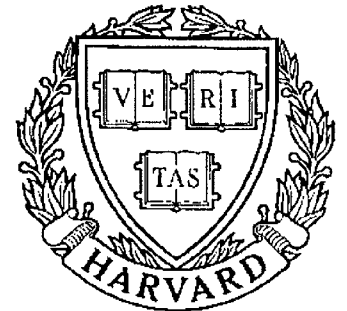


TECHNICAL RESEARCH REPORT



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Development and Application of a Knowledge Based System for Cellular Manufacturing

by G. Harhalakis, I. Minis and R. Nagi

DEVELOPMENT AND APPLICATION OF A KNOWLEDGE BASED SYSTEM FOR CELLULAR MANUFACTURING

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ABSTRACT

The Inter Class Traffic Minimization Method (ICTMM) that arranges the production equipment of a machine shop into manufacturing cells in order to minimize the inter cell traffic of parts is presented in this paper. All quantitative tasks of this method are performed by algorithms that are embedded in a knowledge base. The aggregation rules and the problem constraints form the core of this knowledge base. Two other methods of factory flow analysis are also presented in order to compare their criteria and objectives to the ICTMM. Finally, all three systems are applied to a large size industrial project and the results obtained are presented and evaluated. We conclude by suggesting further research directions for a most comprehensive solution to the layout of a cellular manufacturing facility.

1.0 INTRODUCTION

Traditionally, the layout of a typical discrete parts, batch manufacturing shop has been functional; that is, the sets of functionally similar work centers are grouped in dedicated areas of the shop floor. The principal benefit of this type of layout is the balancing of machine loads. Since some of the work centers in a set are interchangeable, incoming parts are routed to the work center with the lightest load. However, the flow of parts and materials within a functionally arranged shop is highly erratic, thus resulting in long transportation times, increased materials handling expenses, and high volume of work-in-process inventory (Hyer and Weemmerlöv [5]; Ingram [6]). Furthermore, each work center usually processes a wide spectrum of parts and therefore requires frequent and lengthy set-ups, which contribute to longer queue times.

An alternative layout concept is offered by cellular manufacturing (Jackson [7]). A manufacturing cell is usually a group of functionally dissimilar machines that are physically adjacent and dedicated to the production of a family of parts with common processing requirements, fixturing and tooling. The immediate benefit of the cellular layout is increased throughput that is resulted from considerable reductions in transportation and queue times. Furthermore, the decomposition of the shop to smaller, decoupled sub-systems facilitates both scheduling and shop floor control. These functions no longer involve the entire shop but a number of independent, less complex cells and their corresponding part families. Additional advantages of the cellular layout include savings in both set-up times and material handling costs.

Several methods have been developed to group the work centers of a given shop in manufacturing cells that are capable of processing parts with given production routings. These methods are classified into two major types. The first includes algorithms that are based on cluster analysis; such as the bond energy method developed by McCormick *et al* [13], the rank order clustering method proposed by King [8], the direct clustering algorithm of Chan and Milner [1], and the GPM method developed by Garcia and Proth [2],[3]. The common objective of this class of algorithms is to arrange the available work centers into cells and to partition the entire set of parts into families in such a way that the number of operations performed to each part family, within its corresponding cell, is maximized.

In the second class of grouping methods, work centers are progressively aggregated into cells depending on the degree of "similarity" among them. The similarity between a pair of work centers is usually defined as the ratio of the number of parts that are jointly processed by both these work centers over the total number of parts that are processed by at least one of them. The same procedure is followed for the aggregation of parts into families. This class of methods includes the single linkage algorithm developed by McAuley [12], the method of Leskowsky *et al*, who used the Average Common Part Weighing Metric [11], and the Knowledge Based Group Technology (KBGT) system proposed by Kusiak [9],[10]. It is noted that the objective of these algorithms is not expressed by mathematical functions.

It has already been mentioned that the reductions in both transportation times and materials handling costs are among the principal motives of a cellular arrangement. Thus, a realistic objective for an aggregation algorithm should be to minimize the number of inter cell part transfers that are required for the manufacture of the entire set of parts. The algorithms described above are not capable of pursuing this objective, since they are all based on the use of the part-machine incidence matrix that does not reflect the sequence of operations in a part's production routing.

A new bottom-up aggregation procedure, the Inter Class Traffic Minimization Method (ICTMM), has been recently proposed by Harhalakis *et al* [4] to minimize the travel of parts within the shop. It was developed in order to address a large size industrial project. Both the method, i.e. the algorithm and the knowledge base, and the project under consideration are presented in this paper. Two other representative methods (GPM and KBGT) have also been used for the solution of the same industrial project. Section 2 presents the industrial project and the approach taken for its analysis. All three methods used are discussed in Section 3, and the results obtained are presented and compared in Section 4. Analysis of these results reveals valuable insights for the refinement of the Inter Class Traffic Minimization Method in order to be able to address most aspects of the cellular layout problem. Research efforts in this direction currently under way are discussed in Section 5. The conclusions of this study are summarized in Section 6.

2.0 THE INDUSTRIAL PROJECT

2.1 Company Background

Kop-Flex, Inc. manufactures flexible shaft couplings, clutches, and related rotational parts. Product lines consist of mechanically-flexible gear couplings, of which Kop-Flex is the world's largest supplier, and a wide range of material-flexing couplings, which incorporate either elastomer materials or metal membrane elements.

The company manufactures almost 1,200 make-to-stock parts. In addition, an average of 1,500 make-to-order parts are in process at any given point in time. All manufactured parts are cylindrical and span over a wide range of sizes and shapes. The machine shop is functionally arranged and includes over 200 work centers, such as lathes, gear-shapers, drills, milling machines, etc.

2.2 Case Analysis

The make-to-stock part base was used as the foundation of the analysis, since; i) it is almost static over time, ii) strong similarities exist between make-to-stock and make-to-order parts with respect to both design features and manufacturing characteristics, and iii) common work centers are used for the manufacture of both these segments of the part population. The merit of the solution that results by only considering the make-to-stock parts will be validated later using a sample of make-to-order parts to determine whether they can be processed within the proposed cells.

The data required for the case analysis include; i) the list of work centers, ii) the production routings of all make-to-stock parts (1186), and iii) the production volume of these parts over a certain time period (16 months). The validity of the part data was verified by comparing the standard production routings against the time keeping records, which report the actual sequence of operations performed. When necessary, the routings were revised to reflect consistent current practices.

After the completion of the data collection and validation phase the following steps were performed:

i) The present shop layout was drawn and each work center was assigned a unique identification number. Thus identical machines that were initially defined by the same company designation can now be considered as separate work centers, (see item iv).

ii) Central facilities, such as packing, storage areas, work-ups, etc., which are visited by almost any part in the system, were removed from the routings under consideration. All inspection work stations were also ignored, since all inspection operations that are not performed in-process require special metrology equipment, which cannot be assigned to a particular cell.

iii) Work centers that process most of the manufactured parts, such as saws and rough-out drills, were assigned to a special area of the shop and were not included in the analysis, since they are visited by every part family. The incorporation of this equipment to cells would cause unnecessary high inter cell traffic.

iv) Special considerations were employed to address work centers that include more than one identical machine tools. In contrast to the existing functional layout, these machines can no longer be considered as a single work center but they must be distributed to different cells. If such a work center were assigned to a single cell, then all parts that are processed by it must visit this particular cell, thus generating a considerable number of unnecessary part transfers. Furthermore, since this work center contains more than one machine tools, some of the other members of the cell must be removed to facilitate the cell size constraint. The problem of distributing identical machine tools to different cells has not been addressed by any of the grouping methods mentioned in Section 1. In the present project this case was treated by artificially assigning an equal number of parts to each of these identical machines. Thus they can now be considered as unique work centers. It is noted that such an assignment is completely artificial and directly influences the formation of cells. An improved algorithm that does not require this treatment of the routings, but properly assigns identical machines to cells using capacity considerations is discussed in Section 5.

The result of the above four-step procedure is summarized in Fig. 1, which depicts the part-machine incidence matrix of the industrial project. This matrix contains 1186 rows that represent the production routings of the make-to-stock parts under consideration. Its columns form two sub-matrices. The first contains the 134 work centers that were considered for the formation of cells. The second contains the work centers that were excluded from the analysis; i.e., central facilities, inspection work stations, and those work centers that process most of the manufactured parts as explained in paragraphs (ii) and (iii) above. All operations that are performed by these work centers were removed from the production routings of the parts. The resulting set of routings is the input to all three algorithms used.

Fig.1 The part-machine incidence matrix of the industrial project. The first, last, and intermediate operations in each part's production routing are represented by F, L, and I, respectively.

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3.0 METHODS APPLIED FOR THE SOLUTION OF THE CELLULAR LAYOUT PROBLEM

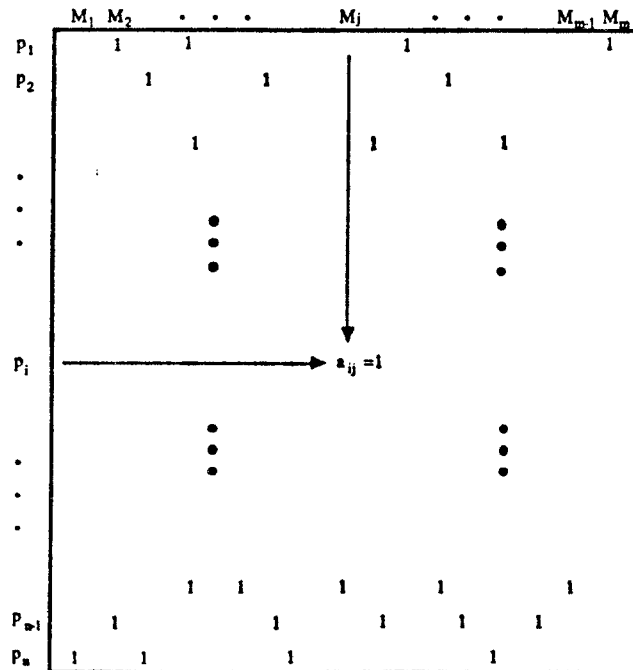
Three alternative methods were applied to form manufacturing cells in the industrial case under consideration; two representative algorithms, one from each class of grouping methods discussed in the introduction, and the Inter Class Traffic Minimization Method.

3.1 The GPM Cross-Decomposition Algorithm

The objective of the Garcia-Proth Method (GPM) [2],[3] is to arrange the available work centers into cells and to partition the entire set of parts into families in such a way that the number of operations performed to each part family within its corresponding cell is maximized.

The cross-decomposition problem can be formulated considering the part-machine incidence matrix shown in Fig. 2. Each row of the matrix corresponds to a part, and each column corresponds to a work center. The entry a_{ij} takes the value of 1 if part p_i is processed by machine M_j , and the value of 0 otherwise. Thus the i -th row of the matrix represents the production routing of part p_i . The desired form of the incidence matrix is depicted in Fig. 3. The matrix has been transformed to a block diagonal form using both column and row permutations; i.e., rearrangement of work centers and parts, respectively. Each block represents a production sub-system of work centers that perform the majority of operations required for the manufacture of the corresponding part family. It is noted that the off-diagonal non-zero entries represent operations that are performed on a part outside its corresponding cell. Such scattered operations are present in any realistic case, since a perfect decomposition of the system is highly improbable.

Fig. 2 The part-machine incidence matrix of a typical functionally arranged machine shop.

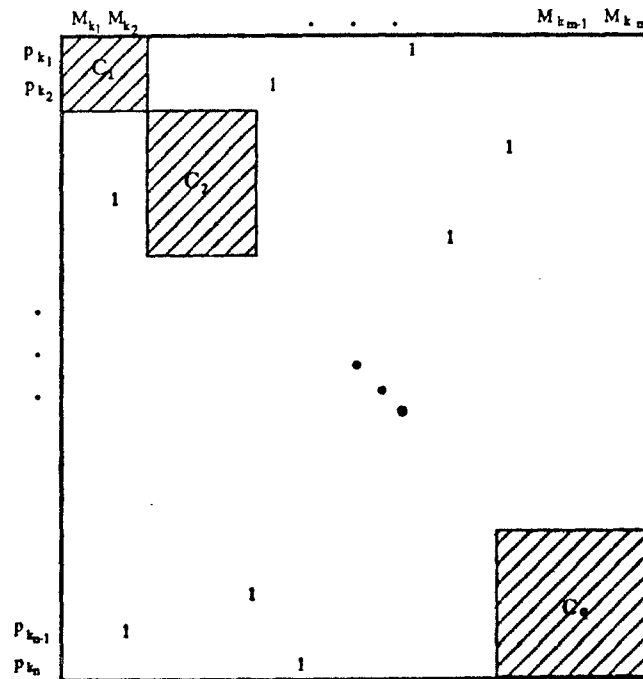


The objective function used by GPM awards those operations that are performed within the set of diagonal blocks D , while penalizing the operations outside D . The relative weight of the former over the latter is selected by a user defined constant h . The objective function is given by the following relationship;

$$\text{MAX: } y = h \sum_{i,j:a_{ij} \in D} u_i a_{ij} + (1-h) \sum_{i,j:a_{ij} \notin D} u_i (1-a_{ij}) \quad (1)$$

where a_{ij} is the corresponding entry of the incidence matrix, D is the set of entries included in the diagonal blocks, and u_i the weight of part i , which may represent the volume of production in a given time period, or a user defined cost factor. Although the original GPM algorithm does not incorporate any constraints during the formation of cells, a later version proposed by Nagi [14] facilitates the cell size constraint; i.e., the maximum number of work centers in each cell is not permitted to exceed a user specified value.

Fig. 3 The form of the incidence matrix after the k -th iteration of the GPM system.



The algorithm requires an arbitrary initial partition of both the set of work centers and the set of parts in q classes respectively, where q is selected by the user. Two major steps are then executed: i) A given work center (column) is examined for placement in any of the q cells. For this purpose the value of the objective function is evaluated for each candidate cell separately, assuming it includes the work center under consideration. This work center is then placed in the cell that maximizes the objective function. This process is performed for each work center in the incidence matrix. ii) A given part (row) is examined for placement in any of the q part families. The value of the objective function is evaluated for each candidate part family separately, assuming it includes the part under consideration. The part is then placed in the family that maximizes the objective function. This process is performed for each part of the incidence matrix. The above steps are executed

recursively until the value of the objective function ceases to increase. If the number of work centers in a cell violates the size constraint, then the work center selected for removal is the one that yields the minimum decrease in the value of the objective function.

Garcia and Proth [3] have proven that the above algorithm converges. It is noted that the quality of the solution depends on the initial partition of the incidence matrix. Thus the algorithm may have to be iterated with different initial settings until a good solution is obtained.

3.2 The KBGT Knowledge Based System

The objective of the KBGT system, which was developed by Kusiak [9],[10], is to form work center cells and part families in such a way that each part family is manufactured exclusively by work centers in its corresponding cell or by bottleneck machines that do not belong in any cell. Thus, parts are not allowed to visit more than one cells. Three constraints are also included in the formulation of the grouping problem: i) The total processing time required for the manufacture of all parts that are processed by each work center is less than or equal to its capacity available. ii) The material handling requirements of each part family do not exceed the capacity available of the cell's material handling system, which is expressed in frequency of trips. iii) The number of work centers in each cell does not exceed a specified value. These constraints are critical in order to obtain a practical solution for a realistic industrial application, since they reflect two fundamental problems of cellular manufacturing; i.e., cell size and work load.

A generalized form of the part-machine incidence matrix is the basis of KBGT. Each non-zero entry a_{ij} represents the total processing time of operation j performed on part i ;

$$a_{ij} = u_i \times tr_{ij} + b_i \times ts_{ij} \quad , \quad \forall a_{ij} \neq 0 \quad , \quad (2)$$

where u_i and b_i represent the volume of production and the number of issues of part i over a given time period, respectively, and tr_{ij} , ts_{ij} represent the run and set-up times of operation j performed on part i , respectively. The values of the processing times a_{ij} are used for the calculation of the capacity required at each work center.

The KBGT system consists of two major interacting components; i) a knowledge based sub-system, which includes all clustering rules, and ii) an algorithm that performs the required quantitative tasks. Here is a brief description of the system's operation.

Prior to the start of the clustering process, all parts that require a number of operations greater than the cell size limit are removed from the incidence matrix, since they cannot be manufactured within a single cell. Then a search is initiated for a group of work centers that can form a cell. The first candidate group includes the work center that processes the largest number of parts along with all other work centers required for the manufacture of these parts. If the size of this group does not violate the size constraint, then; i) the first work center is included in the cell, ii) all of its parts are included in the corresponding part family, and iii) all other work centers of the selected group are assigned to a special list of candidates. If, however, the size constraint is violated, then this work center is considered as a bottleneck machine and the search is continued for a group of appropriate size.

Once the formation of a cell has been initiated, all work centers that remain in the list of candidates are examined. The similarity of each with the members of the cell is determined using a certain similarity measure (Kusiak and Wadood [10]). The work center with the highest degree of similarity is then selected and all of its corresponding parts are found along with the other work centers that process them. These work centers are also included in the list of candidates only if the sum of the size of the resulting list plus the size of the cell does not violate the cell size constraint. In this case the work center selected becomes a member of the cell and its parts are included in the corresponding part family. Otherwise it is returned to the incidence matrix. This process continues until the list of candidates is empty and thus the cell formation is concluded. Only then the family of parts is examined against the processing time constraints. All parts that violate them are removed from the family and are placed in a part waiting list. All work centers included in the cell just been formed, and all parts of the corresponding part family are then removed from the incidence matrix so that they will no longer be considered in the grouping process. The formation of cells is continued until the incidence matrix is empty.

The results of KBGT include the list of work centers per cell, the list of parts per corresponding family, a list of bottleneck machines that do not belong to any cell, and a list of parts not included in any family.

3.3 The Inter Class Traffic Minimization Method (ICTMM)

Harhalakis *et al* [4] have proposed the following approach to solve the cellular layout problem: i) Work centers are aggregated into cells in order to minimize the traffic of the entire set of parts between these cells. ii) The size of each cell must not exceed a specified limit. The algorithm penalizes the moves of parts between cells, while ignoring the moves within each cell.

This method accounts for the sequence of operations required for the manufacture of each part. Thus, in contrast to the algorithms discussed previously, the incidence matrix is not appropriate to represent the part-machine data. In this case it is necessary to consider the entire production routing of each part. This offers an additional advantage in those cases that a part is processed by the same work center more than once, non-consecutively. Although such operations are equally important in terms of material handling, they cannot be represented in the incidence matrix and are thus ignored by the previous algorithms.

The proposed method uses a three-part heuristic procedure, which is embedded in the knowledge base, in order to reach a good, if not optimal solution. During the first part, work center cells are formed to minimize inter cell traffic. In the second part the knowledge base validates the assignment of each work center to its corresponding cell. After the formation of cells is finalized the entire set of parts is partitioned into families, each corresponding to a single cell.

The system starts by placing each work center in a separate cell. Then cells are progressively merged provided that the cell size limit is not exceeded. In the first step of the aggregation procedure, the rule that evaluates the traffic between any possible pair of cells uses the following equation;

$$t_{ij} = \sum_{k=1}^n u_k (x_{ij}^k + x_{ji}^k) \quad (3)$$

where t_{ij} is the traffic between cells c_i and c_j , x_{ij}^k represents the number of times that part k must be moved from c_i to c_j , and u_k is the weight of part k , which may represent the volume of production, or the number of batches, or a user defined cost factor. Equation (3) indicates that the trips from cell c_j to cell c_i are also considered in the calculation of t_{ij} . The traffic between two cells is normalized using;

$$T_{ij} = \frac{t_{ij}}{N_i + N_j} \quad (4)$$

where N_i and N_j represent the sizes of cells c_i and c_j , respectively. This normalization points to the traffic between small cells.

During the second step, the knowledge base utilizes an aggregation rule, whereby the pair of cells with the maximum normalized traffic $T_{ij,MAX}$ is merged, provided that the resulting cell does not exceed the size limit. The total inter class traffic is thus reduced by $T_{ij,MAX}$. The traffic between the cell just been formed and all remaining cells is calculated using Eqs. (3) and (4), and the procedure is repeated until it is either impossible to create a new cell within the specified size limit, or the traffic between all existing cells is zero.

According to this aggregation procedure once a work center 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 by the second part of the system, where the initial assignment of each work center is validated. In this part the work center under examination is no longer considered a member of a cell and its normalized traffic with each of the existing cells is evaluated. It is then assigned to the cell that corresponds to the maximum traffic value. Although a given work center is usually assigned to its initial cell, possible re-arrangements may result to violations of the cell size constraint.

Only after the formation process is finalized, the entire set of parts is partitioned into part families, each corresponding to a given cell. The underlying rule is that each part be assigned to the cell where the maximum number of operations required for its manufacture are performed. The merit of such an assignment is realized if the part's production routing is modified in order to revise operations that are currently performed outside the part's cell. This task is more feasible when a minimum number of operations is considered for modification.

4.0 SOLUTIONS OBTAINED

The results of the three grouping methods that were employed for the industrial project are presented and discussed in this section.

All three algorithms were applied under the following common conditions:

- i) The input data were generated by the four-step procedure described in Section 2. They consist of the production routings of 1186 make-to-stock parts, which are processed by 134 work centers. The required production volume data were also provided for each of these parts for a 16-month period.
- ii) The maximum number of work centers per cell was set to eight.
- iii) No part processing times or work center capacity availability were considered at this phase.

The solutions obtained are evaluated with respect to the reduction of inter class transfers of parts within the shop, since this is one of the critical objectives of cellular manufacturing. The measure used to quantify the merit of each solution is given by the following equation;

$$e = \frac{I - U}{I} \quad (5)$$

where I and U represent the total number of transfers required for the manufacture of all parts in the functional and cellular layouts, respectively. The quantity I is calculated from;

$$I = \sum_{i=1}^n \frac{u_i}{F_i} (r_i - 1) \quad (6)$$

where n is the total number of parts, r_i represents the number of operations contained in the production routing of part p_i , u_i is the total volume of production of p_i , and F_i is the number of parts p_i transferred within the shop in a single trip of the materials handling system. A similar relationship is used to determine U ;

$$U = \sum_{i=1}^n \frac{u_i}{F_i} (q_i - 1) \quad (7)$$

where q_i is the number of inter cell transfers required to manufacture part p_i . All transfers between work centers of the same cell are considered local, hence they were not accounted for the calculation of q_i .

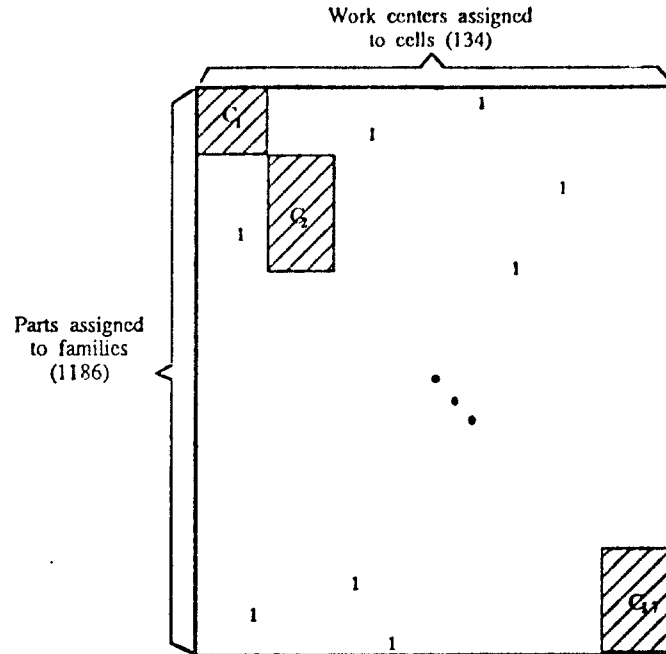
It is emphasized that the efficiency measure given by Eq. (5) represents the objective of the Inter Class Traffic Minimization Method. The objectives of the two other grouping methods used are not directly related to this measure. Thus the comparison between the values obtained for the three different solutions is expected to favor the Inter Class Traffic Minimization Method.

4.1 Results of the GPM Cross Decomposition Method

It has already been mentioned in Section 3.1 that the result of the GPM algorithm (Garcia and Proth [2],[3]) depends on the initial partition of the part-machine incidence matrix. Thus, a number of different arbitrary partitions were used until a good solution was obtained. This solution is depicted in the form of an incidence matrix in Fig. 4.

The available work centers were arranged in 17 cells. Sixteen contained 8 work centers each, while one cell contained 6 work centers. The non-zero entries outside the diagonal blocks of the incidence matrix indicate operations that cannot be performed within each part's corresponding cell. These operations can be classified in two types according to their order in a part's production routing: i) Operations that are first or last in a production routing. These require a single transfer of the corresponding part to or from its own cell, respectively. ii) Intermediate operations that require two transfers from and to the part's own cell. Although the GPM cross-decomposition algorithm minimizes the number of such external operations, it does not differentiate between the above two types of transfers. Thus, the solution obtained is not optimal with respect to the minimization of travel within the shop. The value of the efficiency measure e for this solution is 0.32; i.e., the proposed solution offers a 32% reduction in the total number of part transfers within the shop.

Fig. 4 The incidence matrix of the solution obtained from the GPM system.

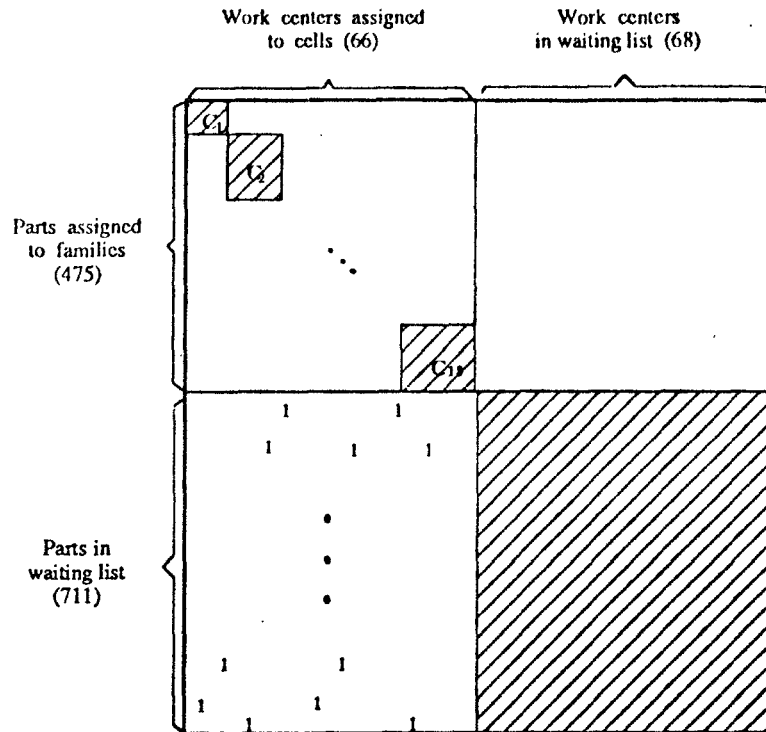


4.2 Results of the KBGT System

Figure 5 illustrates the solution that was obtained from the KBGT system (Kusiak [9],[10]). The part-machine incidence matrix is divided into four major blocks. The first block contains the manufacturing cells. From the entire set of manufactured parts (1186) only 475 (40%) were assigned to part families. The remaining 711 parts (60%) were placed in the part waiting list, since none of them can be manufactured in a single cell. This is consistent with the objective of the KBGT system, which forms cells and part families in such a way that each part family is manufactured exclusively by the work centers in its corresponding cell, or by bottleneck machines. Eighteen cells were formed with sizes that range from 2 to 7 work centers per cell. These cells include only 66 (49%) of the available work centers. The remaining 68 work centers (51%) are exclusively used by the 711 parts contained in the part waiting list. Figure 5 shows that the parts of the waiting list may also visit some cells.

The proposed solution indicates that the shop floor must be divided into two separate areas. The first contains the manufacturing cells, while the second contains the remaining work centers. The parts assigned to the first area are completely processed within their corresponding cells and thus do not cause any inter cell traffic. However, the parts that are assigned to the second area are not only transferred between the work centers of this area, but may also visit some manufacturing cells. This generates considerable part traffic within the shop. Thus, the value of the efficiency measure, e , obtained from the proposed solution, was only 0.21. It is noted that each part transfer between the work centers of the general area was equivalent to an inter cell transfer.

Fig. 5 The incidence matrix of the solution obtained from the KBGT system.



4.3 Results of the Inter Class Traffic Minimization Method (ICTMM)

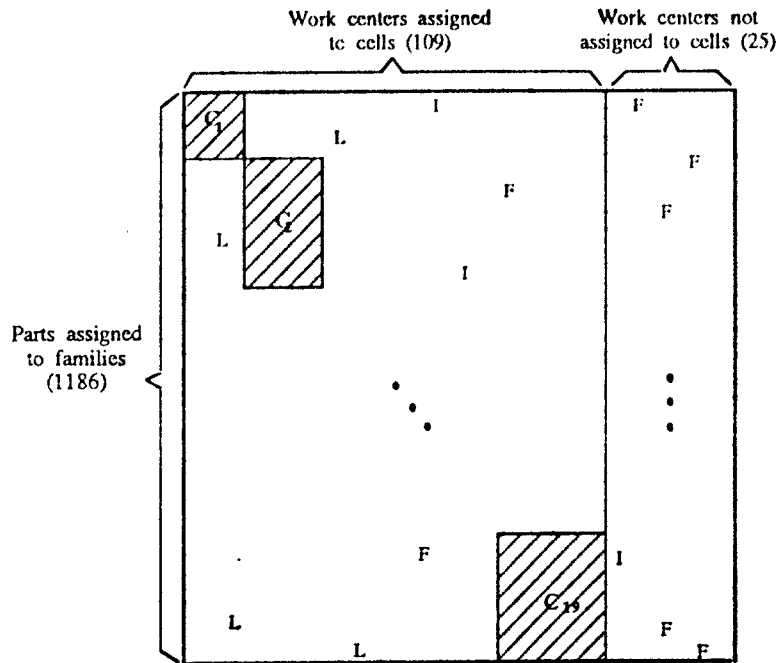
The incidence matrix of the solution obtained by ICTMM (Harhalakis *et al* [13]) is shown in Fig. 6. It consists of two major blocks. The first one contains 109 work centers that were assigned to cells with two or more members. The second block contains 25 work centers that were not placed in any cell. These work centers share a low number of common parts with the cells been formed. Therefore they are not part of the cellular arrangement and must be located in a separate area of the shop floor.

The system formed 19 manufacturing cells. Nine cells contained 8 work centers each and two cells contained 7 work centers each. The size of the other cells ranged from 2 to 6 work centers per cell. Although each part was assigned to a part family, it may still visit work centers outside its corresponding cell. This is indicated by the non-zero entries that are not included within the diagonal blocks of the incidence matrix. Since the algorithm minimizes the inter class traffic, most of these operations are first or last in the corresponding parts' production routings.

The proposed solution offers a substantial reduction in the total number of inter class transfers. The value of the efficiency measure, e , obtained was 0.587, which indicates a 58.7% reduction in the required travel of parts within the shop. In this calculation, each part transfer between work centers that do not belong to any cell was considered as equivalent to an inter class transfer.

It is noted that, in addition to the minimization of part traffic within the shop, the proposed arrangement offers a substantial decrease in the number of operations that are performed on each part outside its corresponding cell.

Fig. 6 The incidence matrix of the solution obtained from the ICTMM system. The first, last, and intermediate operations in each part's production routing are represented by F, L, and I, respectively.



The results obtained from all three systems are summarized in the following table.

Table 1
Results of the Grouping Methods

	GPM		KBGT		ICTMM	
	No. of Cells	Machines per Cell	No. of Cells	Machines per Cell	No. of Cells	Machines per Cell
	16	8	1	7	9	8
	1	6	2	6	2	7
			2	5	1	6
			5	4	3	3
			1	3	4	2
			7	2		
Total No. of Cells	17		18		19	
Machines Removed	None		68		25	
Parts Removed	None		711		None	
Efficiency e	0.320		0.210		0.587	

5.0 CURRENT WORK

The Inter Class Traffic Minimization Method (ICTMM), which was presented in Section 3.3, assumes infinite capacity available for each work center in the shop. This leads to considerable difficulties in the case of work centers that include more than one identical machine tools (see Section 2.2). In order to properly distribute these machines to different cells, the method is currently being enhanced to incorporate work load rules into the knowledge base that forms the manufacturing cells. In contrast to the original system, parts are no longer artificially assigned to each of the identical machines. Furthermore, these machines must now be identified by a common designation, as per the company policy.

The proposed new system contains two major parts. During the execution of the first part, infinite capacity available is assumed and the cells are formed according to the original method. However, only one of several identical machines is allowed to join each cell. The assignment of these machines will be re-examined in the second part of the system. After the initial cell formation, the work load of each work center is determined and compared to the capacity available. Any overloads of work centers with no identical substitutes are reported, but no further action is taken. If one of the multiple machines is overloaded, however, the feasibility of assigning a second machine into the corresponding cell is examined, in order to satisfy the capacity required. Such a re-arrangement will be performed only if; i) the cell size constraint is not violated, and ii) the number of part transfers in the resulting layout is less than the transfers in the original one. All such cases are investigated until no further reductions in part travel are possible.

6.0 CONCLUSIONS

The present work investigates the arrangement of the equipment of a machine shop into manufacturing cells to minimize the total number of part transfers that are necessary for the manufacture of the entire set of parts. The knowledge based Inter Class Traffic Minimization Method is presented here and applied to a large size industrial project. This method accounts for the sequence of operations required for the manufacture of each part and forms cells in order to minimize the inter class traffic. Two other methods of factory flow analysis, GPM and KBGT, were also employed for the same application. It is noted, however, that the objectives of both these methods are not directly related to the minimization of the travel of parts within the shop. Nonetheless, the comparative results obtained still provide a useful insight to alternative cellular layout approaches.

The analysis of the industrial project indicated that some work centers cannot and must not be included into the manufacturing cells. Furthermore, special considerations were necessary to address the work centers that contain more than one identical machine tools. Although all three grouping methods were applied under identical conditions, the cellular arrangement obtained from the Inter Class Traffic Minimization method yielded a considerably higher reduction in the number of total part transfers within the shop.

This method is currently being enhanced to incorporate work load rules that are necessary for smooth work loading through proper distribution of identical machine tools into different cells.

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REFERENCES

1. Chan, H.M. and Milner, D.A., "Direct Clustering Algorithm for Group Formation in Cellular Manufacturing," *Journal for Manufacturing Systems*, 1 (1), 1982.
2. Garcia, H. and Proth, J.M., "Group Technology in Production Management: The Short Horizon Planning Level," *Applied Stochastic Models and Data Analysis*, 1, 1985.
3. Garcia, H. and Proth, J.M., "A New Cross-Decomposition Algorithm: The GPM. Comparison with the Bond Energy Method," *Control and Cybernetics*, 15 (2), 1986.
4. Harhalakis, G., Nagi, R. and Proth, J.M., "An Efficient Heuristic in Manufacturing Cell Formation for Group Technology Applications," submitted for publication to the *International Journal of Production Research*, 1988.

5. Hyer, N.L. and Weemmerlöv, U., "Group Technology Oriented Coding Systems: Structures, Applications, and Implementation," **Production and Inventory Management**, 2nd Quarter, 1985.
6. Ingram, F., "Group Technology," **Production and Inventory Management**, 4th Quarter, 1982.
7. Jackson, D., **Cell System of Production**, Business Books, London, 1980.
8. King, J.R., "Machine-Component Grouping Using ROC Algorithm," **International Journal of Production Research**, 18 (2), 1980.
9. Kusiak, A., "EXGT-S: A Knowledge-Based System for Group Technology," **International Journal of Production Research**, 26 (1), 1988.
10. Kusiak, A. and Wadood, I., "Knowledge-Based System for Group Technology," **1st International Conference on CIM**, RPI, Troy, NY, May 22-25, 1988.
11. Leskowsky, Z., Logan, L. and Vannelli, A., "Group Technology Decision Aids in an Expert System for Plant Layout," **Modern Production Management Systems**, Elsevier Science Publisher, 1987.
12. McAuley, J., "Machine Grouping for Efficient Production," **Production Engineering**, 51 (53), 1972.
13. McCormick, W.T., Schweitzer, P.J. and White, T.E., "Problem Decomposition and Data Re-organization by a Clustering Technique," **Operations Research**, 20 (993), 1972.
14. Nagi, R., "Selection and Layout of Facilities for Cellular Manufacturing Systems," M.S. Thesis, **University of Maryland**, December 1988.

