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Manufacturing Cell Formation with Multiple, Functionally Identical Machines

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Manufacturing Cell Formation with Multiple, Functionally Identical Machines

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ABSTRACT

A comprehensive methodology for the formation of manufacturing cells in an environment consisting of unique as well as multiple, functionally identical machines is presented in this paper. The proposed method presupposes the existence of generic process plans that specify the types of machines required for the manufacture of each part, although more than one machine of the same type may be available in the shop. The production equipment is grouped into manufacturing cells and the manufactured parts are assigned to part families, based on an inter-cell traffic minimization criterion and subject to capacity constraints. Two or more functionally identical machines are included in a cell, only if necessitated by capacity considerations, or traffic minimization arguments. The method also considers both part set-up and run times for the evaluation of the capacity requirements, and uses pallet traffic as opposed to individual part traffic in the minimization criterion.

1. Introduction

The layout of a discrete parts manufacturing shop can be classified into two types: (i) Functional, wherein each group of functionally similar machines occupies a dedicated area of the shop floor. (ii) Cellular, wherein the production equipment is disaggregated into manufacturing cells. In this case, each cell contains most of the machines that are required to produce one or more families of parts with similar processing requirements.

Immediate benefits of cellular manufacturing include reductions in traffic of parts within the shop, which, in turn, reduce material handling efforts and costs [1,2]. Furthermore, since the machines within each cell are dedicated to the production of similar parts, set-up times are minimized, thus, leading to significant reductions in work-in-process inventory levels and product queue times [1,2]. Finally, the scheduling problem is simplified, since it can now be addressed at two different levels, the shop floor level and the aggregate or cell level. The principal disadvantages of cellular manufacturing include uneven distribution of workloads within cells and the disruptive effects of machine breakdowns [2]. A comprehensive study that compares the performance of cellular and functional layouts is presented in [3].

Extensive research efforts have focused on the development of methods to disaggregate a machine shop into manufacturing cells. They can be categorized into two classes. The first class of such methods models the production system by a part-machine incidence matrix, each column of which represents one machine type and each row the production routing of a part. Clustering analysis is then used to re-arrange the rows and columns of the matrix in order to obtain a block-diagonal matrix form. The machines and parts that correspond to each block are considered to form a manufacturing cell and a part family, respectively. A wide spectrum of clustering techniques have been proposed to re-arrange the part-machine incidence matrix in such a way that the number of operations performed on the part families within their cells is maximized. These include the rank order clustering approach of King [4], the method of McCormick *et al.* [5], the direct clustering algorithm of Chan and Milner [6], and the GPM method of Garcia and Proth [7,8]. Various measures have also been proposed to quantify the similarity between the columns and rows of the incidence matrix. Pairs of machines (parts) that correspond to high values of these measures are placed in the same cell (part family). Clustering approaches based on similarity measures have been proposed by McAuley [9], Leskowsky *et al.* [10], and Carrie [11], who applied Weishardt's algorithm in practical cases.

Those grouping methods that simply re-arrange the part-machine incidence matrix have the disadvantage that they do not consider certain important characteristics of the production system, i.e.: (i) The sequence of operations in a part's production routing, although critical for material flow applications, is not represented in the incidence matrix, since each entry a_{ij} can only signify whether or not machine j is used to manufacture part i. (ii) Workload data such as capacity required by parts and capacity available on machines are not considered either. As a result, the final cell formation may not be feasible due to overloads of certain machines within certain cells. It is noted that Choobineh [12] has proposed an improved clustering approach by introducing a similarity measure that accounts for the sequence of operations.

The second class of grouping methods is based on material flow considerations, which have traditionally been used for the layout of functional shops [11,13]. Tabucanon and Ojha [14] proposed a heuristic that forms manufacturing cells and the corresponding part families in order to minimize the inter-cell traffic of parts within the shop. The same objective is targeted by the Inter-Cell Traffic Minimization Method of Harhalakis *et al.* [15] (see also Nagi [16]). Although both techniques account for the sequence of operations in a part's production routing, they do not consider workloads and assume infinite capacity availability on work-centers.

Capacity considerations are critical in the case in which more than one machine of the same type may be present in the production system. It is emphasized that the presence of one or more groups of functionally identical machines that are represented by a single work-center designation is common practice in a job shop. Grouping methods that do provide for the case of functionally identical machines include the Knowledge Based Group Technology system of Kusiak [17] and Choobineh's two-stage grouping technique [12]. Both methods, however, create perfect cells between which no traffic flow is allowable. Consequently, the first technique results in a large general shop which processes those parts that cannot be manufactured entirely in a single cell. Furthermore, each group of functionally identical machines is assigned into a single cell, which constitutes a sub-optimal solution. The second method assigns to each cell as many machines as are needed to satisfy both the processing and the capacity requirements of the corresponding part family, considering no constraints on the number of machines available. Co and Araar [18] have also considered the case of functionally identical machines. During the first stage of a three-stage procedure, they distribute the parts processed by a group of functionally identical machines in such a way that the distribution of workload between the members of the group is even. The assignment procedure, however, does not consider the remaining operations in the parts' routings. Thus, very similar parts may be assigned to different machines of the group, resulting either in unnecessary traffic within the shop, or in the grouping of two or more identical machines to the same cell, although this is not necessitated by capacity requirements.

This paper presents a comprehensive methodology for manufacturing cell formation, which is unique, in that it minimizes the inter-cell material flow and properly distributes the functionally identical machines to accomodate capacity constraints. The proposed approach assumes the existence of generic routings that specify the types of machines required for the manufacture of each part. Furthermore, the number of units of each machine type is given. The method accounts for the sequence of operations in a part's routing. Two or more functionally identical machines are included in a cell only if necessitated by capacity requirements. The cell formation heuristic takes into account important parameters, such as the production volume of each part over a given time horizon, its average batch size, the set-up and run times for each operation in the part's production routing, and the average number of units of the part type that can be handled during a single transfer of the materials handling system. For simplicity this number is referred to as the pallet size.

The paper is organized as follows. The problem under consideration is formulated in Section 2. The detailed algorithm is presented in Section 3. An example which demonstrates the various features of the proposed system, and the application of the method to a large industrial case are included in Section 4. The conclusions of this study are presented in Section 5.

2. Problem Formulation

The problem consists of forming the set of manufacturing cells $C = \{c_1, c_2, \ldots, c_w\}$ in a way that minimizes the total traffic between cells (inter-cell traffic). Furthermore, the production routings of parts which visit one or more groups of identical work-centers have to be rewritten in order to reflect specific machines from each of these groups. The latter is performed concurrently with the cell formation process, in a manner that minimizes the traffic between cells. Finite capacities of machines are also taken into account while assigning parts to them. Figure 1 illustrates the framework of the problem and the appropriate notations employed. We consider a set of '(u+g)' machine types and a set of 'n' part types with pre-specified relationships between the two sets in the form of part production routings. The set of machine types is divided into two subsets: (i) the set of 'u' unique machines $M_U = \{m_1, m_2, \ldots, m_u\}$, and (ii) the set of 'g' groups of identical machines $M_G = \{G_1, G_2, \ldots, G_g\}$, wherein each group G_k includes K_k identical machines. A unique production routing r_h corresponds to each part type $p_h : p_h \in P = \{p_1, p_2, \ldots, p_n\}$, P being the set of part types. This routing identifies the sequence of machines used to manufacture the part under consideration, i.e.,

$r_h = < m_h(1), m_h(2), \ldots, m_h(L_h) > \;;\quad h = 1, \ldots, n,$

where $m_h(\lambda) \in M = M_U \cup M_G$ is the work-center required for the λ^{th} operation of part type p_h. L_h is the total number of distinct operations required for the manufacture of part p_h.

Note that a common designation is used to identify an operation performed on a part by any machine within a group of identical work-centers. This is the usual practice in most functionally arranged manufacturing shops and signifies the interchangeability among the machines of each group. The production volume of part type p_h over a given time horizon is represented by N_h.

The objective function of the problem can now be stated as follows :

Minimize:

$$T = \sum_{i=1}^{w-1} \sum_{j=i+1}^{w} \frac{t_{ij}}{q_i + q_j} , \qquad (1)$$

where w is the total number of manufacturing cells, q_i and q_j represent the number of machines in cells c_i and c_j respectively, and t_{ij} is the traffic between these cells, in terms of the number of pallet transfers; i.e.,

$$t_{ij} = \sum_{h=1}^{n} B_h(i,j)\, x_h(i,j) \,, \tag{2}$$

where $x_h(i,j)$ is the number of times part p_h has to be transferred between cells c_i and c_j during its manufacture. This number is determined by examining the number of times two machines, one belonging to cell c_i and the other belonging to cell c_j, appear in sequence within the production routing of part p_h. $B_h(i,j)$ is the number of pallet transfers required to move the corresponding number of units of part type p_h between cells c_i and c_j , and is defined as follows:

$$B_h(i,j) = \begin{cases} s_h(i,j)/\mu_h & \text{if } \operatorname{Mod}[s_h(i,j),\mu_h] = 0 \\ \operatorname{Int}\left(\dfrac{s_h(i,j)}{\mu_h}\right) + 1 & \text{if } \operatorname{Mod}[s_h(i,j),\mu_h] \neq 0 \,, \end{cases} \tag{3}$$

where μ_h is the pallet size of part type p_h and $s_h(i,j)$ is the number of units of part type p_h transferred between cells c_i and c_j.

Note that the ratio $t_{ij}/(q_i+q_j)$ used in the objective function of Eq.(1) represents the normalized traffic between the two cells. It is employed in order to favor the union of smaller cells at each step of the merging process [15].

The minimization of inter-cell traffic is subject to two sets of constraints:

(i) cell size constraints :

$$q_i \leq Q \qquad\qquad i = 1,\ldots,w, \tag{4}$$

where Q is the maximum number of machines allowable per cell, determined by the user. The value of Q depends on several factors, such as the volume of work, the interdependence between workers and machines, the labor skills required, the sizes of the machines, etc. [19].

(ii) machine capacity constraints for each machine G^k_j that belongs to group G_j :

$$\sum_{h=1}^{n} S_h(G^k_j) \left[\frac{\theta_h^{su}(G^k_j)}{\beta_h} + \theta_h^{run}(G^k_j) \right] \leq T_j \qquad k = 1,\ldots,K_j;\, j = 1,\ldots,g\,, \qquad (5)$$

where :

$S_h(G^k_j)$ is the number of units of part p_h processed by machine G^k_j,

$\theta_h^{su}(G^k_j)$ and $\theta_h^{run}(G^k_j)$ are the set-up and run times for part type p_h on machine G^k_j,

β_h is the average batch size of part type p_h, and

T_j is the capacity of each machine in group G_j.

It is noted that capacity constraints are only considered for those machines that belong to a group of functionally identical machines. Capacity overloads of unique machines are assumed unavoidable and are only reported by the system.

3. The Algorithm

The proposed method utilizes a bottom-up heuristic aggregation procedure wherein the maximum normalized inter-cell traffic is reduced at each iteration. The basic steps of the method are similar to the ones in the Inter Class Traffic Minimization Method (ICTMM) presented in references [15,16]. However, major enhancements were necessary in order to address a general manufacturing environment that consists not only of unique machines, but also contains groups of functionally identical machines with finite capacities. The principal steps of the method are summarized in the flow-chart of figure 2 and are described in detail below.

Step 1

Initially, each machine from the set of unique machines M_U and each group of functionally identical machines from the set M_G is placed in a separate cell. Thus, at the beginning of the algorithm, the total number of cells is equal to the number of machine types available :

$c_i = \{m_i\} : i = 1,\ldots,u$

$c_{u+j} = \{G^1{}_j, G^2{}_j, \ldots, G^{K_j}{}_j\} : j = 1,\ldots,g.$

Step 2

The inter-cell traffic t_{ij} is calculated for all pairs of cells (c_i, c_j). This is the traffic between all possible pairs of machines formed by considering one machine from either cell. The general equation for the evaluation of traffic between two cells is presented in the appendix. Three distinct cases are considered in these traffic calculations:

(a) The traffic between a pair of unique machines (m_i,m_j) is determined using Eq.(2) for machines m_i and m_j.

(b) The traffic between a pair (m_i,G_j), formed by a unique machine m_i and a group G_j, is determined by considering a single representative of the group G_j, say $G^k{}_j$ $(k=1,\ldots,K_j)$. Parts from among those that contain the sequence $\{m_i,G_j\}$, or the sequence $\{G_j,m_i\}$, are selected in such a manner that this traffic figure is maximized within the available capacity limit (T_j) of the machine under consideration. This is accomplished by first calculating the average processing time $b_h(G_j)$ of part p_h on the work-center G_j using the equation:

$$b_h(G_j) = \frac{\theta_h{}^{su}(G_j)}{\beta_h} + \theta_h{}^{run}(G_j) \quad , \qquad (6)$$

where $\theta_h^{su}(G_j)$ and $\theta_h^{run}(G_j)$ are the set-up and run times, respectively, of part p_h on work-center G_j, and $ß_h$ is the average batch size of part type p_h. All parts that contain the above sequence are then ranked in ascending order of the average processing time $b_h(G_j)$. In the case that work-center G_j is utilized for more than one operation on part type p_h, each occurrence of the work-center in the part's production routing is considered separately. This might result in the part appearing more than once in the above mentioned list, and incorporates the flexibility to assign multiple operations on the same work-center type to different machines, if necessitated by traffic considerations. Starting from the top of this ordered list, we then select as many parts as allowed by the capacity T_j of work-center $G^k j$. Thus, if the two cells under consideration are merged at a later stage, the maximum possible traffic between the two cells, within the existing capacity constraints, will be eliminated.

In the case that the entire production volume of part p_z, which is selected last from the ordered list, cannot be processed by machine $G^k j$ due to the capacity constraint, a special procedure must be used. This is necessary since part p_z may have a high set-up time on machine G_j, which may consume most of its remaining capacity. Thus, this part may no longer be the one among the remaining parts in the list that contributes the maximum pallet traffic to the traffic value under consideration. The procedure used selects the most appropriate part in terms of traffic contribution from the remainder of the list. It should be noted here that the capacity constraints of Eq.(5) are automatically satisfied, since parts are assigned to a particular machine only if its capacity has not been exhausted. Figure 3 shows the detailed flow chart for the evaluation of traffic in the case under consideration.

(c) The traffic between two groups of functionally identical machines (G_i,G_j) is determined by considering a single representative from each group, say G^f_i and G^k_j and their respective capacities T_i and T_j. Parts from among those that contain the sequence {G_i,G_j} or the sequence {G_j,G_i}, are selected in such a manner that this traffic figure is maximized. This is accomplished by first ranking all the above mentioned parts in ascending order of the higher among the two processing times $b_h(G_i)$ and $b_h(G_j)$, expressed as percentages of the remaining capacities of machines G^f_i and G^k_j , respectively. Starting from the top of this list, as many parts as allowed by the capacities T_i and T_j are used to determine the value of the traffic under consideration. This procedure also yields the maximum possible reduction in traffic when the two cells are merged. The algorithm for the traffic evaluation between machines G_i and G_j is essentially the same as the one shown in Figure 3. However, the initial ranking of the parts is modified as described above, and, at each step, the appropriate capacity constraints are considered for both G^f_i and G^k_j.

Step 3

The normalized traffic T_{ij} between all pairs of cells c_i and c_j is calculated. The pair that corresponds to the maximum normalized traffic value is identified, and the following operations are performed:

(a) The two cells are merged, subject to the merging rules described below.

(b) The routings of all parts which contributed to the traffic between the two cells, and which are processed by one or more groups of functionally identical machines, are changed to reflect the specific machine(s) that belong to the newly formed cell. Thus, these parts now have unique production routings.

At the end of this step, the total inter-cell traffic is reduced by the traffic value between the two cells being merged. It is emphasized that this is the maximum possible traffic that could have been reduced by merging any pair of cells at this iteration, based on the way in which the inter-cell traffic is calculated in the previous step.

Merging Rules

(i) The size of the newly formed cell should not violate the cell size constraint.

(ii) The size of a newly formed cell is the sum of the sizes of the two cells being merged. This, however, is not the case if a cell containing only a group of functionally identical machines is merged with any other cell. In this case, only one machine from the former is merged with the latter, since the capacity of a single machine of this group is considered in the traffic evaluation procedure.

Step 4

The cell configurations are updated.

Steps (2) through (4) are repeated until either the traffic between all pairs of cells becomes lower than a user defined value (which is normally zero), or it is impossible to further merge any cells without violating the cell size constraint.

Step 5

This step validates the initial assignment of each machine to a cell. According to the aggregation procedure of the ICTMM [15,16], once a machine is assigned to a particular cell it cannot be withdrawn, even if its assignment to a new cell becomes more appropriate. This problem is addressed here, wherein each machine is examined for placement in each of the cells formed in steps (2) through (4). It is then assigned to the cell which yields the greatest reduction in the objective function. The latter is performed only if permitted by the cell size constraint.

Step 6

Parts which are processed by a group of identical machines, but are not yet assigned to a specific representative of this group, are now assigned in such a manner that the traffic is minimized, subject to the capacity constraints. Potential capacity overloads, if any, are reported.

Step 7

Each part is assigned to the cell which contains the maximum number of machines required for its manufacture. This helps in forming part families that contain parts with similar processing requirements.

4. Application of the Cell Formation Method

A theoretical example is first presented in order to illustrate the features of the proposed method. The effectiveness of the method is then tested in a large machine shop.

4.1 Example

Consider a manufacturing system consisting of 30 part types and 16 machine types. Work-centers 15 and 16 represent groups of functionally identical machines, and include 5 and 2 machines, respectively. The part and machine data are shown in Table 1. The first column indicates the part production volume over a given period of time. Columns 2 and 3 show the average batch-size and pallet size, respectively, for each part type. Note that in this example only transfers of individual parts were considered. The part identification numbers are indicated in column 4. Each row of the incidence matrix represents the production routing of a part and indicates the sequence of operations performed by the machines present in the system. Table 2 shows the production routing, along with the corresponding set-up and run times, for each part. The capacity of each of the machines of type 15 and 16 is set to 8.0 units over the given time horizon. The maximum number of machines allowed per cell is set to 6.

The results of the grouping method are shown in Figure 4. The five machines corresponding to work-center number 15 are renumbered during the cell formation process from 17 through 21. Similarly, the two machines corresponding to work-center 16 are renumbered to 22 and 23. As can be seen from the final results, two machines of type 15 have been included in the second cell. This is necessary, since the available capacity of a single machine is not sufficient to satisfy the capacity requirements of all the parts that visit this cell. The remaining three machines of this type have been assigned to different cells based on traffic considerations.

The following criteria, as suggested in [16], were used to evaluate the solutions obtained:

(1) **Global Efficiency :** It is the ratio of the total number of operations that are performed within each part's own cell, to the total number of operations in the system. This criterion quantifies the effectiveness of the method in confining the operations on parts within their corresponding cells.

(2) **Group Efficiency :** It is given by the difference between the maximum number of external cells that could be visited and the total number of external cells actually visited by parts in the cellular layout, divided by the former number. The value of this criterion quantifies the effectiveness of the proposed solution in confining the manufacture of each part to as few external cells as possible.

(3) **Group Technology Efficiency :** This is the ratio of the difference of the maximum number of inter-cell pallet transfers possible and the number of inter-

cell pallet transfers actually required in the cellular layout, to the maximum number of inter-cell pallet transfers possible.

The values of the three measures for the present example are shown at the bottom of Figure 4.

The proposed algorithm has been coded in the 'C' language and runs on a Sun/Unix system. The results of this example were obtained in less than 2 seconds of c.p.u. time, which indicates a good capability for applications of much larger dimensions. The short execution time allows for the possibility of carrying out simulations with varying numbers of machines for each machine type.

4.2 Industrial Application

Kop-Flex, Inc. is a manufacturer of shaft couplings, clutches and similar rotational parts. The company is the world's largest supplier of flexible gear couplings, and has a product range consisting of about 1200 make-to-stock parts. In addition, an average of about 1500 make-to-order parts are in process at any given point in time. Most of the manufactured parts are rotational and comprise a wide range of sizes and shapes. The production facility is functionally arranged and consists of over 200 work-centers, such as lathes, gear-shapers, drills, milling machines, etc.

The analysis was performed on the make-to-stock segment of the company's product line and considered 1186 parts and 173 individual machines. The data required for the analysis included; (i) the list of work-center types including the number of machines of each type and their capacities, (ii) the production routings, including the set-up and run times for each operation, and (iii) the production volume over a period of 16 months, and the average batch and pallet sizes of each part. The pallet sizes were set to 1, 10 or 100, depending upon the physical characteristics of the part being considered. The batch-sizes were set equal to the pallet sizes after consultation with the manufacturing staff of the company.

A certain amount of pre-processing had to be performed on the original data. This included; (i) elimination from the part routings of those work-centers that are visited by almost all the parts in the system. These included saws, rough-out drills, packaging stations, storage areas, etc., which were considered as central facilities , and (ii) representation of all the remaining machine *types* by unique identification numbers in the part routings.

After the pre-processing, a total of 70 machine types remained for the purposes of the analysis. Nine of these consisted of more than one functionally identical machine, with the number of machines within each type varying from 2 to 10. The total number of machines was 99. The results obtained from the analysis for cell size limits of 6 and 8 machines are shown below. The number of cells includes only those of sizes 3 or greater.

Case I - Cell Size Limit 6	Case II - Cell Size Limit 8
Total no. of cells obtained = 12	Total no. of cells obtained = 11
Global Efficiency = 70.44%	Global Efficiency = 76.46%
Group Efficiency = 54.75%	Group Efficiency = 65.86%
G.T. Efficiency = 72.07%	G.T. Efficiency = 79.96%

In each case, the algorithm converged to the final solution in about 30 minutes. These results indicate that the proposed cell formation method is appropriate for large-sized problems. Furthermore, they reveal the suitability of cellular layout in the make-to-stock machine shop of Kop-Flex, Inc.

5. Conclusions

A new method for the formation of manufacturing cells in an environment consisting of both unique machines and groups of functionally identical machines has been presented. The method minimizes the inter-cell material flow within the shop and properly distributes the functionally identical machines to the various cells respecting the capacity of each machine. Given a set of generic production routings for the parts manufactured in the system, specific machines are also selected on which each part is to be processed.

Since the proposed approach is based on the existence of generic routings, the merit of the solution obtained depends directly on the quality of these routings. It is also noted that the cell formation is performed by assuming given production requirements over a finite time horizon. Therefore, the method is most appropriate for a make-to-stock environment, in which the product mix does not vary greatly with time. Although the primary application of the system would be to re-arrange an existing functionally laid out job shop into manufacturing cells, it is equally applicable to planned facilities with forecasted product demand and known manufacturing processes. Moreover, the algorithm allows for simulations with "what if" questions, regarding the number of machines of each type available, and provides the appropriate cell configurations for each case. The latter helps in decision making for procurement of the appropriate number of machines of each type.

The major features of the proposed system can be summarized as follows:

- The functionally identical machines are assigned to cells based on both traffic and capacity considerations.

- The sequence of operations is taken into account while evaluating the traffic between machines and/or cells.
- Multiple, non-consecutive operations on the same machine type are taken into account and are individually treated.
- The method minimizes the total number of inter-class movements of pallets as opposed to movements of individual parts. However, individual part transfers can also be considered as a special case, by setting the pallet size equal to unity for all parts.
- Both the set-up and run times along with the average batch-size are used to compute the capacity requirements for each part.
- Encroached cases, wherein a perfect decomposition of the manufacturing facility into cells is not possible, can also be addressed.
- The algorithm provides for simulations for determining the optimum number of machines of each type to minimize the traffic while ensuring sufficient capacity availability.

The proposed method can be complemented by the work of Ang and Willey [19], who consider a given layout and propose a number of strategies to optimize the real-time performance of the production system by transferring workloads between functionally identical machines belonging to different cells, based on a given cellular layout. These strategies can be used for enhancing system performance once the manufacturing cells have been formed using the method proposed in this paper.

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Appendix

Traffic Evaluation

Consider two cells c_s and c_r:

$c_s = M_s \cup G_s$

$c_r = M_r \cup G_r$ (A1)

where M_x represents the set of unique machines and G_x represents the set of representatives from the groups of functionally identical machines that belong to cell c_x $(x = s,r)$.

The traffic between these two cells is the traffic between all possible pairs of machines formed by considering one machine from either cell. For a pair that contains a representative machine $G^k{}_i$ of a group of identical workcenters G_i , two cases must be considered : (i) the traffic contributed by those parts that have already been routed to machine $G^k{}_i$, and (ii) the traffic contributed by parts that have not yet been assigned to a specific machine within the group G_i. For the latter case all machines of type G_i that belong to each cell are considered as a single entity $G_i(x)$ $(x = s,r)$. The sum of their remaining capacities represents the remaining capacity of that machine type in the cell.

The traffic between cells c_s and c_r is evaluated from the following equation:

$$t_{sr} = \sum_{m_i \in M_s} \sum_{m_j \in M_r} t[m_i,m_j] + \sum_{m_i \in M_s} \sum_{G^k{}_j \in G_r} t[m_i,G^k{}_j]$$

$$+ \sum_{m_i \in M_r} \sum_{G^k{}_j \in G_s} t[m_i,G^k{}_j] + \sum_{G^k{}_i \in G_s} \sum_{G^f{}_j \in G_r} t[G^k{}_i,G^f{}_j]$$

$$+ \sum_{G_i(s) \in G_s} \sum_{\substack{G_j(r) \in G_r \\ j \neq i}} t[G_i(s),G_j(r)] + \sum_{m_i \in M_s} \sum_{G_j(r) \in G_r} t[m_i,G_j(r)]$$

$$+ \sum_{m_i \in M_r} \sum_{G_i(s) \in G_s} t[m_i, G_i(s)] \ . \qquad \text{(A2)}$$

The first term on the right hand side of equation (A2) represents the traffic between all pairs of unique machines in the two cells. The second, third and fourth terms represent the traffic contribution of the parts which have already been routed to specific machines from within the groups of identical machines. The last three terms represent the potential traffic contribution of those parts that have not yet been assigned to specific representatives within the group(s) of functionally identical machines. These terms are based on the remaining capacities of each of the groups of functionally identical machines within the two cells.

Table of Symbols

Part Information

n	total number of parts in the system
P	set of part types $\{p_1, p_2, \ldots, p_n\}$
N_h	production volume of part type p_h over a chosen time horizon
β_h	average batch size of part type p_h
μ_h	number of units of part type p_h that can be transferred in one trip of the materials handling system
r_h	routing (process plan) of part type p_h
L_h	total number of operations in routing of part type p_h
$\theta_h^{su}(G_j)$	set-up time for part type p_h on machine G_j
$\theta_h^{run}(G_j)$	run time for part type p_h on machine G_j
$b_h(G_j)$	average processing time of part p_h on the work-center G_j

Machine Information

u	total number of unique machines in the system
M_U	set of unique machines $\{m_1, m_2, \ldots, m_u\}$
g	number of functionally identical machine groups
M_G	set of functionally identical machine groups $\{G_1, G_2, \ldots, G_g\}$
M	set of all machine types $M = M_U \cup M_G$
K_i	number of machines in the machine group G_i
G^j_i	j^{th} machine in machine group G_i
T_i	capacity of each machine in machine group G_i
$S_h(G^k_j)$	the number of units of part p_h processed by machine G^k_j

Cell Information

w	total number of cells
C	set of cells $\{c_1, c_2, \ldots, c_w\}$
q_i	number of machines in cell c_i
t_{ij}	traffic between cells c_i and c_j
T_{ij}	normalized traffic between cells c_i and c_j

List of Figures

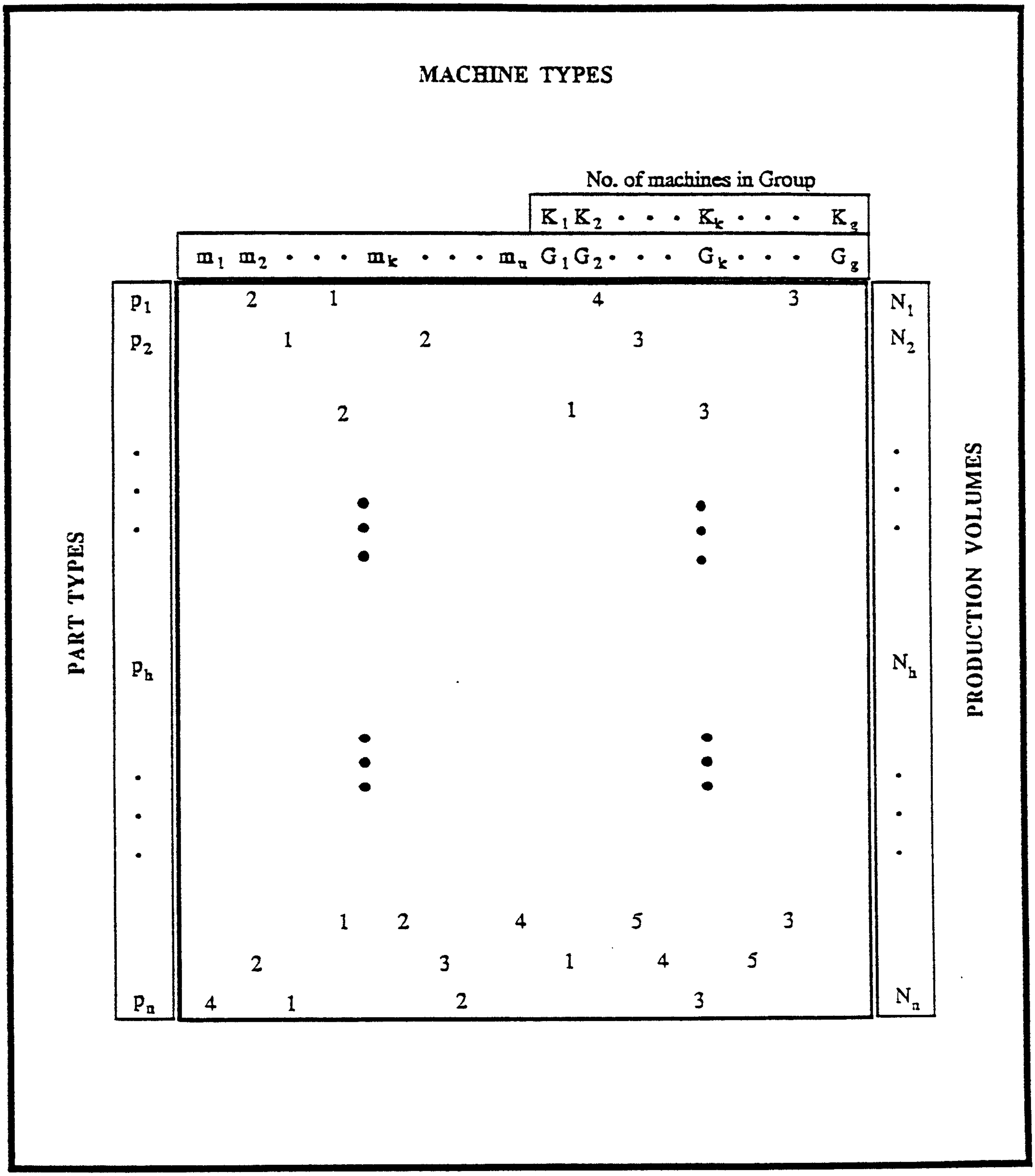
MACHINE TYPES
No. of machines in Group
K1 K2 . . . Kk . . . Kg
m1 m2 . . . mk . . . mu G1 G2 . . . Gk . . . Gg
PART TYPES
p1
p2
ph
pn
PRODUCTION VOLUMES
N1
N2
Nh
Nn

Figure 1

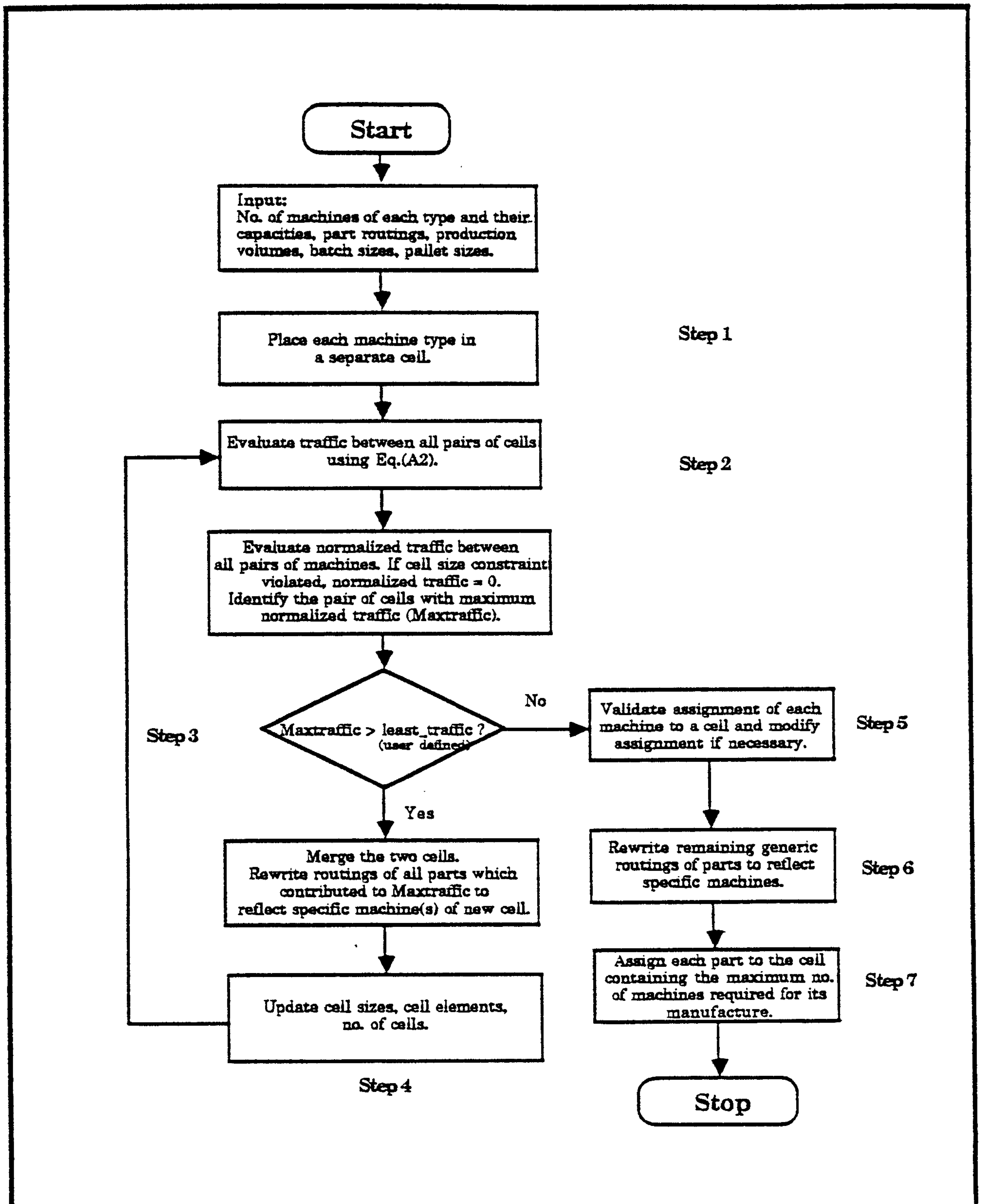
Start
Input:
No. of machines of each type and their capacities, part routings, production volumes, batch sizes, pallet sizes.
Place each machine type in a separate cell.
Step 1
Evaluate traffic between all pairs of cells using Eq.(A2).
Step 2
Evaluate normalized traffic between all pairs of machines. If cell size constraint violated, normalized traffic = 0. Identify the pair of cells with maximum normalized traffic (Maxtraffic).
Maxtraffic > least_traffic ? (user defined)
No
Yes
Step 3
Validate assignment of each machine to a cell and modify assignment if necessary.
Step 5
Merge the two cells. Rewrite routings of all parts which contributed to Maxtraffic to reflect specific machine(s) of new cell.
Rewrite remaining generic routings of parts to reflect specific machines.
Step 6
Assign each part to the cell containing the maximum no. of machines required for its manufacture.
Step 7
Update cell sizes, cell elements, no. of cells.
Step 4
Stop

Figure 2

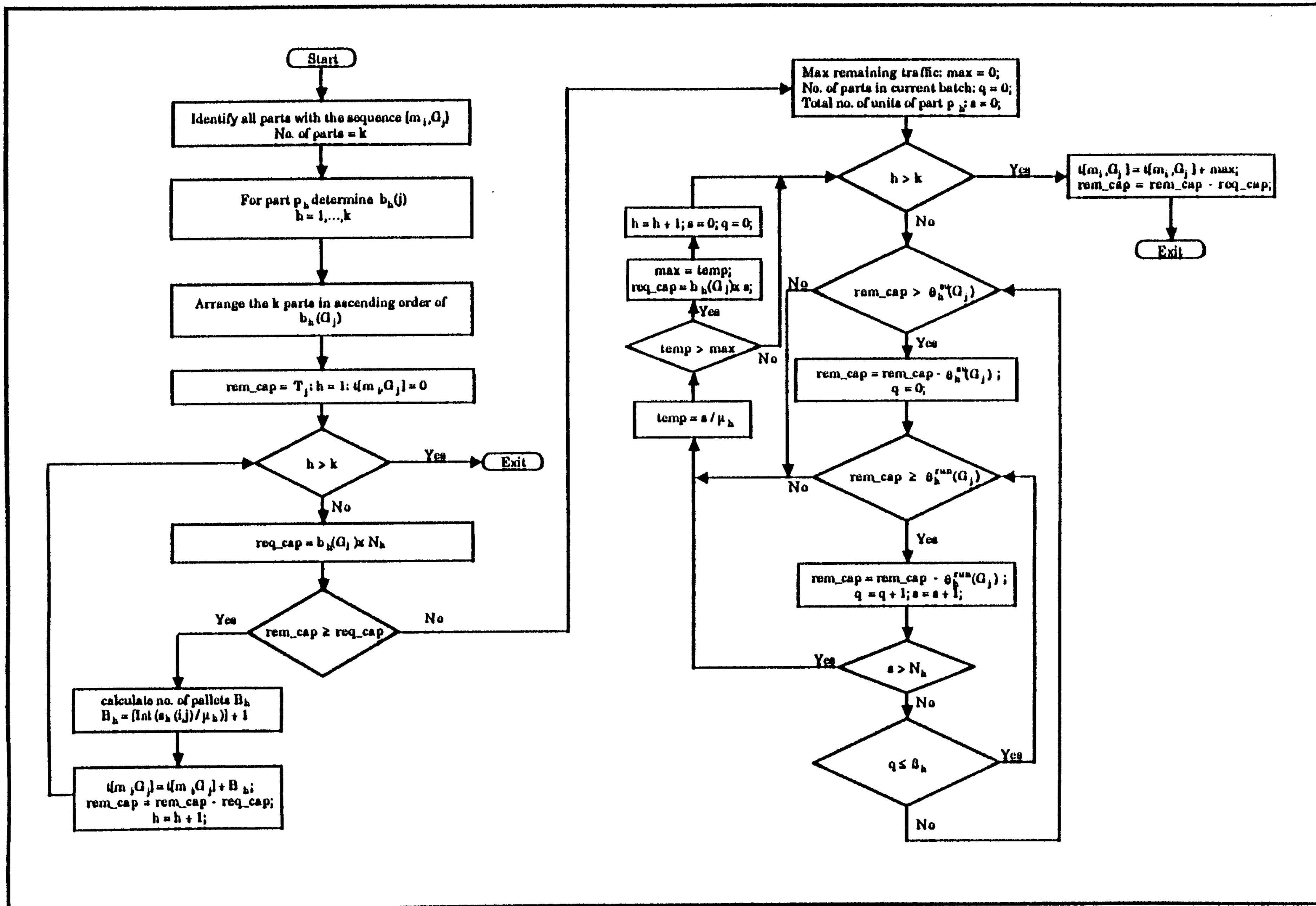
Start
Identify all parts with the sequence (m_i, Ω_j)
No. of parts = k
For part p_h determine b_h(j)
h = 1,...,k
Arrange the k parts in ascending order of b_h(Ω_j)
rem_cap = T_j; h = 1; t(m_i, Ω_j) = 0
h > k
Yes
Exit
No
req_cap = b_h(Ω_j) x N_h
rem_cap ≥ req_cap
Yes
No
calculate no. of pallets B_h
B_h = [Int (s_h (i,j) / µ_h)] + 1
t(m_i, Ω_j) = t(m_i, Ω_j) + B_h;
rem_cap = rem_cap - req_cap;
h = h + 1;
Max remaining traffic: max = 0;
No. of parts in current batch: q = 0;
Total no. of units of part p_h: s = 0;
h > k
Yes
t(m_i, Ω_j) = t(m_i, Ω_j) + max;
rem_cap = rem_cap - req_cap;
Exit
No
rem_cap > θ_h^su(Ω_j)
No
Yes
rem_cap = rem_cap - θ_h^su(Ω_j);
q = 0;
rem_cap ≥ θ_h^run(Ω_j)
No
Yes
rem_cap = rem_cap - θ_h^run(Ω_j);
q = q + 1; s = s + 1;
s > N_h
Yes
No
q ≤ B_h
Yes
No
temp = s / µ_h
temp > max
Yes
No
max = temp;
req_cap = b_h(Ω_j) x s;
h = h + 1; s = 0; q = 0;

Figure 3

us us	Part I.D.	01	05	08	17	20	02	04	11	21	23	03	06	09	14	18	07	12	19	22	10	13
12	2	1	2	3	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
6	5	4	1	3	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1	6	1	4	2	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
3	9	2	3	4	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
8	10	5	.	1	.	6	.	.	.	.	.	4	2	.	.	3	.	.	.	.	.	.
3	18	4	2	3	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
6	22	3	1	4	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1	27	.	1	2	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1	30	4	3	1	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1	31	3	1	4	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1	1	.	.	.	.	.	1	2	4	3	5	.	.	.	.	.	.	.	.	.	.	.
1	8	.	.	.	.	.	2	3	5	1	4	.	.	.	.	.	.	.	.	.	.	.
2	11	.	.	.	.	.	4	1	2	.	3	.	.	.	.	.	.	.	.	.	.	.
1	15	.	.	.	.	.	3	4	1	2	5	.	.	.	.	.	.	.	.	.	.	.
1	23	.	.	.	.	.	4	2	1	3	5	.	.	.	.	.	.	.	.	.	.	.
2	24	.	.	.	.	.	5	2	3	4	1	.	.	.	.	.	.	.	.	.	.	.
2	3	.	.	.	.	.	.	.	.	.	.	5	4	3	2	1	.	.	.	.	.	.
1	4	.	.	.	.	.	.	.	.	.	.	4	5	1	3	2	.	.	.	.	.	.
5	16	.	.	.	.	.	.	.	.	.	.	1	2	5	4	3	.	.	.	.	.	.
2	20	.	.	.	.	.	.	.	.	.	.	1	.	3	2	4	.	.	.	.	.	.
1	21	.	.	.	.	.	.	.	.	.	.	4	3	2	1	5	.	.	.	.	.	.
2	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	1	2	4	.	.
2	12	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4	2	1	3	.	.
3	13	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	3	4	1	.	.
1	19	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	3	1	.	.
1	25	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	3	2	4	.	.
4	26	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	1	.	3	.	.
4	28	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	4	1	3	.	.
3	14	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	2
2	17	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	1
3	29	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	2

Global Efficiency = 97.619049
Group Efficiency = 98.936172
G. T. Efficiency = 94.007492

Figure 4

List of Tables

Table 1

Part and Machine Data for the first Example

Part Details				Machines															
prod vol	batch size	pallet size	I.D	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16
1	1	1	1	.	1	.	2	.	.	.	.	.	.	4	.	.	.	3	5
12	3	1	2	1	.	.	.	2	.	.	3	.	.	.	.	.	.	4	.
2	1	1	3	.	.	5	.	.	4	.	.	3	.	.	.	.	2	1	.
1	1	1	4	.	.	4	.	.	5	.	.	1	.	.	.	.	3	2	.
6	2	1	5	4	.	.	.	1	.	.	3	.	.	.	.	.	.	2	.
1	1	1	6	1	.	.	.	4	.	.	2	.	.	.	.	.	.	3	.
2	2	1	7	.	.	.	.	.	.	3	.	.	.	.	1	.	.	2	4
1	1	1	8	.	2	.	3	.	.	.	.	.	.	5	.	.	.	1	4
3	2	1	9	2	.	.	.	3	.	.	4	.	.	.	.	.	.	1	.
8	4	1	10	5	.	4	.	.	2	.	1	.	.	.	.	.	.	6	.
2	1	1	11	.	4	.	1	.	.	.	.	.	.	2	.	.	.	.	3
2	1	1	12	.	.	.	.	.	.	4	.	.	.	.	2	.	.	1	3
3	3	1	13	.	.	.	.	.	.	2	.	.	.	.	3	.	.	4	1
3	1	1	14	.	.	.	.	.	.	.	.	.	1	.	.	2	.	.	.
1	1	1	15	.	3	.	4	.	.	.	.	.	.	1	.	.	.	2	5
5	4	1	16	.	.	1	.	.	2	.	.	5	.	.	.	.	4	3	.
2	1	1	17	.	.	.	.	.	.	.	.	.	2	.	.	1	.	.	.
3	3	1	18	4	.	.	.	2	.	.	3	.	.	.	.	.	.	1	.
1	1	1	19	.	.	.	.	.	.	2	.	.	.	.	.	.	.	3	1
2	1	1	20	.	.	1	.	.	.	.	.	3	.	.	.	.	2	4	.
1	1	1	21	.	.	4	.	.	3	.	.	2	.	.	.	.	1	5	.
6	2	1	22	3	.	.	.	1	.	.	4	.	.	.	.	.	.	2	.
1	1	1	23	.	4	.	2	.	.	.	.	.	.	1	.	.	.	3	5
2	2	1	24	.	5	.	2	.	.	.	.	.	.	3	.	.	.	4	1
1	2	1	25	.	.	.	.	.	.	1	.	.	.	.	3	.	.	2	4
4	2	1	26	.	.	.	.	.	.	2	.	.	.	.	1	.	.	.	3
1	3	1	27	.	.	.	.	1	.	.	2	.	.	.	.	.	.	3	.
4	3	1	28	.	.	.	.	.	.	2	.	.	.	.	4	.	.	1	3
3	1	1	29	.	.	.	.	.	.	.	.	.	1	.	.	2	.	.	.
1	2	1	30	4	.	.	.	3	.	.	1	.	.	.	.	.	.	2	.

Table 2

Part Routings for the first Example

Part ID, Sequence of Machines, Set-up and Run Times.

1	2	0.1	0.2	4	0.1	0.2	15	0.4	.42	11	0.1	0.2	16	0.2	0.4
2	1	0.2	.15	5	0.3	0.2	8	0.2	0.1	15	0.2	.15			
3	15	.32	.45	14	0.1	0.4	9	.25	0.4	6	0.2	0.3	3	0.2	0.2
4	9	.25	0.2	15	0.4	.51	14	0.1	0.2	3	0.1	0.3	6	0.2	0.1
5	5	0.2	0.5	15	0.1	0.3	8	0.3	0.1	1	0.5	0.4			
6	1	0.3	0.2	8	0.1	0.1	15	.16	.25	5	0.6	0.1			
7	12	0.2	0.7	15	0.3	.31	7	.23	0.3	16	0.2	.25			
8	15	0.6	.11	2	0.3	0.9	4	.34	0.4	16	0.3	0.3	11	0.5	0.1
9	15	.09	0.3	1	0.3	0.1	5	0.3	0.2	8	0.2	0.2			
10	8	0.2	0.4	6	0.5	0.2	15	.09	0.1	3	.21	0.1	1	0.3	.15
	15	0.5	0.1												
11	4	0.2	.18	11	0.5	0.2	16	0.1	.25	2	0.5	0.3			
12	15	0.4	0.2	12	0.3	0.1	16	.23	0.3	7	0.1	0.1			
13	16	0.2	0.2	7	0.2	0.1	12	0.1	0.1	15	0.5	.12			
14	10	0.3	.25	13	0.2	0.2									
15	11	0.2	0.2	15	.78	.25	2	0.3	0.2	4	0.3	0.2	16	.18	0.3
16	3	0.3	0.1	6	0.5	0.1	15	0.3	.15	14	0.5	0.2	9	0.2	0.1
17	13	0.3	0.2	10	0.2	0.2									
18	15	.12	0.5	5	0.3	0.2	8	0.1	0.1	1	0.3	0.2			
19	16	0.1	0.1	7	0.4	0.1	15	0.2	0.4						
20	3	0.5	0.3	14	0.2	0.1	9	0.1	0.1	15	0.6	.38			
21	14	0.2	0.2	9	0.3	0.2	6	0.2	0.3	3	1.0	0.2	15	0.8	.55
22	5	0.2	0.3	15	0.3	0.2	1	0.6	0.3	8	0.5	0.2			
23	11	0.1	0.1	4	0.1	.05	15	.62	.35	2	0.1	0.2	16	0.4	0.2
24	16	0.1	0.4	4	0.2	0.3	11	0.6	0.3	15	.49	0.4	2	0.4	0.1
25	7	0.7	0.3	15	0.1	.16	12	0.9	0.3	16	0.2	.15			
26	12	0.5	0.2	7	0.4	.08	16	0.2	0.2						
27	5	0.2	0.3	8	0.6	0.3	15	.26	0.1						
28	15	0.1	.11	7	0.1	0.1	16	0.3	0.2	12	0.1	.06			
29	10	0.4	0.2	13	0.6	0.1									
30	8	0.2	0.1	15	0.4	.22	5	0.3	0.2	1	0.1	0.1			