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A Practical Method for Design of Hybrid-Type Production Facilities

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A practical method for design of hybrid-type production facilities

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A comprehensive methodology for the design of hybrid-type production shops that comprise both manufacturing cells and individual workcenters is presented. It targets the minimization of the material handling effort within the shop and comprises four basic steps: (1) identification of candidate manufacturing cells, (2) evaluation and selection of the cells to be implemented, (3) determination of the intra-cell layout, and (4) determination of the shop layout. For the cell formation step the ICTMM technique has been enhanced to cater for important practical issues. The layout of each significant cell is determined by a simulated annealing (SA)-based algorithm. Once the sizes and shapes of the selected cells are known, the shop layout is determined by a similar algorithm. The resulting hybrid shop consists of the selected cells and the remaining machines. The methodology has been implemented in an integrated software system and has been applied to redesign the shop of a large manufacturer of radar antennas.

1 Introduction

The design of a discrete parts manufacturing shop can be classified into one of two basic types: (1) functional, in which each group of functionally similar machines occupies a dedicated area of the shop floor, or (2) cellular, in which individual resources are aggregated into manufacturing cells, each dedicated to the manufacture of one or more part families. The important benefits of cellular manufacturing have been itemized by Ham *et al.* (1985) and include: reduction in material handling, simplification of material flow, reduction of setup times, simplification of scheduling and production control, improvement of quality, and increased cell worker motivation.

A pure cellular production system may not be appropriate for batch production and job-shop environments, in which batch sizes become progressively smaller and the product variety increases. Consequently, similarities within a part family decrease and most parts have to visit one or more resources outside their cell. In such cases a hybrid-type shop, consisting of manufacturing cells and individual machines, is most appropriate. A hybrid shop design methodology is also valuable when the resources of existing functional shops are reorganized to form manufacturing cells. In this case it is usually not economically feasible or even beneficial, to implement a pure cellular configuration. Hybrid shop design requires the identification of significant manufacturing cells and the layout of the resulting mix of machines and cells within the available shop area. A methodology that addresses these issues is presented in this paper. It is based on our previous work on cell formation and layout (Jajodia *et al.* 1992, Nagi *et al.* 1990) and extends these methodologies to address the unique requirements of hybrid facilities.

Extensive research efforts have focused on the problem of aggregating machines into manufacturing cells. The methods described in the literature can be broadly classified into three basic categories: (1) clustering approaches, which use part similarity measures (McAuley 1972, Kusiak and Wadood 1988, Leskowsky *et al.* 1987, Wei and Kern 1989), (2) methods that form cells and part families simultaneously using the part-machine incidence matrix (McCormick *et al.* 1972, King 1980, Chan and Milner 1982, Garcia and Proth 1985 and 1986), and (3) other methods which target higher-level criteria of practical significance, such as inter-cell traffic and cost measures (Askin and Subramanian 1987, Tabucanon and Ojha 1987, Harhalakis *et al.* 1990).

The clustering approaches and the incidence matrix methods have several major drawbacks: (1) The machine workload requirements and their available capacities are not considered, and thus, machines within cells may be overloaded possibly creating infeasible cell formations. (2) Similarities in setups are not considered even though they may result in significant cycle-time benefits. (3) The sequence of operations in a process plan is typically not considered, although it is critical to material flow considerations. Exceptions include the methods of Choobineh (1988) and Tam (1990). The third class of algorithms are more comprehensive. However, none addresses setup considerations directly. Furthermore, only a few methods have considered the case of a shop consisting of functionally identical machines. This type of environment is quite common in a job or batch manufacturing shop, which comprises functional areas. In a cellular arrangement, the functionally identical machines have to be aggregated into different cells. In addition, the part process plans must be altered to designate a specific member of the group of identical machines on which an operation is to be performed. It is emphasized that part assignment directly influences the material flow within the shop, and therefore, has to be considered carefully.

Facility layout has been addressed by a rich body of literature. Most of the proposed methods utilize the Quadratic Assignment Problem (QAP) formulation and seek to minimize the total weighted distance between resources. The weights are defined by adjacency priorities or material flow volumes (Tam 1992). This problem has been proven to be NP-complete by Sahni and Gonzalez (1976). Thus, many of the methods employed are heuristics seeking to obtain near-optimal solutions and may be classified into five basic categories: (1) construction methods (Lee and Moore 1967, Seehof and Evans 1967, Apple and Deisenroth 1972, Edwards *et al.* 1970, Hassan *et al.* 1986, Kusiak and Heragu 1987), (2) improvement methods (Amour and Buffa 1963, Buffa *et al.* 1964, Nugent *et al.* 1968, Hillier 1963, Hillier and Connors 1966, Picone and Wilhelm 1984, O'Brien and Abdel Barr 1980, Golany and Rosenblatt 1989), (3) hybrid methods

(Drezner 1980, 1987, Scriabin and Vergin 1985), (4) methods based on graph theory (Carrie *et al.* 1978, Tam 1992, Geotschalckx 1992, Montreuil *et al.* 1987, Montreuil and Ratliff 1989), and (5) methods based on simulated annealing (Jajodia *et al.* 1992, Heragu and Alfa 1992, Kouvelis *et al.* 1992, Proth and Souilah 1992). A comprehensive survey of most of these methods is provided in Kusiak and Heragu (1987).

The drawbacks of the construction, improvement, and hybrid layout methods include: (1) The final solution is very sensitive to the initial conditions. (2) Most methods are greedy, leading to local optima. (3) Most methods utilize equidimensional entities, and therefore, area conflicts may result in the final layout. The graph theory-based methods share many of the same drawbacks; area constraints are not considered, optimality is not guaranteed, and the transformation of the graph to a feasible layout is accomplished by a second stage which may lead to further sub-optimalities. The simulated annealing (SA) methods succeed to a great extent in overcoming the sensitivity of the final solution to the initial conditions, and they typically converge to a near-optimal solution. Our SA-based method, CLASS (Jajodia *et al.* 1992), has been extensively enhanced in this work to address both intra-cell and shop layout.

An integrated design methodology for hybrid manufacturing shops has been developed in this study. It targets a consistent objective, i.e. the minimization of the material handling effort within the shop, and accounts for most important practical issues. It includes four steps: (1) cell formation, (2) evaluation of cells, (3) determination of intra-cell layout, and (4) determination of hybrid shop layout. In he first step, cell formation aspects that are of concern in industry are addressed including the distribution of functionally identical machines among cells and the preservation of setup families. The second step of the methodology retains only the cells that yield substantial reductions in material handling. The third step determines the layout of these cells to minimize a cumulative measure of traffic and distance, respecting all physical constraints. Finally, the inter-cell layout is determined in the fourth step considering important issues, such as, dimensions of the shop, dimensions of manufacturing resources, restrictions to the shop area, and realistic flow paths.

2 The Production Environment

We consider a discrete parts manufacturing facility that includes multiple workcenters. Each workcenter comprises one or more functionally identical machines. The shop design problem consists of forming a set of significant manufacturing cells, determining the layout of each of these cells, and designing the layout of the shop that includes the cells as well as the remaining individual machines. The global objective is to minimize the material flow within the shop. In the context of cell formation, this objective is realized by minimizing the inter-cell traffic of parts. In the layout stage, in which the physical placement of the manufacturing resources is addressed, the objective function considers both the part traffic and the distance travelled.

The assumptions, upon which the methodology is based include:

- A single process plan exists for each part which specifies the sequence of workcenters required for its production, the run time per part and the set-up time per batch.
- Workcenter capacity is assumed to be sufficient to satisfy the production requirements.
- Machines belonging to the same workcenter are assumed to be inter-changeable.
- Workcenters are assigned a moveability status according to Table 1.

Only type A, B and C workcenters are considered in the cell formation stage. Type D workcenters are visited by almost every part and, thus, they cannot be grouped into any particular cell. Note that types A, B, and C are defined to differentiate workcenters during the layout stage of the problem.

The layout problem entails the physical placement of machines within a cell, as well as the physical placement of the cells and independent machines on the shop floor. The general framework, upon which the approach for both cases is based, is shown in Fig. 1. A square grid is imposed on the area available for the placement of the resources. The latter are enclosed within a rectangular envelope and may occupy one or more nodes of the grid depending on the resource size. The resolution of the grid is defined such that the basic system entities, i.e., resources, material handling corridors, as well as the details of the shop area can be described adequately.

Restricted areas are excluded from this grid as shown in Fig. 1, i.e. no nodes are assigned to these areas.

3 Cell Formation

The objective function of the cell formation problem is expressed as:

$$\text{Minimize} : T = \sum_{i=1}^{N} \sum_{j=1}^{i-1} t_{ij} \tag{1}$$

where T is the cumulative traffic between all cells; N is the number of manufacturing cells; t_{ij} is the traffic between these cells in terms of the number of pallet transfers. It is provided by:

$$t_{ij} = \sum_{h=1}^{M} \left\lceil \frac{d_h}{ps_h} \right\rceil \times x_h(i,j) \tag{2}$$

where M is the number of part types; d_h is the demand of part type p_h within the time horizon of interest; ps_h is the average pallet size for part type p_h i.e. the average number of parts which may be moved in one pallet; and $x_h(i,j)$ is the number of times part p_h is transferred between cells c_i and c_j during its manufacture. The minimization of inter-cell traffic is subject to the following constraints:

Limiting Cell Size Constraint

$$q_i \leq Q; i = 1, 2, \ldots, N \tag{3}$$

where q_i is the number of machines in cell c_i and Q is the user-defined maximum number of machines allowed per cell. The limiting cell size depends on several factors, such as volume of work, inter-dependencies between workcenters and machines, labor skills required, and machine size (Ang and Wiley 1984).

Machine Capacity Constraint

$$\sum_{i=1}^{M} \sum_{j=1}^{NP_i} \left[\left(SUT_i^j \left\lceil \frac{d_i}{bs_i} \right\rceil + RUT_i^j \times d_i \right) \times y(i,j,k) \right] \leq \left(\frac{W_k \times NM_k}{PF_k} \right); \forall k = 1,2,3,\ldots,Z \tag{4}$$

where Z is the number of workcenters, M is the number of part types, NP_i is the number of operations required for the production of part type p_i , SUT_i^j is the setup time of operation j of part type i, RUT_i^j is the processing time of operation j of part type p_i , d_i is the demand of part type p_i , bs_i is the average batch size of part type p_i , W_k is the available capacity of each machine of workcenter type k, NM_k is the number of functionally identical machines of workcenter type k, PF_k is the performance factor of machines of workcenter type k, and y(i,j,k) is defined as:

$$y(i,j,k)=\begin{cases} 1 & \text{if operation j of part type } p_i \text{ is performed by workcenter k} \\ 0 & \text{otherwise} \end{cases} \qquad (5)$$

Note that RUT_i^j and SUT_i^j are the standard setup and run times, provided in the production routing of part p_i . The performance factor, PF_k, adjusts these times based on the historical performance of workcenter k. Additionally, note that the demand, d_i, of part p_i is defined over a user-specified time horizon, which is consistent with W_k.

Setup Part Families Constraint

The parts that are processed by each workcenter k (k = 1, 2,..., Z) are grouped into part sets, $R_1^k, \ldots, R_{n_k}^k$, as follows:

$$R_j^k = \{p_i\text{: } p_i \text{ requires setup of type j on workcenter k}\} \qquad (6)$$

Thus, each part set, R_j^k, contains those parts that use a similar setup on workcenter k. All parts in R_j^k should be assigned to the same machine of workcenter k in order to take advantage of the similarity in setups.

$$\mathcal{A}(p_i \in R_j^k) = M_q^k \;\forall\, j = 1, 2, \ldots, n_k, \;\forall\, k = 1, 2, \ldots, Z \qquad (7)$$

where $\mathcal{A}(\bullet)$ denotes the machine to which p_i is assigned and M_q^k is the q-th machine of workcenter k. The definition of the part sets for each workcenter is performed prior to the cell formation procedure and is described in section 5.

An iterative heuristic procedure which reduces the maximum normalized inter-cell traffic at each iteration has been employed to solve the cell formation problem. The basic steps of this heuristic are similar to the ones in the Inter-Class Traffic Minimization Method (ICTMM) proposed in Harhalakis *et al.* (1990) and Minis *et al.* (1990). However, further enhancements were necessary to address the setup part family constraint. In addition, the criterion for assigning parts to specific members of a multi-machine workcenter is different from the one used previously.

The following input information is necessary for the cell formation heuristic:

- The set of workcenters (workcenter number, description, number of functionally identical machines, performance factor, moveability status, and capacity).
- The set of parts (demand over a pre-defined horizon, average pallet size, average batch size, and part description).
- The production routings, or process plans, of all parts.
- The maximum number of machines allowed per cell.
- For each workcenter k, the sets of parts, $R_1{}^k,\ldots,R_{n_k}{}^k$, which have similar setups .

The principal steps of the cell formation algorithm are summarized in the flow-chart shown in Fig. 2. In the initial shop partition each machine is placed into a distinct cell. Multi-machine workcenters are represented by a single member. For each pair of cells (c_i, c_j) the normalized inter-cell traffic $\bar{t}_{ij}$ is evaluated using Eq. (8)

$$\bar{t}_{ij}=\frac{t_{ij}}{q_i+q_j}=\frac{\sum_{u\in c_i}\sum_{v\in c_j} t_{uv}}{q_j+q_j} \qquad (8)$$

where q_i and q_j represent the number of machines in cells c_i and c_j respectively and t_{uv} is the traffic between a pair of machines (u, v) with $u \in c_i$ and $v \in c_j$. The inter-cell traffic value t_{ij} is normalized in Eq. (8) by $q_i + q_j$ in order to favor the union of smaller cells (Harhalakis *et al.*

1990).

The key step of the algorithm is the second one in which the potential normalized traffic, $\bar{t}_{ij}$, between all pairs of cells is determined. The cell with the maximum normalized inter-cell traffic, max $\{\bar{t}_{ij}\}$, is merged in Step 5 and the total traffic is reduced by the value t_{ij}. Thus, at each iteration of the algorithm the pair of cells with the maximum normalized inter-cell traffic are merged respecting all constraints. The procedure continues until the cell size constraint prevents further cell merging.

To evaluate t_{uv} three distinct cases are considered: (1) a pair (u, v) consists of two unique machines, (2) a pair (u, v) consists of a unique machine and a member of a multi-machine workcenter, and (3) a pair (u, v)consists of machines belonging to different multi-machine workcenters. Case (1) is the simplest since the assignment of parts to machines is pre-defined and the traffic value, t_{uv}, is computed directly from Eq. (2). In cases (2) and (3), however, those parts that are processed by the multi-machine workcenter have to be assigned to a specific member of this workcenter. The assignment affects the value of t_{ij} and, thus, should be performed prior to its calculation.

This traffic t_{uv} is computed in a manner that respects both the capacity and the part setup constraints. To compute t_{uv} for case (2), the list of all parts that visit the unique machine M_u and the multi-machine workcenter G^p in sequence (M_u, G^p) or (G^p, M_u) is compiled and ranked. Parts are selected from this list and assigned to a specific member, G_v^p, of this workcenter. The part list is ranked according to the following criterion.

$$f_h^{uv} = \frac{e_h^{uv}}{b_h^{uv}} \tag{9}$$

where e_h^{uv} is the inter-cell pallet traffic contributed by the movement of part p_h between M_u and G_v^p and b_h^{uv} is the processing time required by this part on G_v^p. Parts with high f_h^{uv} values contribute considerable traffic between M_u and G_v^p, while consuming a small percentage of capacity of G_v^p. If such parts are assigned to G_v^p and the two machines are merged to a single cell, then a large number of inter-cell moves will be saved.

If the part under consideration is a member of a setup part family, the entire part family must be considered in the traffic value. Note that only the members of the family with the proper sequence between M_u and G^p are considered when computing the traffic, c_h^{uv}. However, since the entire part family must be assigned to a machine as a single unit, the cumulative run time of all parts of the family is considered when computing b_h^{uv} ; only a fraction of the cumulative setup time is used, however, in order to reflect the savings in setup. All parts/families in the above list are then ranked in descending order of of Eq. (9). The traffic between M_u and G_v^p is calculated by starting at the top of the list and considering the parts in decreasing order of f_h^{uv} until the capacity of G_v^p is exhausted. Thus, if the two machines under consideration are merged into one cell in *Step 5* of the algorithm, the maximum possible traffic between the two cells will be eliminated within the existing capacity and setup family constraints.

In case (3) t_{uv} is determined by considering a single representative from each of the two functionally identical machines and their respective capacities. The manner in which the parts are then assigned to Gu^p and Gv^q, and the calculation of t_{uv}, is similar to the procedure for case (2) discussed above.

The output of the algorithm of Fig. 2 includes (1) the assignment of machines to cells, and (2) the assignment of parts and/or part set-up families to specific members of multi-machine workcenters. Prior to implementing proposed cells, two evaluation tests are performed. First, the benefits resulting from the formation of each cell are estimated. Secondly, the robustness of the cellular arrangement with respect to changes in the product mix is assessed. Both tests are discussed and illustrated in the case study of section 5.

4 Facility Layout

Given the framework presented in section 2, the objective of the layout problem is stated as follows:

$$\text{Minimize: } E = \sum_{i=1}^{M} \sum_{j=1}^{(i-1)} \left(t_{ij} \times d_{ij}\right) \tag{10}$$

where E is the total distance resulting from part transfers between resources within the specified time horizon, M is the number of resources, t_{ij} is the traffic between resources i and j expressed in the number of pallet transfers, and d_{ij} is the shortest feasible distance between resources i and j. This distance is computed from the exit of resource i to the entrance of resource j in a manner that avoids passing through resources and shop floor restrictions. In the intra-cell layout case, resources are the machines belonging to a cell, while in the shop layout case resources are the cells and remaining unassigned machines.

The problem is subject to area overlap constraints, which ensure that one and only one resource block (Fig. 1) is assigned to each node, Eq. (11), and that each resource block is assigned to a grid node, Eq. (12).

$$\sum_{i=1}^{M} \sum_{r=1}^{N_i} K_{rq}^{i} \leq 1 \qquad q = 1,\dots,S \tag{11}$$

$$\sum_{q=1}^{S} K_{rq}^{i} = 1 \qquad i = 1,\dots,M;\ r = 1,\dots N_i \tag{12}$$

$$K_{rq}^{i} \in \{0,1\} \tag{13}$$

where

$$K_{rq}^{i} = \begin{cases} 1 \text{ if block r of resource i is assigned to location q} \\ 0 \text{ otherwise} \end{cases} \tag{14}$$

In Eq. (11) through Eq. (14), S is the number of nodes of the grid, M is the number of resources, and N_i is the number of building blocks required to satisfy the area requirements of resource i.

As previously noted, the layout problem is NP-complete, and thus a heuristic method has been developed to find a near-optimal solution in a reasonable amount of time. The method employs simulated annealing (SA) in order to avoid local optima and to provide several alternate solutions from the same initial configuration. The shortest distance, d_{ij}, between all pairs of resources is determined at each iteration of the method through repeated applications of

Dijkstra's algorithm, (Cormen *et al.* 1990), which is an optimal method to solve the standard shortest path problem. The distances between resources are computed from the exit of the output resource to the entrance of the input resource along the grid edges of the shortest path. The following input information is necessary for the layout method:

- For each resource the following data are provided: the size of its rectangular envelope, its moveability status, and the location of its exit and entrance. Figure 3 shows the conventions used to define this information. For the example in Fig. 3, the location of the resource entrance is given by the pair (3, x_2), where 3 is the side of the rectangular envelope which contains the entrance and x_2 is its distance from the origin of side 3.
- The set of area restrictions, defined by location and rectangular size.
- The geometry of the area that is available for the placement of resources. Note that the dimensions of the shop, the resources, and the restricted areas should be given in the same units.
- The minimum width of material handling corridors. This value is used to artificially increase the size of each resource and to allow for material transfer corridors between resources.
- The input parameters required for the SA algorithm.

Figure 4 provides the flow chart of the layout algorithm. First, the resources are placed randomly onto the available area. Note that in the case of cell and/or shop re-design the resources of moveability type C are placed onto the grid at user specified locations. These entities are immovable throughout the layout analysis. The SA parameters defined in Step 2 are provided in Table 2. Given an initial configuration, new system configurations are generated in step 3 by applying the following operations: (1) **Swap**: Exchanges two entities. (2) **Translate**: Moves an entity one unit from its original position along one of four orthogonal directions: up, down, left, or right. (3) **Rotate** Rotates an entity by 0°, 90°, 180°, or 270°. A random number generator is utilized at each iteration to select the type of operation to be performed: swap, translate, or rotate. Since SA is most effective when small configuration changes are performed, the probability of choosing between these operations is not uniform. **Swap** alters the "energy" of the system the most, and thus, it has the lowest probability of being selected (0.2). The other two remaining operations, **translate** and **rotate** have a smaller impact on the system's energy, and thus are selected with probability of 0.4 each.

Note that the superiority of SA-based algorithms to other facility layout methods has been shown conclusively in Jajodia *et al.* (1992), in which a large set of classical layout problems were solved by several methods, in addition to SA. In each case, SA outperformed all other methods. The present method is possibly the most advanced version to-date of SA-based algorithms, since it considers (1) the size of resources, (2) restricted areas, and (3) realistic material handling paths that do not cross through resources and restrictions.

4.1 Intra-cell Layout

The general algorithm presented above is utilized as is for the intra-cell layout problem. This algorithm is executed for each significant cell identified by the cell evaluation stage. The following assumptions are used:

- The cell entrance and exit are defined as unit square "resources" from which the parts enter and leave the cell. The location of these "resources" within the available area is to be determined by the procedure.
- The part routings are modified appropriately to include the entrance and exit "resources."
- Acceptable cell configurations are only those which allow unobstructed access to the entrance and exit of the cell along one of the four orthogonal directions.

The size and shape of the cell may or may not be given as input. In the latter case, the initial area is unrestricted and the final configuration defines the cell boundaries. The engine described in Fig. 4 is utilized to solve the problem and provides the following outputs:

- The optimal or near-optimal intra-cell layout
- The size and shape of the cell, if not given as input
- The location of the cell's entrance and exit

- The flow paths between each pair of machines
- The final value of the objective function.

4.2 Shop Layout

The shop layout problem is also solved using the same SA-based algorithm described in Fig. 4. The resources considered include the significant manufacturing cells designed in the previous step as well as the remainder of the machines in the shop. The shop layout algorithm considers two additional critical issues that have not been addressed by the general SA algorithm.

Re-assignment of parts to independent machines

This issue arises from the fact that more than one functionally identical machines may be included among independent machines to be placed on the shop floor. For every new system configuration involving the movement of member G_i^j of a multi-machine workcenter G^j the assignment of all operations which utilize such a machine should be re-examined for the following reason. Consider a part which visits G_i^j for a particular operation in its routing. Also consider that the preceding and succeeding operations to G_i^j in the part's routing are performed in resources R_u and R_v, respectively. Since the relative distances $d_{(R_u, G_i^j)}$ and $d_{(G_i^j, R_v)}$ have been changed, the assignment of this part to another member of the G^j workcenter may be more appropriate with respect to inter-resource distance.

Note that re-assignment of operations already assigned to machines that are members of cells is not considered, since the cell formation was based on these assignments. For each iteration of the algorithm, which involves the movement of such a machine G_i^j, the following heuristic procedure is employed for operation re-assignment. A list is generated to include all operations assigned to all independent machines of workcenter G^j. For such operations all possible sequences, $(R_u G_i^j R_v)$are determined, where as before R_u and R_v are the predecessor and successor operations (which are fixed), and G_i^j may be any of the available members of G^j. Furthermore, for each such sequence the distances, $d_{(R_u G_i^j)} + d_{(G_i^j R_v)}$, are evaluated. The list of all sequences for all operations is ranked in ascending order of $d_{(R_u G_i^j)} + d_{(G_i^j R_v)}$. Starting from the top of the list the sequences with the lower distance values are selected and the operations are assigned to the appropriate workcenter. This is repeated until all operations have been assigned. The part assignment is performed consistently with the objective of the algorithm and respects all problem constraints.

Swap between Cells and Machines

Since the size of a cell is usually much larger than the size of an independent machine, a cell-machine swap is usually not feasible. In this case, one or more machines are swapped with a cell as follows. The cell is moved to the location of the machine considered for the swap, Fig. 5. Any other machines encroached by the footprint of the cell are moved to the cell's original location, Fig. 5.

The modified algorithm provides the following outputs:

- The optimal or near-optimal shop layout
- The flow paths of the optimal or near-optimal solution between each pair of resources
- The final part routings which specify the assignment of all operations to the most appropriate machines.
- The final value of the objective function.

5 Case Study

The integrated methodology for hybrid shop design was utilized to partially re-arrange the existing radar chasis production facility of a large manufacturer of radar antennas. The redesign effort included both manufacturing cell formation and design of the shop layout. At any given time more than 4,000 different parts are active in the MRP II system of the radar chassis facility. These parts span a wide variety of shapes and a large range of sizes. The production shop consists of approximately 160 workcenters, some of which include more than one machines. It is functionally arranged and includes lathes, brakes, welding stations, assembly stations, painting stations, plating stations, and bonding stations.

In order to rearrange the radar chassis manufacturing facility, the inputs listed in sections 3 and 4 were obtained directly from the MRP II system in files which were pre-processed to conform to the input requirements of the software system. Note that functionally identical machines were represented by common designations in the part routings. This implied that an operation could be processed by any member of a multi-machine workcenter. The analysis employed the following assumptions:

- The redesign was based on the production volumes for two years (1993 and 1994). The demand beyond 1994 was not utilized due to the uncertainty associated with it. The actual demands for previous years (1990-1992) and the forecasted demand for 1995 were used to test the robustness of the cell formation solution.
- The capacity of each machine was set to 8,320 hours; over the two year horizon this corresponds to two 8-hr. shifts per day, five days per week.
- A limiting cell size of six was selected for the cell formation stage after consulting with company industrial engineering personnel.
- Inspection workcenters were removed from the analysis, since they could not be assigned to a specific cell.
- Several workcenters were consolidated, including: (1) The machines of the model shop; the resulting workcenter was given a moveability status of C. (2) The plating baths, which are always visited by the parts in sequence. The resulting workcenter was given a type D moveability status. It is noted that most manufactured parts are processed through this workcenter.

After pre-processing, the redesign problem included 69 workcenters, containing a total of 103 machines, and 3,271 parts.

<u>Setup Family Formation</u>

A simple utility was developed to aid the company's personnel to identify the setup part families. It consists of 2 steps. The first step computes for each workcenter the percentage of operating time spent in setup, and the overall utilization of the workcenter. The partial output of the first step (first 32 workcenters) is shown in Table 3. This information identified: (1)

underutilized workcenters, (2) bottleneck workcenters, and (3) workcenters that spend a significant portion of their available capacity in setup. In the second step, for each bottleneck workcenter, a list of all parts that are processed by it was generated. These parts were ranked in descending order of the ratio of setup time to total time (setup and run time) required for the corresponding operations. Table 4 shows the ranked parts for workcenter FDHB03 (#32 of Table 3). The latter was chosen for further analysis due to its high utilization. The drawings and process plans of the 44 parts which visit this workcenter were examined by the company's industrial engineering personnel to determine similarities in setup and to standardize their jigs and fixtures. Other potential workcenters to be analyzed are workcenters FJKB02 (#18) and FDHK01 (#21) of Table 3.

Cell Formation

The pre-processed manufacturing data were provided as inputs to the cell formation stage of the software system. This module identified 27 cells, 11 of which consisted of six machines. The efficiency of the proposed cellular arrangement was evaluated from:

$$\text{Group Technology Effeciency} = \frac{T^F - T^C}{T^F} \times 100\% \qquad (13)$$

where T^F is the inter-departmental traffic in the initial shop configuration and T^C is the inter-cell traffic in the cellular arrangement. The G.T. effeciency was found to be 50.11%. Note that a major source of inter-cell traffic in the proposed solution is the plating workcenter, which (1) cannot be included in any cell and (2) is visited by the majority of parts in the system. If the unavoidable inter-cell traffic to and from this workcenter is not considered in the calculation, the resulting G.T. efficiency value increases to 65.24%.

The proposed cells were ranked by the number of parts processed by each cell (as a percentage of the total number of parts in the system). Table 5 shows the seven most significant cells and the corresponding cell utilization ratio. In addition, the machines comprising each cell are listed. The index in parenthesis following some of the machine numbers identifies the particular member of a multi-machine workcenter. Three of these cells, #15, #19, and #20, already existed in the facility. The fact that the cell formation method yielded these three cells is significant since (1) it validates the cell formation criterion with respect to company expectations and (2) it validates the cell formation algorithm. The four remaining significant cells, #2, #6, #9, and #27, were proposed for implementation.

The benefit of creating the proposed four cells was evaluated by calculating the expected reduction in inter-cell traffic. This was done by computing the number of inter-group moves for the current shop configuration, then recomputing this value with the addition of the suggested significant cells. Intra-group moves in the functional configuration are those within a department or an existing cell while in the hybrid configuration are those within the cells. Table 6 provides the results obtained based on a two-year horizon (1993-1994). The creation of the proposed cells yields a reduction of 7,603 inter-group moves (25.18% of the total inter-group moves). Note that in the functional configuration each inter-group move consists of: (1) transfer from a department (cell) to an inspection station, (2) transfer to the dispatch center, and (3) transfer to the next department (cell). Thus, by confining inter-group moves within cells, the material handling within the shop as well as the corresponding logistics are dramatically reduced.

The second evaluation test examined the robustness of the proposed cellular formation with respect to changes in production volumes and/or changes in part mix. Three time horizons, each spanning a four-year interval, were utilized to determine the effectiveness of the solution with respect to savings in material handling. These horizons included the demands between 1990-1993, 1991-1994, and 1992-1995. For each time horizon a separate arrangement was obtained using the cell formation stage of the method: A_1 for 1990-1993, A_2 for 1991-1994, and A_3 for 1992-1995. The results of the robustness analysis are shown in Table 7. Each entry, a_{ij}, of the matrix represents the G.T. Efficiency [see Eq. (13)] of cellular arrangement A_j over time horizon i. Thus, the column corresponding to each arrangement shows the change in G.T. Efficiency under different production volumes. Notice that the differences among the matrix elements are not statistically significant. Thus, for this case, the efficiency of the cells is unaffected by changes in the production volume and part mix.

Currently, one of the four proposed cells has been constructed in the company facility. The implementation of the three remaining significant cells will be completed in the near future.

Intra-cell layout

The intra-cell layout of each of the significant cells given in Table 5 was determined using the method described in section 4.1. The SA parameter values used and the machine size and entrance-exit location data can be found in (Lu 1993).

Figure 6 shows the layout of cell #2. Note that the cell is arranged compactly in a triple row configuration. This solution provides for short material handling distances between the machines of the cell. Table 8 provides the traffic between all pairs of machines in this cell. Note that the largest intra-cell traffic value corresponds to machines FDVM01 and OUT which have been placed in adjacent locations within the cell. In general, a high intra-cell traffic value between two machines corresponds to an adjacent placement. There are three distinct areas in the cell which are left empty: the top right, the top left, and the bottom right areas. This is due to the shapes and sizes of the machines in the cell. These areas can be utilized as buffers for incoming or outgoing parts. If they are not included in the cell, its envelope will no longer be rectangular, which may or may not be a desirable solution. The layouts of the remaining cells are given in Lu (1993).

Shop layout

The final stage of the hybrid facility design is the placement of the significant manufacturing cells and the remaining individual machines on the shop floor. The sizes of the manufacturing cells and the locations of their entrance and exit were determined from the cell layouts and are given in (Lu 1993). The dimensions of the shop area, as well as the restricted shop sub-areas were determined from shop drawings. The grid representing this area was provided to the software as input. In the first step of the analysis, the machines with moveability status C and the cells that contain such a machine were placed on the shop grid. These resources remain immovable throughout the execution of the algorithm, since they have been designated by the industrial engineering personnel of the company as very costly to move. Both these restrictions and the immovable machines/cells are appropriately identified in the Fig. 8. The SA parameters employed by the algorithm are given in (Lu 1993).

The final layout of the facility is shown if Fig. 8. To validate this solution, the pairs of resources which share high traffic were examined to ensure that they are located adjacent to one another. Table 9 shows the five pairs with the highest inter-resource traffic. Note that all of these resources are adjacent to one another. Furthermore the effectiveness of the part reassignment was validated by examining the process plans of several parts. In all reassignment cases, the distance travelled by the parts was reduced.

The unoccupied space between the resources may be explained by the large variation in resource size and the immovability of some of the resources. This layout may further be improved with user manipulation. For example, in the present study, inter-resource corridors are defined from the shortest paths between the corresponding entities, which may potentially create a very large number of corridors. The user may shift some entities to create inter-cell avenues, on which the majority of material will flow.

5. Conclusions and recommendations

An integrated methodology for hybrid facility design was presented in this paper. It may be used for both the re-design of existing shops and the design of planned facilities with forecasted product demands and pre-defined process routings. The methodology comprises four stages: (1) formation of logical manufacturing cells, (2) evaluation of significant cells, (3) determination of the intra-cell layout, and (4) determination of the hybrid shop layout.

One of the most important contributions of this methodology is its practicality. Major features include: (1) Formation of practical cells while respecting machine capacity and preserving part families with similar setups. (2) Evaluation of the cellular arrangement with respect to savings in material handling and to robustness in demand changes; it is noted that only robust arrangements are appropriate for implementation in practice. (3) Design of a hybrid shop layout consisting of machines and cells. The latter is the most appropriate type of layout for the majority of practical manufacturing systems.

The following conclusions were obtained from the development and application of the hybrid facility design methodology:

- A pure cellular arrangement is not practical in typical industrial environments.
- The hybrid (cellular/functional) facility design problem is conveniently decomposed in a sequence of subproblems, i.e. cell formation and evaluation, cell layout, and shop layout.
- These subproblems may be solved more than once to arrive at a good solution.
- It is necessary to consider a consistent objective for all stages of the facility design problem.
- Practical issues, such as similarities in setups and changes in production mix, should be considered, if the final solution is to have practical significance.
- The objective of minimizing material handling within the shop is a critical one. This was validated by the fact that some of the proposed cells in the case study were already implemented in the facility.

Acknowledgements

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Figure Index

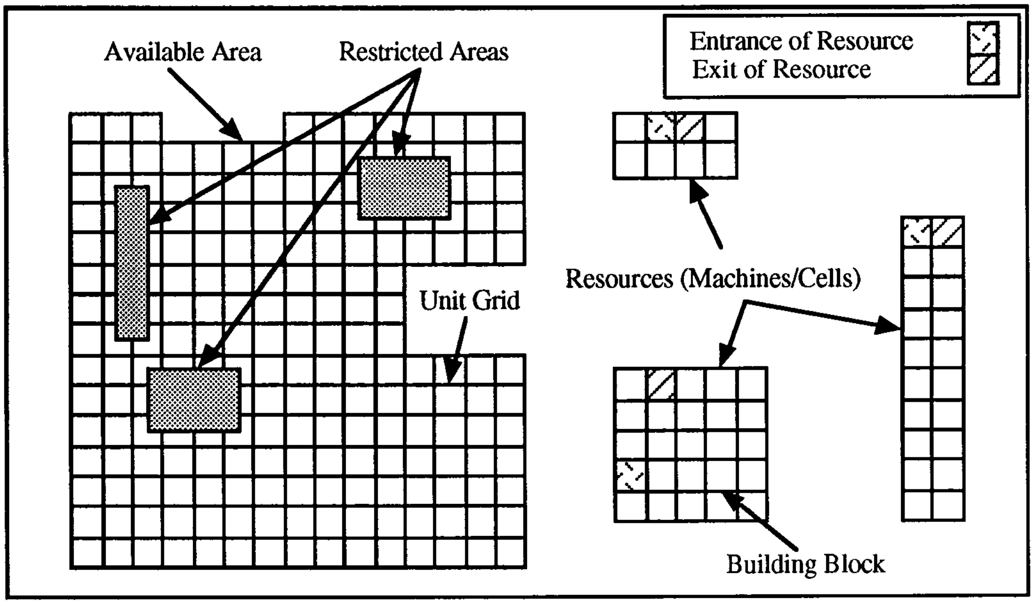

Entrance of Resource
Exit of Resource
Available Area
Restricted Areas
Unit Grid
Resources (Machines/Cells)
Building Block

Figure 1

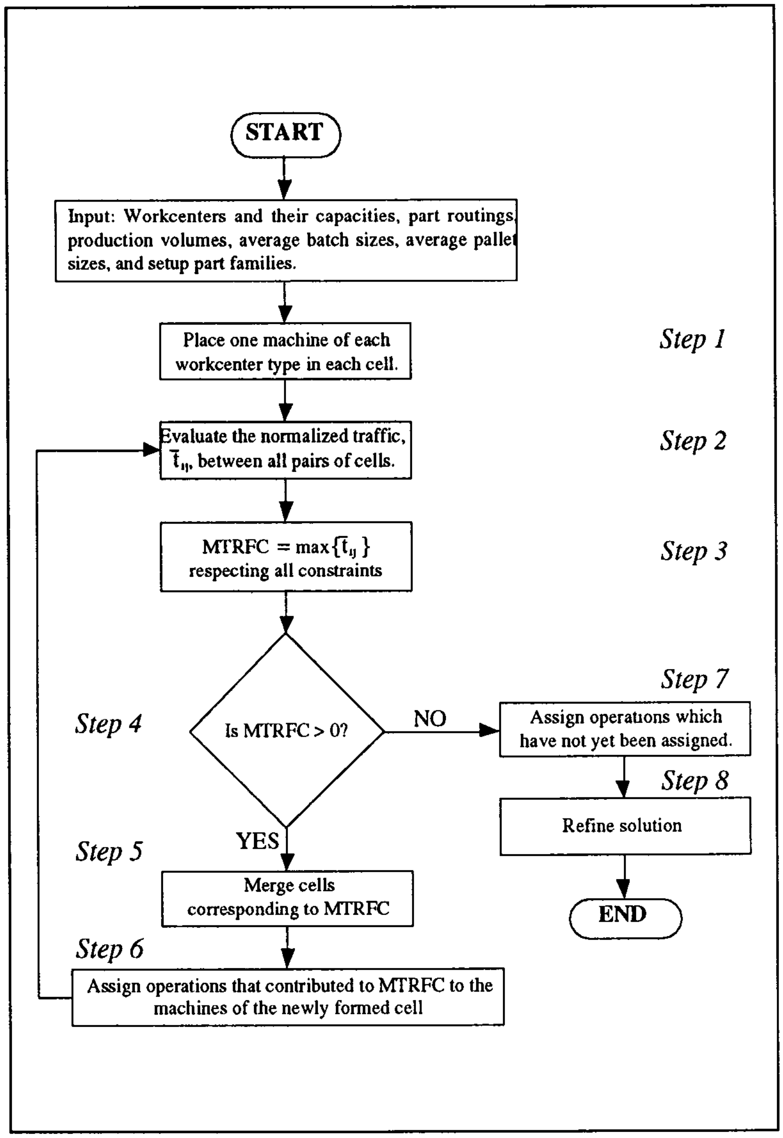
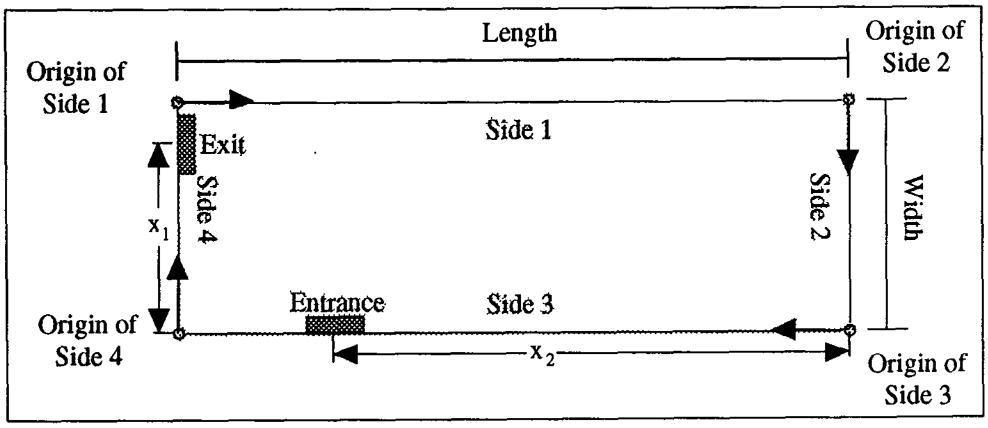

START
Input: Workcenters and their capacities, part routings, production volumes, average batch sizes, average pallet sizes, and setup part families.
Place one machine of each workcenter type in each cell.
Step 1
Evaluate the normalized traffic, $\bar{t}_{ij}$, between all pairs of cells.
Step 2
MTRFC = max{$\bar{t}_{ij}$}
respecting all constraints
Step 3
Step 4
Is MTRFC > 0?
NO
Step 7
Assign operations which have not yet been assigned.
Step 8
Refine solution
END
YES
Step 5
Merge cells corresponding to MTRFC
Step 6
Assign operations that contributed to MTRFC to the machines of the newly formed cell

Figure 2



Length
Origin of Side 1
Origin of Side 2
Side 1
Exit
Side 4
x_1
Side 2
Width
Entrance
Side 3
Origin of Side 4
x_2
Origin of Side 3

Figure 3

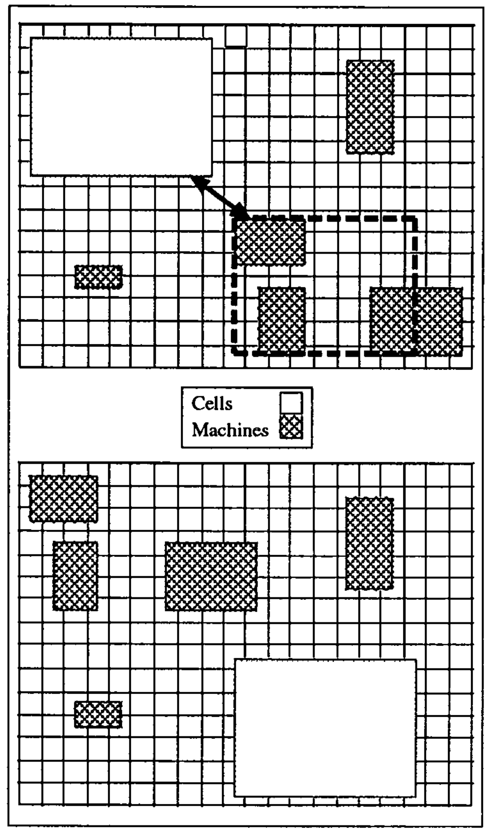


Figure 5

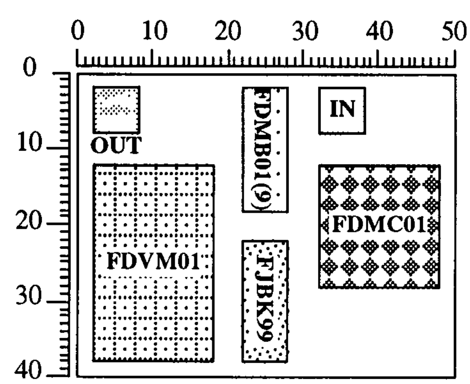


Figure 6

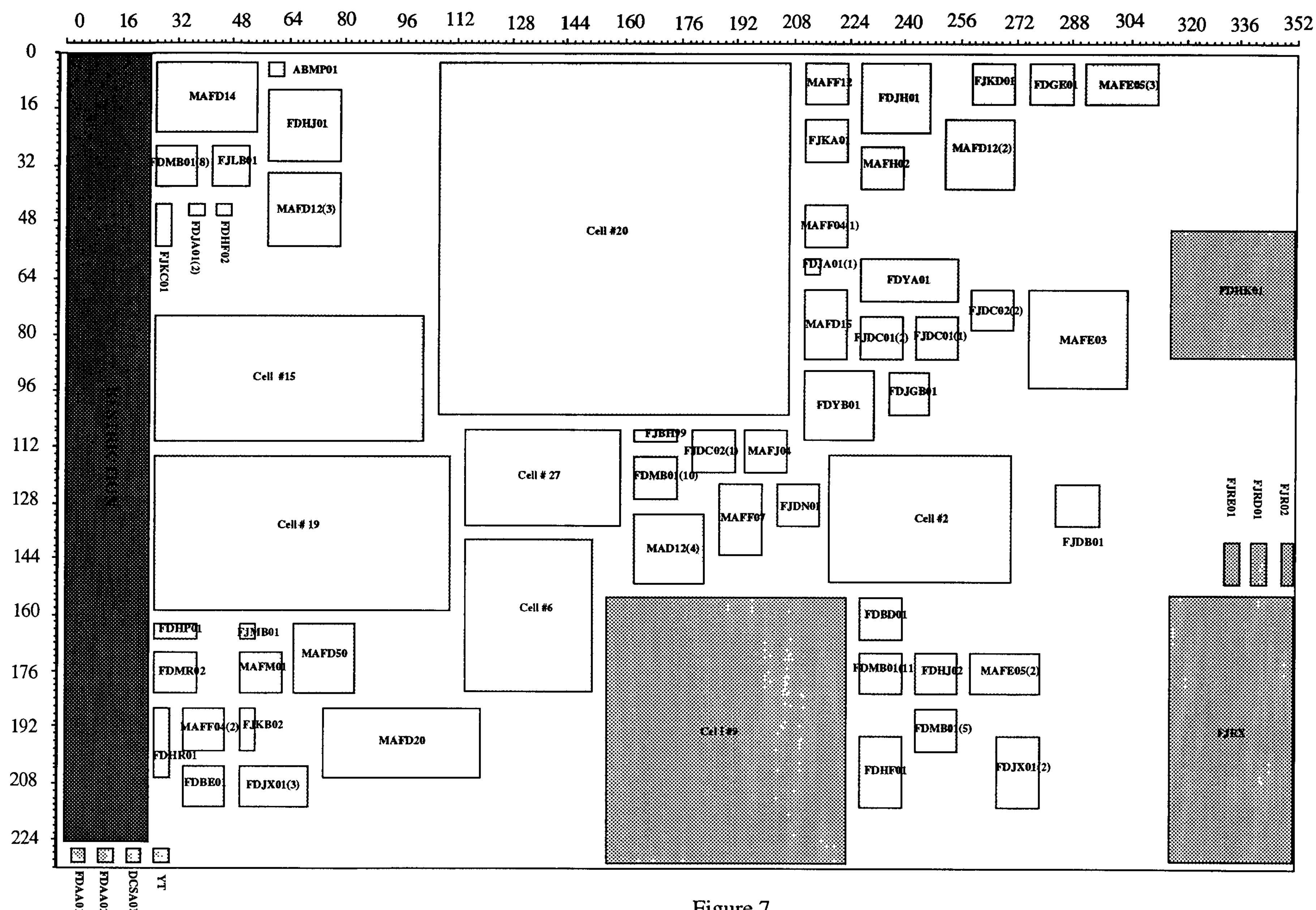

0
16
32
48
64
80
96
112
128
144
160
176
192
208
224
240
256
272
288
304
320
336
352
ABMP01
MAFD14
FDHJ01
FDMB01(8)
FJLB01
MAFD12(3)
FJKC01
FDJA01(2)
FDHF02
Cell #15
Cell #20
Cell # 19
Cell # 27
Cell #6
FDHP01
FJMB01
MAFD50
FDMR02
MAFM01
MAFF04(2)
FJKB02
FDHR01
MAFD20
FDBE01
FDJX01(3)
MAFF12
FDJH01
FJKD01
FDGE01
MAFE05(3)
FJKA01
MAFH02
MAFD12(2)
MAFF04(1)
FDJA01(1)
FDYA01
FJDC02(2)
MAFE03
FDHK01
MAFD15
FJDC01(2)
FJDC01(1)
FDYB01
FDJGB01
FJBH09
FJDC02(1)
MAFJ04
FDMB01(10)
MAFF07
FJDN01
Cell #2
FJDB01
FJRE01
FJRD01
FJR02
MAD12(4)
Cell #9
FDBD01
FDMB01(11)
FDHJ02
MAFE05(2)
FDMB01(5)
FDHF01
FDJX01(2)
FJRX
FDAA01
FDAA02
DCSA01
YT

Figure 7

Table Index

Table 1

Status	Assumption
A	Workcenter is easily moveable; moving costs are negligible
B	Workcenter is moveable if necessary; moving costs are significant
C	Workcenter is immovable; moving costs are prohibitive
D	Workcenter is not to be merged with other machines

Table 2

Variable	Definition
T	Initial temperature
TFTR	Annealing schedule factor (0.0-1.0)
NITER	Total number of temperature changes
NTEMP	Total number of iterations at each temperature
NSUCC	Number of successes at each temperature before continuing to the next temperature

Table 3

	Workcenter	SU/(SU+RU)	(SU+RU)/CP
1	FDHJ02	98.002%	0.016%
2	FDHJ01	95.029%	0.145%
3	FDGB01	92.308%	0.008%
4	FDHF02	86.483%	0.279%
5	FDHG01	85.860%	5.039%
6	FDHB01	82.525%	7.626%
7	FDHF01	78.406%	2.877%
8	FDHB02	77.804%	6.643%
9	FJKD01	74.622%	0.035%
10	FDHP01	73.072%	0.143%
11	FJKC01	64.888%	0.268%
12	MAFE12	63.155%	4.752%
13	FDGE01	61.757%	0.127%
14	FJBH99	59.866%	0.148%
15	FJRD01	59.524%	0.010%
16	FDHR01	54.645%	0.002%
17	MABF01	53.854%	0.513%
18	FJKB02	49.779%	11.191%
19	FDJA01	48.644%	2.570%
20	MAFE03	43.871%	4.982%
21	FDHK01	42.935%	15.903%
22	MAFE05	41.777%	8.406%
23	FDFJ04	40.887%	3.718%
24	FDJH01	39.500%	0.948%
25	FJDN01	39.185%	0.005%
26	FDYC01	36.089%	0.426%
27	MAFF12	34.145%	2.551%
28	FDYA01	33.789%	1.632%
29	FDHN01	32.442%	5.166%
30	FJRE02	28.289%	0.059%
31	DCSA01	27.083%	1.957%
32	FDHB03	25.050%	69.407%

Table 4

	Part Number	SU/(SU+RU)
1	3D60822H01	93.46%
2	612J728G01	70.59%
3	612J724G01	49.95%
4	612J726G01	48.87%
5	613J123G01	44.44%
6	3D55187G01	36.54%
7	3D55422G01	33.58%
8	613J014G01	30.62%
9	3D55426G01	28.38%
10	3D55421G01	26.95%
11	3D55425G01	23.09%
12	613J125G01	23.08%
13	159C469H01	22.72%
14	3D55424G01	22.50%
15	3D55423G01	22.50%
16	3D55418G01	9.09%
17	612J729G01	4.76%
18	613J017G01	4.52%
19	613J001G01	4.40%
20	613J124G01	4.40%
21	613J012G01	3.55%
22	613J011G01	3.55%
23	613J010G01	3.55%
24	613J009G01	3.55%
25	613J008G01	3.55%
26	613J007G01	3.55%
27	613J006G01	3.55%
28	613J005G01	3.55%
29	613J004G01	3.55%
30	613J013G01	3.55%
31	613J003G01	3.55%
32	613J002G01	3.55%
33	613J021G01	3.41%
34	613J023G01	3.33%
35	613J022G01	3.33%
36	613J020G01	3.33%
37	613J019G01	3.33%
38	613J018G01	3.33%
39	613J016G01	3.33%
40	613J015G01	3.33%
41	612J725G01	0.00%
42	612J596G01	0.00%
43	3D58640G01	0.00%
44	612J727G01	0.00%

Table 5

Cell	Cell Utilization	Machines
Cell #20	14.41%	FDGA01 FDHK01(1) FDHK03 FDHN01 FDHB03 FDHB02
Cell #9	13.80%	FJLA01 FJLB01(1) FJKB02(1) FDMB01(1) FJLB01(2) FDMB01(7)
Cell #15	9.65%	MAFE12 MAFH01 MAFJ04(1) FJDC02(1) FJDC01(1) MAFE03
Cell #2	8.52%	FJBK99 FDMC01 FDVM01 FDMB01(9)
Cell #27	8.15%	FDMD01(1) FJKB02(2) FDMB01(2) FJDB01(1) FDMB01(3) FJKB02(3)
Cell #6	8.15%	F2 FDJX01(1) FDMB01(4) FDMB01(6) MAFD50(1) MAFJ04(3)
Cell #19	7.42%	FDFJ04 FDHB01 FDHG01 FDHF01(1) FDYC01 MABF01(2)

Table 6

	Functional Configuration		Hybrid Configuration	
Number of Inter-group moves	30,190	(78.82%)	22,587	(59.00%)
Number of Intra-group moves	8,112	(21.18%)	15,705	(41.00%)
Total number of moves	38,302	(100.0%)	38,302	(100.00%)

Table 7

Time Horizon	A_1	A_2	A_3
1990-1993	44.19%	43.35%	44.56%
1991-1994	44.62%	43.95%	45.31%
1992-1995	44.37%	43.68%	45.49%

Table 8

	IN	FDVM01	FJBK99	FDMB01(9)	FDMC01	OUT
IN	0					
FDVM01	139	0				
FJBK99	273	533	0			
FDMB01(9)	1405	456	753	0		
FDMC01	1064	138	422	83	0	
OUT	0	1835	23	124	13	0

Table 9

Resource Pair			Inter-resource Traffic
CELL #9	-	CELL #6	2408
FJBH99	-	CELL #20	2066
CELL #15	-	CELL #20	1701
CELL #19	-	CELL #20	1338
CELL #19	-	CELL #27	942