochastic workflow modeling approach (Co *et al.*, 1989). In addition one needs to incorporate schemes for incorporating preferential knowledge as has been addressed in MAHDE. Preferential knowledge reflects the changing acceptability measures for designs as more refined knowledge becomes available. The approach suggested in MAHDE is to use numerical representation in the form of multiattribute utility theory and its extensions to enable rapid knowledge acquisition and increase system flexibility under uncertainty.

Better information-clustering structures have to be formulated based on the experiences gained from explicit representation of production rules to an implicit representation based on information-clustering structures such as objects (King and Fisher, 1986; Banerjee *et al.*, 1992; Trevino and Eom, 1992), frames (Gabbert and Brown, 1989; Yih and Nof, 1991), or some form of implicit numerical structures such as beta distribution or multiattribute utility theory (Gabbert and Brown, 1989).

Using an object-oriented approach the information about objects like cell can be stored within the cell itself and this can replace the need to split the information into pieces and store each piece at different locations in the form of multiple matrices (e.g. Heragu and Kusiak, 1987) or relational tables which are more difficult to manipulate (Sheu and Kashyap, 1988).

5.2. *Role of new knowledge representation and manipulation techniques*

There are a number of emerging avenues for incorporating new knowledge representation and manipulation techniques. These are primarily based on the effective use of multimedia capabilities.

One avenue involves incorporation of 3D graphics and visualization, namely, interactive viewing of the system under design and of the analysis data. For example, graphic simulators have been developed to design robotic systems (e.g. Nof and Rajan, 1992). Engineers can select robots by evaluating, in simulation, alternative manipulators integrated into a workcell, considering machines in the cell. General robot graphic simulators include libraries of numerous robot models from various robot makers. Such simulators can aid the process of workcell layout and placement design decisions (Nof, 1992). A prototype illustration of this concept is given in Fig. 8. Given the above capabilities 3D facilities layout design studies can be pursued with renewed interest, for both

Table 1. Development of framework for KBFP

Planning problem or issue	*Category*	*Recommended approach*	*Reference*
Facilities equipment selection	Technological knowledge base	Problem reduction	Fisher (1986), Fisher and Nof (1987), Gabbert and Brown (1989), Matson *et al.* (1992), Trevino and Eom (1992)
Facilities technology selection	Technological knowledge base	Problem reduction	Fisher and Nof (1987)
Variant layout design	Methodological knowledge base	Problem reduction	Fisher (1986), Fisher and Nof (1987), Heragu and Kusiak (1987)
Generative layout design	Methodological knowledge base	State space	Flemming *et al.* (1988), Banerjee *et al.* (1992)
Capacity, throughput, and other operational characteristics planning	Methodological knowledge base	Algorithmic	Co *et al.* (1989)
Integration of above with multimedia capabilities	Technological and methodological knowledge base	Combination of above	None so far

analytical studies and experimental design for verification of analytical results.

Another avenue is the effective use of audio capabilities. For concurrent, simultaneous engineering design of facility, especially by distributed engineers, it may be essential to add audio conversation capabilities. Audio is also critical for design issues concerned with noise levels (safety, proximity, etc.). Audio can also be used in training to use the design system, with integrated voice and audio signals. Audio signals can now be used for controls (alarms, start/stop signals, etc.), which have not been used in design systems in the past because they were not available.

Based on the above considerations, Table 1 shows the development of a framework for KBFP.

Acknowledgement

This work was supported in part by NSF grant DDM-9209849 awarded to University of Illinois at Chicago, and NSF grant USE-9151608 to Purdue University.

References

Banerjee, P. (1992) A framework for rapid computational prototyping of manufacturing entities. *Journal of Intelligent Manufacturing*, **3**, 363–378

Banerjee, P., Montreuil, B., Moodie, C. L. and Kashyap, R. L. (1992) A modeling of interactive facilities layout designer reasoning using qualitative patterns. *International Journal of Production Research*, **30**(3), 433–453.

Co, H., Wu, A. and Reisman, A. (1989) A throughput-maximizing facility planning and layout model. *International Journal of Production Research*, **27**(1), 1–12.

Driscoll, J. and Sangi, N. A. (1986) The Development of Computer-Aided Facilities Layout (CAFL) Systems, International Survey 1985–86, University of Liverpool, UK.

Fisher, E. L. (1986) An AI-based methodology for factory design. *AI Magazine*, **7**(4), 72–85.

Fisher, E. L. and Nof, S. Y. (1987) Knowledge-based economic analysis of manufacturing systems. *Journal of Manufacturing Systems*, **6**(2), 137–150.

Flemming, U., Coyne, R., Glavin, T. and Rychener, M. (1988) A generative expert system for the design of building layouts—version 2, in *Artificial Intelligence in Engineering: Design*, Gero, J. S. (ed.), Elsevier Science Publishers, pp. 445–464.

Gabbert, P. and Brown, D. E. (1989) Knowledge-based computer-aided design of materials handling systems. *IEEE Transactions on Systems, Man and Cybernetics*, **19**(2), 188–196.

Heragu, S. and Kusiak, A. (1987) KBML: Knowledge Based System for Machine Layout, Working Paper #08/87, Department of Mechanical and Industrial Engineering University of Manitoba, Winnipeg, Canada.

Heragu, S. and Kusiak, A. (1990) Machine layout: an optimization and knowledge-based approach. *International Journal of Production Research*, **28**(4), 615–635.

King, C. U. and Fisher, E. L. (1986) Object-oriented shop-floor design, simulation and evaluation, *IIE Conference Proceedings*, pp. 131–137.

Kumara, S. R. T., Kashyap, R. L. and Moodie, C. L. (1988) Application of expert systems and pattern recognition methodologies to facilities layout planning. *International Journal of Production Research*, **26**(5), 905–930.

Kusiak, A. and Heragu, S. S. (1987) The facility layout problem. *European Journal of Operational Research*, **29**, 229–251.

Malakooti, B. and Tsurushima, A. (1989) An expert system using priorities for solving multiple-criteria facility layout problems. *International Journal of Production Research*, **27**(5), 793–808.

Matson, J. O., Mellichamp, J. M. and Swaminathan, S. R. (1992) EXCITE: expert consultant for in-plant transportation equipment. *International Journal of Production Research*, **30**(8), 1969–1983.

Montreuil, B. (1990) Requirements for representation of domain knowledge in intelligent environments for layout design. *Computer-Aided Design*, **22**(2), 97–108.

Montreuil, B. and Banerjee, P. (1988) Object knowledge environment for manufacturing systems layout design. *International Journal of Intelligent Systems*, **3**(4), 399–410.

Newell, A. and Simon, H. A. (1972) *Human Problem Solving*, Prentice Hall, New Jersey, USA.

Nof, S. Y. (1980) A methodology for computer-aided facility planning. *International Journal of Production Research*, **18**(6), 699–722.

Nof, S. Y. (1984) An expert system for planning/replanning programmable facilities. *International Journal of Production Research*, **22**(5), 895–903.

Nof, S. Y. (1992) Industrial Robotics, in *Handbook of Industrial Engineering*, 2nd edn, Salvendy, G. (ed.), John Wiley, New York, pp. 450–453.

Nof, S. Y. and Rajan, V. N. (1992) A workstation for robotic manufacturing systems design experimentation, Research Memo. 92-19, School of Industrial Engineering, Purdue University, W. Lafayette, IN, October.

Pearl, J. (1984) *Heuristics: Intelligent Search Strategies for Computer Problem Solving*, Addison-Wesley, Reading, MA.

Sheu, P. and Kashyap, R. L. (1988) Object-based knowledge bases in automatic manufacturing environments. *International Journal of Advanced Manufacturing Technology*, **3**(3), 39–52.

Teicholz, E. (1992) *Computer Aided Facility Management*, McGraw-Hill, New York.

Trevino, J. and Eom, J. K. (1992) Intelligent selection, design and control of material handling and storage systems, in *Proceedings of the 1st IIE Research Conference*, pp. 421–425.

Yih, Y. and Nof, S. Y. (1991) Impact of integrating knowledge-based technologies in manufacturing: an evaluation. *Computer-Integrated Manufacturing Systems*, **4**(4), 254–263.