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Thomas Hamann, François Vernadat

To cite this version:

Thomas Hamann, François Vernadat. The Intra-cell layout problem in automated manufacturing systems. [Research Report] RR-1603, INRIA. 1992, pp.20. inria-00074957

HAL Id: inria-00074957
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Submitted on 24 May 2006

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UNITE DE RECHERCHE
INRIA-LORRAINE

Institut National
de Recherche
en Informatique
et en Automatique

Domaine de Voluceau
Rocquencourt
B.P.105
78153 Le Chesnay Cedex
France
Tél.(1) 39 63 55 11

Rapports de Recherche
1992
25ème anniversaire

N° 1603

Programme 5
Traitement du Signal,
Automatique et Productique

THE INTRA-CELL LAYOUT PROBLEM IN AUTOMATED MANUFACTURING SYSTEMS

Thomas HAMANN
François VERNADAT

Février 1992

RR-1603

L'agencement de machines à l'intérieur d'une cellule de production

Résumé

Dans ce papier, nous nous intéressons à l'agencement des machines à l'intérieur des cellules dans un système de production automatisé. La solution présentée est en deux étapes.

La première étape consiste à déterminer le système de transport et le (ou les) type(s) d'agencement possible(s). Ces procédures de choix sont basées sur les caractéristiques (i) des produits, (ii) de leur gamme, et (iii) des machines. Un système expert a été développé pour aider à ces choix.

La seconde étape consiste à optimiser l'agencement (i.e. à minimiser le trafic) compte tenu des choix précédents et des contraintes physiques. Cette seconde étape demande la résolution de problèmes de recherche opérationnelle.

Mots-clés

Agencement intra-cellulaire, Moyens de transport, Système expert, Minimisation du trafic, Optimisation.

THE INTRA - CELL LAYOUT PROBLEM IN AUTOMATED MANUFACTURING SYSTEMS

Thomas HAMANN and François VERNADAT
SAGEP Project, INRIA-Lorraine/CESCOM
Technopôle Metz 2000, 4 rue Marconi
57070 Metz, France
Phone: 87 20 35 00 - Fax: 87 76 39 77

ABSTRACT

The problem of the machine layout inside manufacturing cells (intra-cell layout problem) of an automated manufacturing system is addressed in this paper. The solution presented is divided into two main steps. The first step consists of selecting the materials handling system and the possible machine layout type. This procedure is based on the characteristics of : (i) products (which belong to the same product family), (ii) their manufacturing processes, and (iii) machines. An expert system has been developed for this part. The second step consists of evaluating the alternative arrangements of the machines inside the manufacturing cell in order to minimize the intra-cell traffic (costs) while respecting the physical constraints between the machines, between the machines and their environment, product constraints, technological constraints, user preference, etc. This part is performed using Operations Research algorithms.

KEYWORDS

Intra-Cell Layout Problem, Materials Handling Systems, Machine layout, Expert System, OR-algorithms, Traffic (cost) Minimization

1. INTRODUCTION

This paper addresses the intra-cell machine layout problem, i.e. how to physically position the machines of a cell. This problem has received and is still receiving considerable attention from the research community as well as from industrial engineers, manufacturing engineers, and production engineers.

The focus has primarly been on solving a design problem. In the case of machine layout, we look for the best layout design; in solving the machine location problem we wish to find the optimum arrangement (design) of machines inside a manufacturing cell. There currently exists a small amount of literature dealing with machine layout.

The machine layout design consists of problem definition, analysis of the problem, search for the feasible materials handling systems (MHS), selection of the preferred MHS, search for the feasible types of machine layout, selection of the preferred type of machine layout, and the specification and evaluation of the machine layout.

The paper is organized as follows. First, we discuss the overall machine layout problem. Next, we review the literature. Then, we propose a two-step approach to solve this problem. In the first step, a knowledge-based approach is used to choose the possible materials handling system and the machine layout type (general architecture of the cell). In the second step, mathematical algorithms are used to find the best location of each machine in this type of layout. Finally, conclusions are drawn with a recommendation concerning the extensions of the two-step approach in solving more complex machine layout problems.

2. PROBLEM FORMULATION

The intra-cell layout problem consists of finding a cost-effective and practical machine layout inside manufacturing cells, taking into account available material handling systems, and the basic type of layout to minimize the cell surface and the traffic between machines. The outputs of this task will provide (i) the type of materials handling system, (ii) the type of machine layout, (iii) the physical location of machines inside the cell, (iv) the size of the cell, i.e. the required surface, and (v) the definition of the cell entrance and exit.

This problem can be formulated as follows: n is the number of machines of the cell, $c^k{}_{ij}$ is the handling cost per unit distance to move one part type k, between machine i and machine j, $f^k{}_{ij}$ is the frequency of trips of part type k between machine i and j, μ_k is the quantity of part type k, and d_{ij} is the distance between machine i and machine j. Note that $c^k_{ij} = f^k_{ij} = d_{ij} = 0$ if i=j.

$$\min \sum_{k=1}^{p} \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mu_k \, c^k_{ij} f^k_{ij} \, d_{ij} \qquad i,j = 1, \ldots, n \qquad k = 1, \ldots, p$$

subject to:

$$d_{ij} \geq D_{ij} \text{ , for all } i,j \ (i \neq j) \tag{1}$$

$$s(i) \neq s(j) \text{ , for all } i,j \ (i \neq j) \tag{2}$$

where D_{ij} is the minimum distance allowed between machine i and machine j and s(i) denotes the physical location of machine i. Constraint (1) ensures that the minimum clearance between machines is verified and constraint (2) makes sure that two machines do not share the same location.

The problem is non-trivial for the following reasons: (i) it is difficult to define one good optimization criterion (several criteria must be considered, e.g. inter-machine traffic, cell surface, installation and operation costs, etc.), and (ii) the problem is subject to a wide range of numeric and non-numeric constraints (machine proximity, clearance, safety, product constraints, technological constraints, technological know-how, user preference, etc.).

3. LITERATURE REVIEW

One of the most frequently used formulations to solve the machine layout problem optimally is the quadratic assignement problem (QAP), which is NP-complete (Sahni and Gonzalez, 1976). The largest problem which has been solved optimally is made of 15 machines and 15 sites and requires a very high computational complexity (Finke, Burkard and Rendl,1985). Due to this complexity, researchers have concentrated on developing heuristic methods, which do not guarantee optimality but provide acceptable solutions with reasonable computation times. The existing algorithms to solve this problem may be classified as optimal algorithms and suboptimal algorithms.

3.1 Optimal algorithms

In the 1960's a lot of optimal algorithms for the QAP were developed. Two main classes of algorithms may be distinguished: branch-and-bound algorithms, and cutting plane algorithms.

The first two branch-and-bound algorithms were developed by Gilmore (1962) and Lawler (1963). Both algorithms evaluate all potential solutions. Further, two other algorithms were developed by Land (1963) and Gavett and Plyter (1966). These algorithms assign pairs of facilities to pairs of locations whereas the algorithms of Gilmore and Lawler assign single facilities to single locations. Bazaraa and Elshafei (1979) proposed a branch-and-bound algorithm for the QAP which is based upon a staged assignement of single facilities to unoccupied locations. Kaku and Thompson (1986) provided another branch-and-bound algorithm which performs better than Lawler's (1963) algorithm, particulary for problems of bigger size.

Bazaraa and Sherali (1980) developed a cutting plane algorithm based on Benders' partitioning scheme. Burkard and Bonninger (1983) also developed a cutting plane method to solve the QAP.

The disadvantages of the optimal branch-and-bound and cutting plane algorithms are the high computation time and storage complexity. For example, the largest facility layout problem ever solved optimally by a cutting plane algorithm is the layout problem with eight facilities.

3.2 Suboptimal algorithms

Since optimal algorithms cannot provide solutions for larger problems with acceptable computation times and storage complexities, researchers developed new algorithms which can be classified into constructive algorithms, improvement algorithms, combined algorithms, combined algorithms using knowledge based systems and graph theoretic algorithms.

In constructive algorithms, facilities are assigned to a site, one at a time until the complete layout is obtained.

In the past, a number of such algorithms have been proposed : HC66 (Hillier and Connors,1966), ALDEP (Seehof and Evens, 1967), CORELAP (Lee and Moore, 1967), PLANET (Deisenroth and Apple, 1972), INTALA (Dangelmaier, 1984), EASYLAY (Enghardt, 1985), and FLAT (Heragu and

Kusiak, 1986). Most of these algorithms were designed for the placement of facilities such as departments or rooms, but not manufacturing machines. They pay little to no attention to materials handling systems.

Improvement algorithms such as H63 (Hillier, 1963), CRAFT (Buffa, 1963 and Buffa et al., 1964), COFAD (Tompkins and Reed, 1976 and 1980), PVT (Warnecke, 1981), always start from an initial solution of the machine layout, which is often randomly generated. Systematic exchanges (perturbations) between the facilities are made to improve the layout until the best solution is obtained and no further improvement is possible. The final solution of these algorithms may depend on the quality of the initial solution.

Combined Algorithms mostly use the principles of the construction algorithms and improvement algorithms. They have the characteristics of optimal and suboptimal algorithms. Known algorithms have been created by Elshafei (1977), Burkard and Stratman (1978), Bazaraa and Kirca(1983), and include the algorithms MODULAP (Minten, 1977), FLAC (Sciabin and Vergin, 1985), MICROLAY (Wäscher and Chamoni, 1985), and LAYOPT (Raßpe and Weidenbusch, 1985).

Also a few algorithms using knowledge-based systems have been proposed. Among these are:

FADES (Fisher and Nof, 1984) is an expert system for the facility design problem using first-order predicate logic and a Prolog interpreter. It is not only an aid in facility planning but also in the selection of equipment and economic investment analysis.

IFLAPS (Tirupatikumara et al., 1985) is a generative layout design system using a backward chaining strategy and taking into account multiple objectives such as cost, noise and safety.

KBML (Kusiak, 1990) is a knowledge-based system to determine a machine layout using a flow matrix, a clearance matrix, a relationship indicator matrix and machine dimensions. It makes use of five classes of first-order rules to select the type of material handling system and the layout type. It also includes an algorithm for positionin machines.

These expert systems are prototype systems based on production rules. A more precise model of machines, materials handling systems, manufacturing processes and problem constraints is necessary to address the complexity of real life problems using object orientation.

Graph-theoretic algorithms identify maximal planar subgraphs of weighted graphs which show the relationships between the facilities. The dual of a maximal planar subgraph determines the layout of the facilities. Note that some of the graph-theoretic algorithms can be classified as construction algorithms. Some algorithms have been developed by Seppanen and Moore (1970 and 1975), and Carrie et al.(1978).

Almost all algorithms were designed for the placement of facilities such as departments or rooms but not manufacturing equipment and it appears that too much emphasis has been placed on solution quality of small size layout problems without much regard to computational time and memory requirement. Also, little to no attention to materials handling systems has been paid. In a practical environment, it is often difficult or expensive to obtain accurate flow and cost data. In such cases, one might ask if it is worthwhile to use algorithms which produce solutions of good quality at the expense of computation time, rather than algorithms which produce solutions of relatively lower quality but faster. One might argue that fast computation is not an issue here, since the solutions provided are not to be used in real time. Given, however, the need to work with the system on an iterative basis, and to produce several alternative solutions until the "best" one is obtained, computational speed becomes important.

Furthermore, the user should be able to interact at nearly every stage in order to obtain a good solution appropriate for any case of machine layout.

To overcome these shortcomings, further research is necessary in the specific context of machine layout design.

4. PROPOSED TWO-STEP APPROACH TO THE MACHINE LAYOUT PROBLEM

In the following part, a two-step approach to solve the machine layout problem is presented (see figure 1).

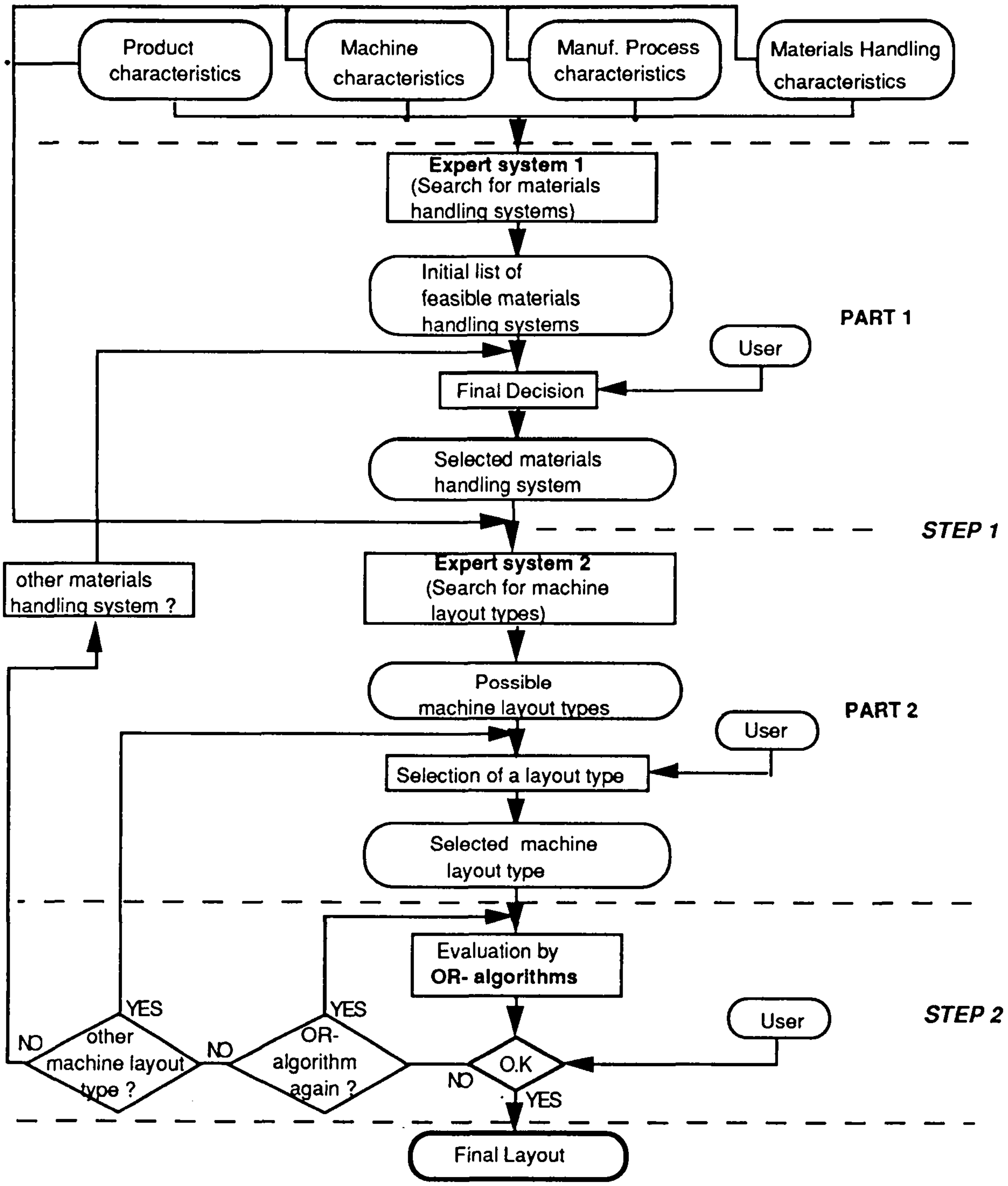

Figure 1. General Methodology for Machine Layout

4.1 *STEP 1*: Expert System

At the time of establishing the expert system, the user has to populate the database with the characteristics of the MHS's available in the market, together with the basic cell configurations. In addition, the user has to enter the rules that help to choose the type of MHS and the type of cell configuration, as explained below. In order for the expert system to be used, each time the cell designer has to enter the characteristics of products, processes and machines involved in a given problem.

Materials handling systems considered include robots, gantry robots, automated guided vehicles (AGV's), conveyors and carts (see figure 2).

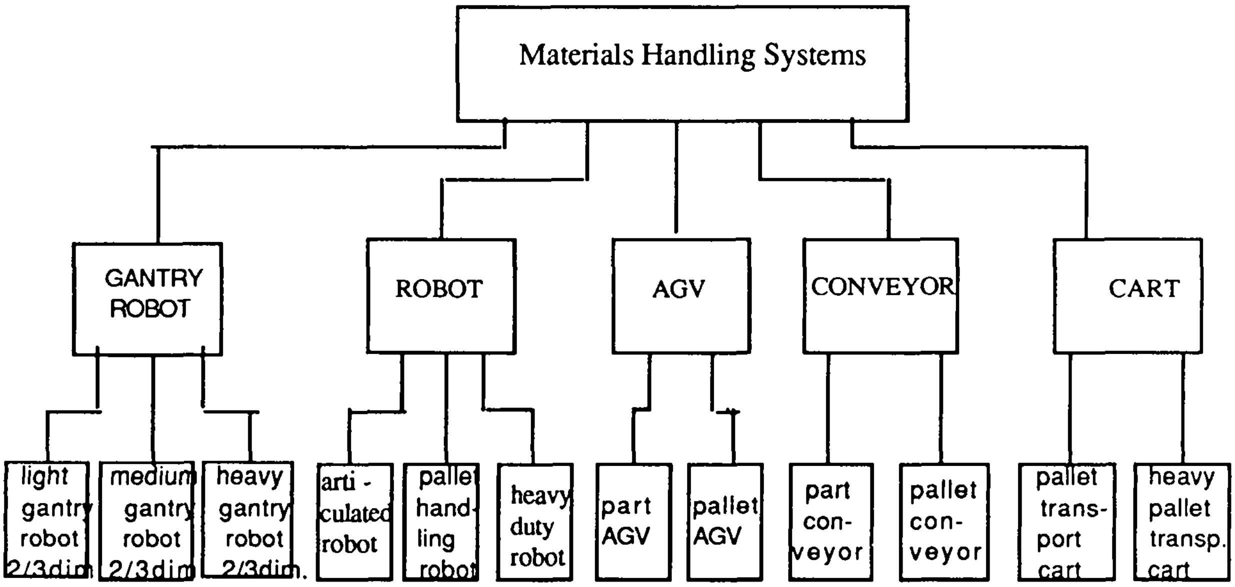

Figure 2. Taxonomy of Materials Handling Systems Considered

The robot class can be further divided into articulated robots, pallet handling robots, and heavy duty robots. The gantry robots are separated into two- or three-dimensional and further in light, medium, and heavy gantry robots. The AGVs and the conveyors can either transport parts or pallets. The carts are divided into regular pallet transport carts and heavy pallet transport carts.

The characteristics considered for MHS's are:

- Possibility of palletisation: boolean
- Max. number of machines to be served: integer
- Max.product length, width, height to be transported: real
- Max. transportation weight: real
- Transportation distance of translation in x-axis, y-axis, z-axis : real
- Transportation velocity in x-axis, y-axis, z-axis : real
- Transportation rotation angle in x-axis, y-axis, z-axis : real
- Transportation rotation velocity in x-axis, y-axis, z-axis : real
- Positioning accuracy: real
- Degree of flexibility: real
- Max. environment temperature: integer
- Max. permitted vibration level: real
- Energysource: list of string
- Capital equipment cost: real
- Security Coefficient: integer

In this approach,the basic machine layout types considered are (see figure 3):

a) circular, single-row,
b) linear, single-row (including single-loop),
c) linear, double-row (including double-loop), and
d) multi-row,

where the circular single-row layout is a special case of the linear single-row layout and the linear double-row layout is a special case of the multi-row layout.

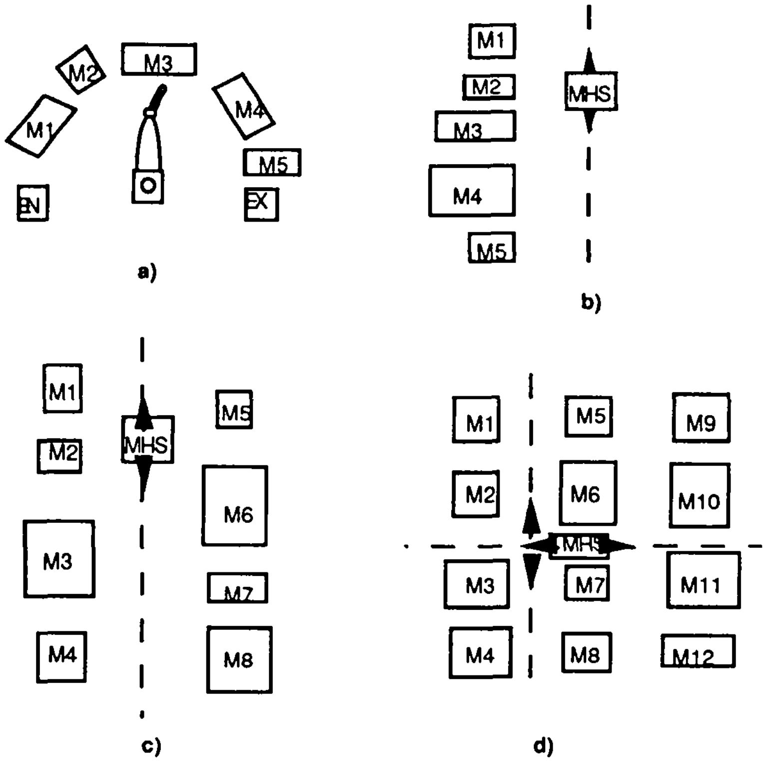

Figure 3. Machine Layout Types

Furthermore, the user has to enter the characteristics of the product types, machines, manufacturing processes, and dimensions of the floor (if given). The following data are required:

Characteristics of products:

- Quantity of each product type: integer
- Length, width, height of the products: real
- Weight of the products: real
- Temperature of the products: integer
- Possibility of palletisation: boolean
- Type of pallet (if palletisation possible): list of string

Characteristics of the manufacturing process types :

- Number of machines: integer
- Number of product types: integer
- Length, width, height of the cell: real
- Horizont of the manufacturing process: list of string
- Type of material flow: list of string
- Frequency of trips (flow): matrix $f^{k}[i,j]$

- Handling cost matrix between machines for each product type $c^k[i,j]$
- Machine relationship matrix $r[i,j]$
- Machine location restrictions $x_{s(i)}$, $y_{s(i)}$

Characteristics of the machine types :

- Length, width, height of machines: real
- Weight of machines: real
- Machine distance (min.clearance) matrix: $D[i,j]$
- Serving distance of translation of the x-axis, y-axis, z-axis: real
- Serving velocity of translation of the x-axis, y-axis, z-axis: real
- Serving rotation angle in x-axis, y-axis, z-axis: real
- Serving rotation velocity in x-axis, y-axis, z-axis: real
- Necessary positioning accuracy: real
- Temperature: integer
- Vibration: integer
- Noise: real
- Energy source: list of string

With the dimensions (length, width, and height) of the space it can be determined whether the layout of machines violates space constraints. It is not absolutly necessary to give this information. If it is not given it is assumed that enough space is available to construct the machine cell in its optimal configuration.

An expert system consisting of a knowledge base and a database, using a forward chaining strategy has to be developed.

The database consists of data related to the machine layout problem. The system interacts with the user and obtains the required data, namely the characteristics of the product types, machine types, manufacturing process types, and dimensions of the space as described above and stores them in its database.

The knowledge base consists of rules to solve the machine layout problem. It is divided into two parts, corresponding to the two expert systems, as mentioned in step 1 of figure 1. In the first part all feasible MHS's are determined. The rules to select the feasible MHS's are based on the characteristics of all available MHS's (see above). Figure 4 shows the hierarchy of characteristics being considered in the rules of the expert system for the MHS type selection. The selection starts by considering if palletization is required. Then, the number of machines in the cell becomes a discriminant factor. If this number is for example less than 5, then robot types can be primarily considered. The maximum weight of parts is also an important characteristic to be considered to determine the type of MHS at this stage. For instance, heavy parts (> 500 kg) require conveyors or heavy gantry robots. Then the number of necessary translations to position the parts on the machines becomes an important factor. Finally, additional constraints (not shown in Fig. 5) are used to select the appropriate subtypes of MHS within a given type (e.g. 2-axis light gantry robot or 3-axis light gantry robot in the light gantry robot class). It is possible that the system may provide several feasible types. In this case, the user is asked to select one.

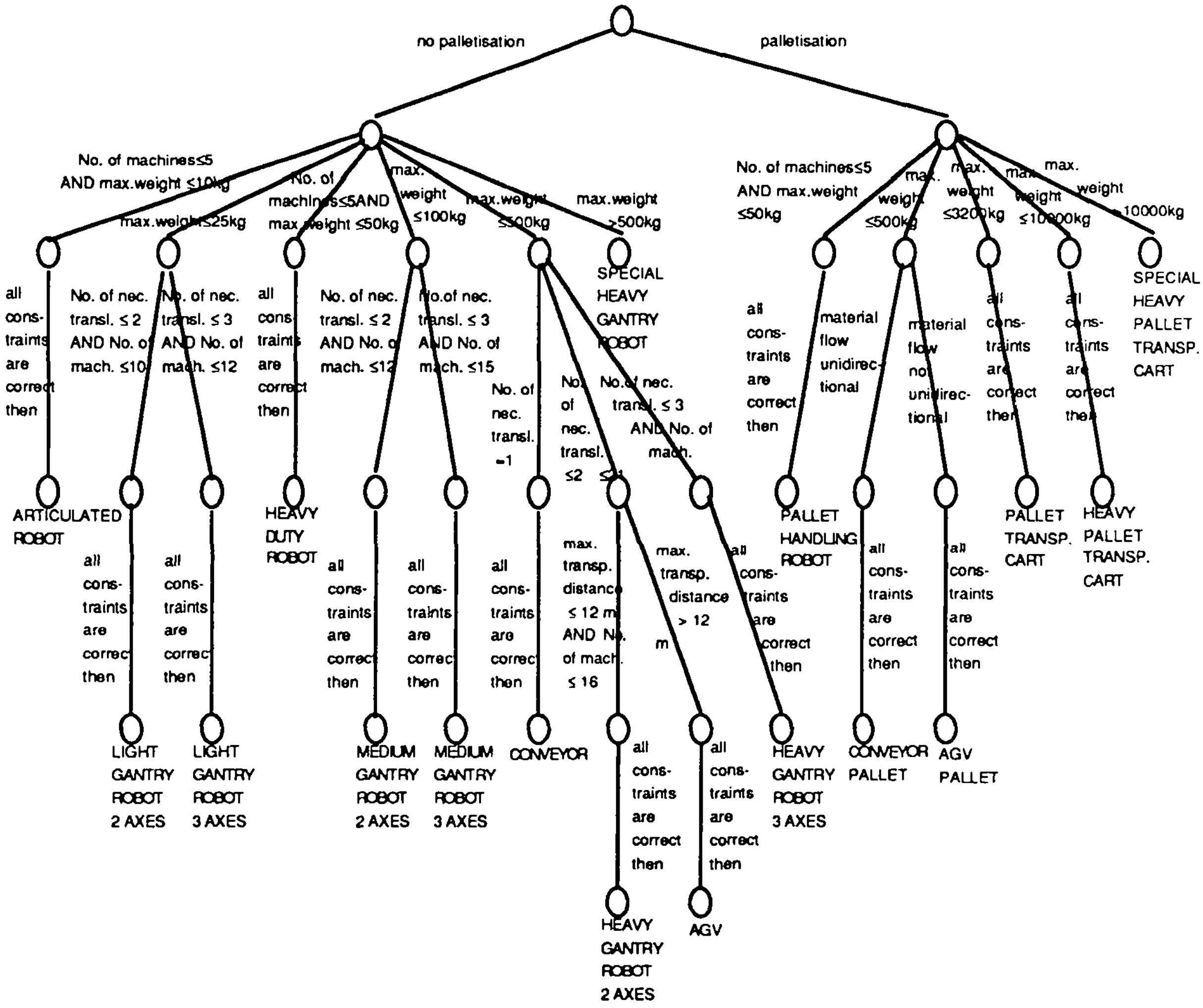

Figure 4. Decision Tree to Select the Material Handling System

In the second part of the knowledge base the feasible type of machine layout is determined. Once a MHS has been decided then the machine layout type can be determined. For some cases, the choice is obvious (e.g. IF MHS = articulated robot THEN Layout = circular single row). In other cases, additional information such as flexibility requirements (eg. changes in product mix, addition of new product types etc.) may be considered. Thus, the system uses another expert system. Figure 5 illustrates the highest levels of the decision tree to select the machine layout type. Figure 6 provides examples of rules to select the machine layout type.

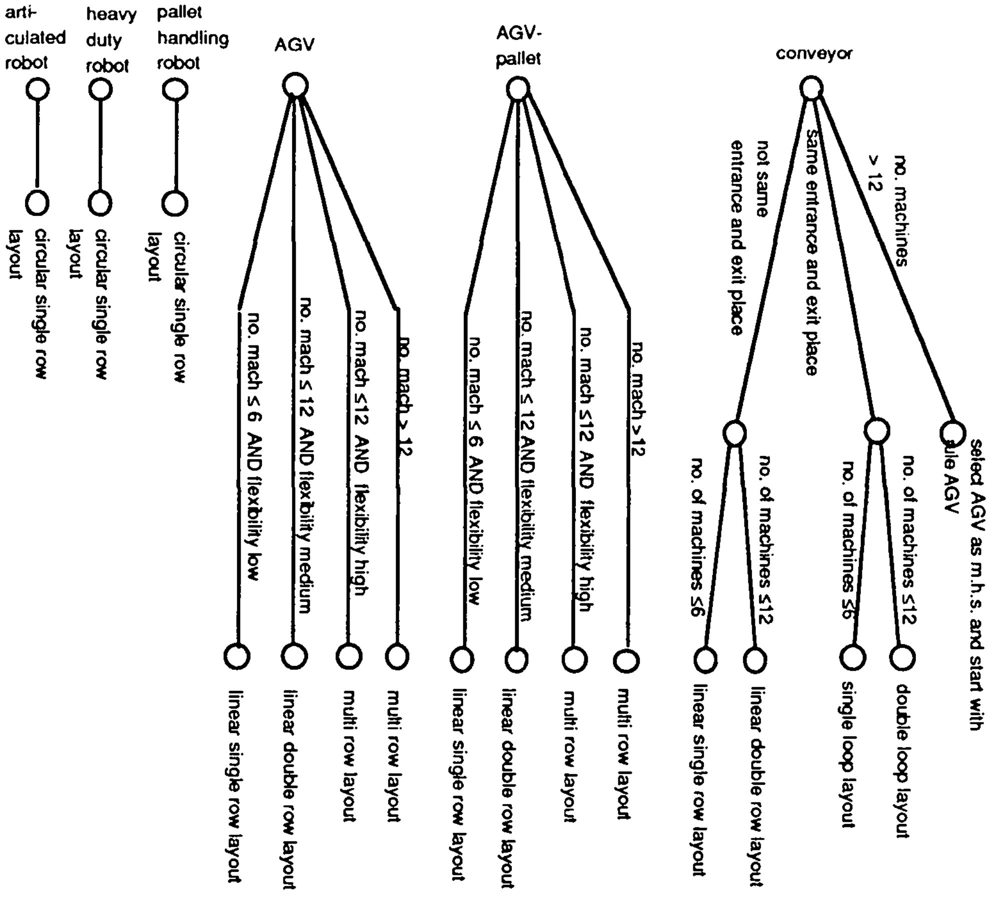

Figure 5. Example of Decision Tree to Select the Machine Layout Type

1. If the m.h.s. is an **articulated robot**
Then select **circular single row layout.**

2. If the m.h.s. is an **AGV**
AND the number of machines ≤ 6
AND the flexibility level is low
Then select **linear single row layout.**

3. If the m.h.s. is an **AGV**
AND the number of machines ≤ 12
AND the flexibility level is medium
Then select **linear double row layout.**

4. If the m.h.s. is an **AGV**
AND the number of machines ≤ 12
AND the flexibility level is high
Then select **multi row layout.**

5. If the m.h.s. is a **conveyor**
AND the number of machines ≤ 6
AND the entrance and exit of the cell
are not at the same place (on the same site)
Then select **linear single row layout.**

Figure 6. Examples of Rules to Select the Machine Layout Type

4.2 *STEP 2:* Machine location - An OR-based approach

The problem now consists of determining the physical location of machines for the type of layout selected, using optimization techniques (bottom-part of Fig. 1).

All the optimization algorithms which we use for machine location attempt to minimize the traffic and the distance between the machines. They all start from a fixed discretization of the maximal clearance between machines, and attempt to place the machines with respect to the criterion, by grouping machines on the smallest floor space possible.

4.2.1 Single-Row Layout

In the case of a linear layout, the problem can be formulated as follows : n is the number of machines of the cell, μ_k is the quantity of part type k, c^k_{ij} is the handling cost per unit distance to move part type k, between machine i and machine j, f^k_{ij} is the frequency of trips of part type k between machine i and j, l_i is the length of machine i (i = 1, 2,..., n), g_{ij} is the clearance between machines i and j, ($c^k_{ij} = f^k_{ij} = g_{ij} = 0$ if i = j) and s(i) is the location of machine i defined by the coordinate x which represents the center of the machine.

$$\min \sum_{k=1}^{p} \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mu_k \, c^k_{ij} \, f^k_{ij} \left| x_{s(i)} - x_{s(j)} \right|$$

subject to

$$\left| x_{s(i)} - x_{s(j)} \right| \geq 1/2 \, (l_i + l_j) + g_{ij} \tag{3}$$

$$x_{s(i)} \geq 0 \; , \tag{4}$$

$$x_{s(i)} \neq x_{s(j)} \, ; \quad i \neq j \, ; \quad i, j = 1, \dots, n \tag{5}$$

(3) defines the distance between the center of machine i and the center of machine j on the x-axis (where x = 0 defines the entry point in the line), (4) verifies that the x-coordinates are positive, and (5) ensures that two machines do not share the same location.

To find a solution and to reduce the problem complexity, we first define all possible machine locations on the x-axis. The discretization step is Δ, where Δ is the largest common divider (LCD) of g_{ij} and l_i (i, j = 1, ..., n; i ≠ j) as shown on Fig. 7.

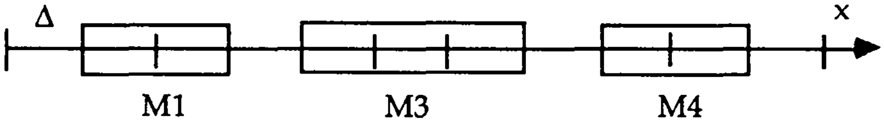

Figure 7: Linear layout

Whenever g_{ij} is undefined (i ≠ j), it is set to Δ to ensure that two adjacent machines are not in contact.

The simulated annealing technique (Kirkpatrick et al. 1983) is used to solve the problem, starting from an initial solution s_0 in which the sequence of machines on the line is generated at random and the clearance between each pair of adjacent machines is set to g_{ij}. A new solution s_1 in the neighborhood of s_0 will be obtained by permutating two machines on the line and verifying constraint (3).

A slightly different formulation of the problem can be given for the circular single row layout, which needs the use of the y coordinate.

4.2.2 Multi-Row Layout

The double-row layout is a special case of the multi-row layout. These types of layout are very suitable when the number of machines exceeds for example 8 and the MHS is an AGV or a gantry robot. However, in some cases a conveyor can also be used.

The multi-row layout problem can be formulated as follows : n is the number of machines of the cell, μ_k is the quantity of part type k, c^k_{ij} is the handling cost per unit distance to move part type k, between machine i and machine j, f^k_{ij} is the frequency of trips of part type k between machine i and j, l_i is the length and w_i is the width of machine i (i = 1, 2,..., n), gx_{ij} is the clearance between machines i and j on the x-axis, gy_{ij} is the clearance between machines i and j on the y-axis, ($c^k_{ij} = f^k_{ij} = gx_{ij} = gy_{ij} = 0$ if i = j) and s(i) is the location of machine i defined by the coordinates x and y which represent the center of the machine.

$$\min \sum_{k=1}^{p} \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mu_k \, c^k_{ij} \, f^k_{ij} \left(\left| x_{s(i)} - x_{s(j)} \right| + \left| y_{s(i)} - y_{s(j)} \right| \right)$$

subject to

$$\left| x_{s(i)} - x_{s(j)} \right| \geq 1/2 \, (l_i + l_j) + gx_{ij} \tag{6}$$

$$\left| y_{s(i)} - y_{s(j)} \right| \geq 1/2 \, (w_i + w_j) + gy_{ij} \tag{7}$$

$$x_s(i) \geq 0 \, ; \quad y_s(i) \geq 0 \, ; \qquad i = 1, \dots, n \tag{8}$$

$$x_s(i) \neq x_s(j) \, ; \quad i \neq j \, ; \qquad i, j = 1, \dots, n \tag{9}$$

Assuming that (x = 0, y = 0) is the reference point of the cell area and that we only consider the positive space of the xy-system and that machines are positioned along their length, (6) and (7) define the distance between the center of machine i and the center of machine j on the x-axis, and on the y-

axis respectively, (8) verifies that the x-coordinates and y-coordinates are positive, and (9) ensures that two machines do not share the same location.
In this case, optimal algorithms such as branch-and-bound algorithms and cutting plane algorithms can be used to solve the problem if the number of machines is not too large (eg. ≤ 8). Otherwise suboptimal algorithms must be used (Kusiak, 1990).
In our approach we use a discretization of the cell area followed by a simulated annealing algorithm to solve this problem, whatever the number of machines in the cell ($n \geq 2$). The discretization step is D_x on the x-axis and D_y on the y-axis, where D_x is the largest common divider of gx_{ij} and l_i and D_y is the largest common divider of gy_{ij} and w_i ($i, j = 1, ..., n; i \neq j$).
The final layout is shown graphicly on the screen. At this point the user has to decide whether he agrees with this solution of machine layout or not. If he doesn't agree he can restart the process with a different initial solution. The second possibility is to choose a different type of machine layout among the list of selected types of machine layouts and to continue with the process as discribed above. The third possibility is to restart with an other type of materials handling system, among the list of selected materials handling systems determined at the beginning of the procedure.

5. CONCLUSION

The purpose of this work is to demonstrate the feasibility of a sound machine layout design approach, based on the use of AI and OR techniques. This approach should serve as a basis for the machine layout design module of commercial software, such as the one to be developed by the COALA project (Proth and Vernadat, 1991).
The paper presents the overall architecture of the system, the approach adopted, the type of knowledge and the kind of algorithms used. This work can be extended in a number of ways to suit industrial needs. First, it can be extended to deal with more sophisticated constraints concerning the selection of material handling systems. Second, it can be extended to deal with more types of material handling systems commercially available. Third, it can be extended to deal with economic evaluations of the proposed solutions.
We are currently in the process of developing and adding new optimization algorithms for the machine location problem, and a small expert system may

be necessary in the OR part of the system to assist in the choice of the best algorithm for the problem at hand.

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Imprimé en France
par
l'Institut National de Recherche en Informatique et en Automatique.

ISSN 0249-6399