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METHODOLOGY TO DETERMINE PERFORMANCE OF A GROUP TECHNOLOGY DESIGN CELL ON THE BASIS OF PERFORMANCE MEASURES

by

RAJUL TANK

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APPROVED:

Timothy J. Greene
T. J. Greene, Ph.D. Chairman

Subhash Sarin
S. C. Sarin, Ph.D.

Konstantinos P. Triantis
K. P. Triantis, Ph.D.

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(ABSTRACT)

There are a large number of Group Technology (GT) based cell formation techniques in the literature, but their applications rare. It is hypothesized that the reason behind the lack of applications of these techniques in practice, is "fear of the unknown". There have been a very limited number of attempts to determine the performance of any of the cell formation techniques. This thesis attempts to demonstrate a method to determine the performance of cell formation techniques by measuring the physical performance of the manufacturing cell.

The methodology involves a manual evaluative approach to determine the cell performance from the data given for the system. The methodology presents selection of important Performance Measures (PMs), data requirement for the measurement of PMs and cell formation technique analysis. The performance measures to determine the performance of these techniques were selected according to their importance to the productivity of the manufacturing cell and their significance among GT principles.

The cell formation techniques selected to demonstrate the method are Rank Order Clustering algorithm (ROC) and Production Flow Analysis (PFA). Using ROC and PFA, part families and machines groups were formed creating cell layouts. From the given data, performance measure values were calculated for a functional layout as well as ROC and PFA layouts. Performance of ROC and PFA layouts were compared to each other and to the functional layout.

Results from the example show that performance improvement can be achieved by the two cell formation techniques in all the performance measures category except in flexibility. Performance of ROC and PFA are the same in the categories of setup time, machine utilization and flexibility. The reason being, similar machine groupings and part families were achieved by both techniques for this example. Material handling performance and flexibility are dependent largely on machine grouping, whereas setup time is dependent on part families. Machine utilization and work-in-process are dependent on machine groups as well as part families. It appears PFA would have better performance in cases of complex problems having large number of machines and parts due to its comprehensiveness and ability to group machines according to the parts′ processing similarities. The advantage of ROC is mainly in its ease of application and rather elegant way of handling bottleneck machines and exceptional parts. Due to the lack of flexibility in GT layouts, system design and operation planning should be done carefully.

Dedicated to Himat and Sharda Tank

for Their Love and Support

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1.0 INTRODUCTION

Manufacturing technology started changing rapidly with the advent of numerical control in the 1960's. Mid 1960's and early 1970's saw more sophisticated numerical control machines. The mid 1970's and early 1980's experienced more sophistication in the development of machining centers and Flexible Manufacturing Systems (FMS). FMS emphasizes the clustering of different machines into cells, usually with automated material handling equipment, and the entire system computer controlled. Due to changing technology and intense competition, the philosophy of manufacturing system design has led to a concept known as "Integrated Manufacturing". Parallel development in the field of computer-aided design/graphics and robotics resulted in "Computer Integrated Manufacturing". Here, the entire process of transformation from raw material into finished product, starting from design and proceeding through to manufacturing, assembly and delivery, is integrated with constant feedback through the computer.

Introduction of sophisticated equipment gave manufacturers tremendous opportunities to increase their productivity and quality. Society and its natural desire to change perpetuated product variety and varied customer demand. Thus, competition, both domestic and international, became intense. European and Japanese manufacturers were able to surge ahead of their American counterparts, mainly because of better utilization of available equipment and better managerial and labor involvement. This brought the realization to U.S. manufacturers that mutual cooperation and compliance to change is vital for survival. The U.S. manufacturers realized that a broad change in overall manufacturing strategy was necessary for successful competition.

The realization for change has brought about a restructuring of the operational and managerial aspects of factories. The trend is to institute changes in managerial functions and shop floor control. To achieve a high standard of productivity and quality with competitive cost, many manufacturing facilities producing low-volume, high-variety goods are changing their method of equipment organization. The traditional method of low-volume high-variety organization, the job shop layout, is giving way to a new manufacturing philosophy, known as Group Technology (Ham, Hitomi 1982). Group Technology (GT) seeks to capitalize on the similarity of parts, machines or manufacturing operations. It is a philosophy with broad applications, and is thought to potentially affect all areas of manufacturing.

One specific application of GT is Cellular Manufacturing (CM). CM is currently the focus of considerable interest from practitioners and academicians alike (Flynn 1986). CM involves processing a collection of similar parts (part families) on dedicated clusters of dissimilar machines, such that a part is completed in a cell entirely or with a minimum number of inter-cell transfers. This implies that parts must be grouped into families to be produced by compatible machines. Thus, there is a need to develop and utilize algorithms for group formation. Today there are various group formation techniques available for part and machine grouping.

Despite having a high variety of techniques to address the problem of part and machine grouping, there are few examples of industrial implementation. It is hypothesized that the reason behind the lack of implementation of GT based cell formation techniques is a lack of apriori knowledge about the performance of these techniques. Therefore, the problem researched here, was to determine a methodology to evaluate the performance of a GT based manufacturing cell in terms of cell Performance Measures (PMs). The methodology involves selection of important performance measures for the system, data requirements for the measurement of the PMs, analysis of the GT cell formation techniques to be compared and performance measurement.

Two of the most common techniques among cell formation techniques are Rank Order Clustering algorithm (ROC) and Production Flow Analysis (PFA). The objectives of this thesis is to identify the important PMs for GT cells; present a method to compare functional layout to cell manufacturing layouts with the help of the PMs. As an example evaluation of the performance of cell layouts, ROC and PFA was done. The contribution of such a work will be in its value to a decision maker in justifying a choice of a layout technique, given the PMs.

The literature review is presented in chapter two on different types of group formation techniques. Each technique is described in terms of its methodology and specific characteristics such as ability to deal with bottleneck machines or user adaptability. Chapter Three presents the methodology to compare GT techniques. In the framework of the methodology performance measures are defined. Performance measures were selected depending upon their importance in GT based layout, and methods of their measurement are described. In Chapter Four, a case study is presented using ROC and PFA cell formation techniques. Both techniques, ROC and PFA are described in detail, and measurement of PMs in both cases are shown. Chapter Five gives the results of the case study problem. Chapter Six gives conclusions and future recommendations.

2.0 REVIEW OF GROUP FORMATION TECHNIQUES

A number of techniques are available in the literature for part family/machine group formation. Each has different procedures and objectives. In this chapter, some of the cell formation techniques which demonstrate different methods in achieving the cell layout are reviewed. A three-pronged organizational scheme which was introduced by Ballakur and Stuedel (1987) is used here.

The three-pronged organizational scheme can be stated as follows:

1. ***Part Family Grouping***: Form part family, and then group machines into cells.
2. ***Machine Grouping***: Form machine cells based on similarity in part routings, and then allocate parts to the cell.
3. ***Machine-Part Grouping***: Form part families and machine cells simultaneously.

All the group formation techniques have the same final objective, i.e. to group parts into families and to form machines into cells, but the ways in which they achieve this objective are different.

2.1 Part Family Grouping

In part family grouping techniques, parts are grouped into specific part families. Following this step, the machines are grouped together, given the part families, to form cells which process these part families. Two existing techniques for part family grouping are:

1. Classification and Coding,
2. Cluster Analysis.

2.1.1 Classification and Coding

Classification and coding is defined as sorting parts into different classes based on certain part characteristics (such as design or routing) and assigning a code (usually alphanumeric) such that parts having similar codes can be grouped into a part family.

The work of Opitz and Wiendahl (1971) used classification and coding as a foundation for determining part families via workpiece statistics. Initially, the parts to be considered are coded and ordered according to the frequency of the occurrence of their code. A computer generated cumulative frequency graph is manually interpreted to obtain the main groups of the part spectrum.

The use of classification and coding in forming part families is also reported by Gongaware and Ham (1981). Coded parts are grouped through the use of a multi-objective clustering algorithm. The distance between two parts, which refers to the similarity between them, is minimized. The user can specify the priority digits to be utilized in part grouping. The priority digit specifies which digit positions have priority in the grouping process. This adds to the flexibility of the process because different users' specifications (design, tooling etc.) may be accommodated during grouping. Han and Ham (1986) extended this analysis using a global programming technique on a coded part database. The distance between parts is minimized subject to the constraint that: (1) a part belongs to one family, (2) all variables remain integers and (3) all parts in one family have the same code on significant digits. Here, significant digits are the ones by whose similarity the grouping is done. The significant digit is a user specified vector that prioritizes which set of digits are given priority in clustering.

The work of Zelenovic (1987) uses a three phase method for designing production cells. The first phase groups together all parts, sub-assemblies and assemblies with the same classification code number. He names such a set of parts as a module. A composite part code containing all the shapes of parts in that code is then developed. With a process route sheet containing all the necessary production information for all the parts, and on the basis of these data, a parameter $T_i > Z.K_i$ determines whether grouping of each module is finished or further addition of parts into the family is necessary. Here T_i is the total machine capacity, K_i is the effective machine capacity (hrs/day) and Z is a whole number.

In the second phase, the individual modules with similar codes are grouped together. The parameter T_i again determines whether further joining of modules is necessary. Here, the parameter T is evaluated with respect to all the work centers in the cell as opposed to the individual work centers in the previous phase. In the third phase, the design of the entire system is done with respect to labor utilization, management suitability, and human relations.

2.1.2 Cluster Analysis

Cluster analysis is defined as the decomposition of the data to identify the part groupings. Carrie (1973) used a cluster analysis procedure known as numerical taxonomy for finding part families. He stated that, "Taxonomy is a science of biological classification of objects based on their possession or lack of relevant characteristics". Numerical taxonomy provides an algorithm for the study of similarities between objects in a quantitative manner. It involves three stages:

1. Prepare a data matrix. This indicates which characteristics are either present or absent, for example, whether a component is rotational or non-rotational. This can be indicated by a series of binary digits rather like an extended code. Other quantities must be specified in numerical values like the diameter of a hole or the batch quantity.
2. Compute a similarity coefficient matrix. From the information contained in the data matrix, the similarity between each pair of objects can be evaluated. The coefficient is defined to have values between 1.0 when two objects are identical and 0.0 when they have nothing in common.
3. Perform cluster analysis. Cluster analysis examines the similarity between each pair of objects and forms the group of objects, so that within each group, the objects are highly similar to one another. Cluster analysis seeks to find groups of objects forming distinct clusters.

Numerical taxonomy is a technique of considerable flexibility. No single formula exists for defining the similarity between objects. The similarity coefficients may be calculated by the method most appropriate to the particular problem. Similarly, many algorithms have been developed for cluster analysis and may be selected to suit the case being studied.

2.2 Machine Grouping

Many part family techniques have two phases where phase one deals with part grouping while the second phase groups the machines together to process the members of the part family. Like the two phase methods of part family techniques, some of the group formation techniques used for machine grouping have two phases too. In the first phase of analysis, the machines are grouped to form cells based on the information contained in part routings. The second phase usually consists of allocating parts to cells and evaluating the cells based on other factors such as machine utilization, etc. These machine grouping efforts can be broken up into two sub-classes namely: (1) non-algorithmic procedures and (2) algorithmic procedures.

2.2.1 Non-Algorithmic

Some of these non-algorithmic techniques, introduced in the late 1970s, use production data and evaluative heuristics to determine the optimum cell structure. Typically, these heuristics attempt to find the most acceptable cell by focussing on parameters like machine utilization, inter-cell moves, distribution of workload, flexibility of the system, etc.

The work of DeBeer (1976), applied a modified form of the PFA technique for cell construction. The author divided all the available machines into primary, secondary and tertiary machines. Primary machines are those that can not appear in more than one cell, secondary machines are those that can appear in more than one cell but not in all cells, and tertiary machines are those that can be distributed to all cells.

The process of distributing the primary machines into cells starts by determining the total number of times the machine appears in routings and arranging the machines in ascending order. Then a matrix is constructed where the rows and columns are arranged in the primary, secondary and tertiary sequence and in ascending order of their frequency of occurrence in routings. For each machine (the rows), the columns are filled with the number of times that the machine occurs in routing in conjunction with other machines when all routings are considered. This yields a preliminary division into primary cells. The relationship of secondary and tertiary machines with the primary machines yields the machine clusters.

As soon as the number of cells are determined, the routings are assigned to cells. Cell workloads are then computed. From these workloads, the required number of machines are determined. The machine-job matrix is manually interpreted to recognize machine groupings. Once this is done, a computer program assigns routings and determines the workloads on machines.

As an extension to the earlier work, DeBeer et. al. (1978), proposed a method named Production Flow Synthesis (PFS). This is a cell design method for product-oriented production systems. The procedure is a series of evaluations made by the designer using matrices, tables and graphs as aids. There are six steps necessary for this procedure:

1. Collect data.
2. Establish preliminary division into sub-systems or cells.
3. Assign routings to sub-system.
4. Comput workloads per sub-system.
5. Establish workflows within sub-systems.
6. Establish workflows between sub-system.

The division into cells in step two is based on routing information. Three types of operations are defined; primary operations, to be performed by one machine only, secondary operations for which a number of machines are available, and tertiary operations which can be done in all cells because a large number of machines are available to accommodate every cell. A matrix is constructed where the rows and columns represent operations arranged in primary, secondary and tertiary sequence and in ascending order of their frequency of occurrence. For each operation (the rows), the columns are filled with the number of times it occurs in conjunction with other operations in a set of routings. From this matrix, a preliminary, manual division of primary cells is possible. Relationships with secondary and tertiary operations yield the initial clusters. The workflows within the cells are evaluated via a matrix where rows and columns indicate operations and the entries (ij) indicate workloads between the operations i and j. A line graph shows the transition of a product from one sub-system to another. This procedure needs substantial manual interpretation of the operation-operation matrix for the machine grouping. Computer aids are only used for matrix construction and route ordering.

2.2.2 Algorithmic Approach

Among all the techniques using an algorithmic approach, many are cluster analysis techniques which started with McAuley (1972) introducing the similarity coefficients between machines. McAuley's method uses matrices to form machine cells. The method involves computing a similarity coefficient between a machine pair as the ratio of the number of parts which visit both machines to the sum of parts visiting either of the machines. In order to clarify this definition consider the following machine-part matrix:

Table 1. Machine-part matrix

		Parts				
		1	2	3	4	5
Machines	1		1	1		1
	2		1	1		
	3	1			1	1
	4		1	1	1	
	5	1	1			1

The similarity coefficient for the machine pair (1,2) is $2/(1+1+1) = 0.67$. Parts 2 and 3 visit both machines whereas part 5 visits one machine. For the given machine-part matrix, similarity coefficients are computed for all machine pairs and a dendogram is drawn. From the dendogram, it is possible to determine the similarity levels of the machine groups by reading the similarity values from the point of union of the two branches. Thus, machine pairs 1 and 2 are similar at the .67 level whereas 1 and 3 are similar at the .20 level. If a horizontal line is drawn at any level of similarity across the dendogram, then the cut branches indicate the corresponding groups formed.

The work of DeWitte (1980) designs cells based on similarity coefficients. Three types of similarity coefficients are defined. In this case, they are:

1. The similarity coefficient showing the absolute relationship between the machines is defined by $SA_{ij} = X_{ij}/AF$ where $AF = \sum X_i/D_i$ and AF is the average frequency for a machine type in a cell, 'X_{ij} is the value in the machine-machine matrix in position ij', N is the total number of machine types, 'D_i is the divisibility number of machine types in position i', and X_{ii} is the value in the combination matrix at position ii. The divisibility number indicates the number of cells which may contain a certain machine type.
2. The similarity coefficient showing the relative mutual interdependence between types is defined by $SM_{ij} = \min(\frac{X_{ij}}{AF_i}, \frac{X_{ij}}{AF_j})$, where $AF_k = \frac{X_{kk}}{D_k}$ and AF_k is the average frequency for a single machine type k.
3. The similarity coefficient showing the relative single interdependence between machine types is defined by $SS_{ij} = \max(\frac{X_{ij}}{AF_i})$.

All the available machines are classified as primary, secondary or tertiary machine types. Primary machines can occur only in one cell, secondary machines in some but not all cells and tertiary machines in all cells. All the machine routings are then considered and the machine-machine matrix is formed. The machine-machine matrix shows the number of times a machine by itself, or in combination with others, occurs in a set of routings. The similarity coefficients are computed for primary, secondary and tertiary machines. Once this is done the machines are clustered into cells using a graph-theoretic approach (Rajgopalan and Batra, 1975). The allocation of parts is then done, and the minimal and maximal workloads are computed.

The work of Waghodekar and Sahu (1984), attempts cell formation with the minimum number of exceptional elements. The author defines three different kinds of similarity coefficients:

1. Similarity Coefficient (SC_{ij}) for the additive type; $SC_{ij} = \frac{NCC_{ij}}{(TNC_i + TNC_j - NCC_{ij})}$.
2. Similarity coefficient of the product type (PSC_{ij}), based on the total number of parts processed by each machine i and j; $PSC_{ij} = (NCC_{ij} x NCC_{ij}).(TNC_i x TNC_j)$.
3. Similarity coefficient based on total flow of common parts processed by a machine ($SCTF_{ij}$); $SCTF_{ij} = \frac{(NCC_{ij} x NCC_{ij})}{(TFC_i x TFC_j)}$, where NCC_{ij} is the number of common parts using both machines i and j; TNC_i is the total number of parts using machine i, N is the number of machines, TFC_i is the total flow of parts processed by machine i with respect to all remaining machines and TFC_i is the sum of all $NCC_{i.}$

The solution procedure starts by determining the similarity coefficients from the inputted machine-part matrix and forms cell thereafter. This completes the first phase of the procedure. The second phase computes all inter-cell flows and similarity coefficients between machines based on $SCTF_{ij}$. The cells are again arranged on this basis. This stage minimizes the inter-cell moves by restructuring cells and hence attempts to minimize the exceptional elements. The last phase allocates the parts to the cells.

The authors claim that their algorithm is able to accommodate the number and sizes of cells as constraining variables and addresses machine duplication through the appropriate cost benefit analysis. With exceptional elements, they suggest further investigation of the merging of near-cells, rerouting exceptional elements for machining within a cell and/or placement of common machines on common boundaries between cells. The authors also state that the use of additive and product type similarity coefficients give similar results.

One other type of algorithmic technique for machine grouping uses operations research techniques. It is known as the graph-theoretic approach presented by Rajgopalan and Batra (1975). This elegant method partitions machines into cells and allocates parts to these cells. A good forecast of products to be manufactured, the quantity of each part, the route card of each part containing the manufacturing sequence, and the set-up and machining times per operation are the inputs. The assumptions for this technique are:

1. Very little change in product profile.
2. Unique code number for each machine.
3. Route cards are correct and accurate.
4. Time estimates are accurate.

The method consists of three phases. In phase one, the input data are analyzed to derive a machine-graph whose vertices represent the machines and edges represent the relationship between the machines by the parts they process. This data analysis produces a quantitative relationship between every pair of machines. Two parameters X_{ij} and X_{ii} are defined. X_{ij} is the total quantity of all the parts using both machines i and j ($i \neq j$), and X_{ii} is the total quantity of all parts using machine i. In this graph, one vertex corresponds to one machine. All vertices corresponding to machines not used by any part are eliminated at this stage. A similarity coefficient S_{ij} is defined by: $S_{ij} = \frac{X_{ij}}{(X_{ii} + X_{jj} - X_{ij})}$. It has a value between zero and one. A matrix (S) of similarity coefficients is derived for every machine pair. A machine-graph is then constructed by including an edge ij only if a coefficient exceeds a certain threshold value T. The determination of T is subjective and judgmental, and this is a drawback of this work. Too small a value of T will result in a dense graph while a large value will result in a sparse one. At this stage, every part for which $S_{ij} \leq T$ is an odd part. The drawings and routings of these parts should be examined for rationalization.

As a first step toward cell formation, the machine-graph is investigated for groups of related machines. This is done with the help of graph theory. In terms of graph theory, a group of items is referred to as clique. In the analysis, a clique is a group of machines, every pair of which has a similarity coefficient greater than T. This yields the initial cells.

In the second phase, these initial cliques are merged to form larger cliques that have strong relationships between members of cliques and weak relationships between distinct cliques. In other words, intra-cell machine relationship is strong whereas inter-cell machine relationship is weak. The authors use a graph-partitioning approach in partitioning these cliques and the minimum number of inter-cell moves is the main criteria.

In the third phase, parts are allocated to these cells such that high machine utilization and uniform cell loading is possible. Allocation is also based on the minimum number of cell moves. The authors report the testing of the method with industrial data, and it seems to produce good results.

2.3 *MACHINE-PART GROUPING*

Machine-part grouping is defined as attempting to group parts into part families and machines into cells simultaneously. Several methods of analysis found in the literature can be included and further subdivided into two types of techniques: heuristic and algorithmic.

2.3.1 Heuristic Techniques:

Two heuristic techniques of machine-part grouping are Production Flow Analysis (PFA) and Component Flow Analysis (CFA). Production Flow Analysis, introduced by Burbidge (1963), is one of the earliest and most comprehensive approaches for cell formation. PFA is a technique devised for finding families of parts, and associated groups of machines for a group technology layout. It is particularly applicable for identifying less similar parts that require common operations. The technique is applied in four successive stages. The main information needed is accurate route cards for every part produced.

By a progressive analysis of information contained in the route cards of parts and assemblies, PFA looks for a natural division of groups and families into which parts will fall on the basis of similar routes in terms of machines used. It sets out to use only existing equipment, tooling, and processing methods. It also identifies any exceptional parts which do not fit the solution for the majority. The four stages of PFA are : Factory Flow Analysis (FFA), Group Analysis, Line Analysis and Tooling Analysis. PFA will be discussed in detail in chapter four.

Another machine-part grouping technique is Burbidge's (1973) "Nuclear Synthesis". This process requires a list of all parts made on each machine type and their frequency of use. The "nucleus" machine - the one that is used to make the smallest number of different parts - is identified next. A "module" (set) is then formed which contains all the parts which use this machine and all other machines used by those parts. The above is repeated for all parts and machines. The modules are then combined to form groups. Exceptions are then eliminated by rerouting, changing methods or by purchasing. Finally, a load check on each group is done.

El-Essawy and Torrance (1973) reported the development of the Component Flow Analysis (CFA) method as an aid to cell formation. There are three stages to this approach. The first stage shows how components, their manufacturing methods and the machine tools required for their production are related. The whole product mix is divided into a number of general combinations of machine tools and components to be manufactured on them. These general combinations of components and machine tools are then analyzed and different parts of these general sections are coordinated to divide the facility into rough groupings for part manufacture. This completes the second stage of analysis. In the third stage, a final design is formulated based upon actual flow patterns and forecasted workloads.

2.3.2 ALGORITHMIC

There are several algorithm based procedures for machine-part grouping. One such example is the Rank Order Clustering Algorithm by King (1980). This method of simultaneous machine-part grouping needs a machine-part matrix as an input. A positive entry, usually a value of one, indicates the requirement of a machine for that part; a zero indicates otherwise. For each row and column of the matrix, the entries are read as a binary word. The row entries are then ranked in a decreasing order of their binary values. Such a reordering process continues until two successive iterations yield the same row order. The process is then continued with columns. At termination, the authors claim, a diagonalized set of clusters should emerge.

This algorithm first assigns binary values to a cell entry. Thus the ranking of rows and columns will depend on the position of their entry in the initial matrix. This is a weakness of the algorithm. Also, there are situations when either a part may require processing in two different groups, or there may be machines which are required by many parts. The first situation is the case of exceptional parts, and second is that of a bottleneck machine. In this algorithm, once an exceptional part is detected, it is temporarily deleted from the matrix. The process is then applied again to obtain a grouping. The deleted entries are then re-entered. In his work, the author does not demonstrate the effectiveness of the method for a sufficiently large data matrix. The situation of bottleneck machines is dealt with by duplicating as many machines as required - one for each group - to obtain distinct groupings. The economic implications of such a move and the effect of increasing the size of the matrix on computer storage requirements was not considered. Also, no evaluative measure for machine-part groupings was given. This method is discussed in more detail in chapter four.

As a further extension to this method, King and Nakornchai (1982) refined the above technique by the use of a computationally efficient sorting procedure. Here, starting from the last column, a row reordering is done. The rows with entries are located and moved to the head of the row list. This is done for all rows. The same procedure is repeated for columns. The final row and column order yields the part-machine grouping.

This algorithm, unlike its previous counterpart, does not assign a binary weightage to the individual cell entries. Therefore, the initial disposition of the matrix will not influence the final grouping to the extent of the previous method. The new procedure for dealing with bottleneck machines is to ignore them during the shift process. After the shifting process is complete, the required number of bottleneck machines are added to the group. This is done on an interactive basis. This procedure does not consider machine or cell loading, cell size limits, or cost restrictions for machine duplication. This raises questions about its effectiveness where such factors come into play.

A procedure very similar to the ROC algorithm was developed by Chan and Milner (1982). The method, named Direct Clustering Algorithm (DCA), is a part-machine matrix rearrangement method. It starts by counting the number of cell entries (k) in each column and row. The matrix is then rearranged with columns in decreasing order of k and rows in increasing order of k. Starting with the first column of the matrix, the rows having cell entries in the first column are transformed to the top of the matrix. This is repeated for all the columns. The same operation is performed for all the rows. Starting from the first row, the columns having cell entries in the first row are transferred to the left most position. All the rows are operated upon in this manner. The procedure terminates when the matrix remains the same for two successive iterations.

The treatment of exceptional machines is identical to the one proposed by King (1980). The treatment of bottleneck machines is a little more divisive. The authors offer two options: (1) the admission of as many additional machines as required for perfect clustering, (2) the allocation of machines to the most demanding group. The evaluation of the final configuration with respect to workload, machine utilization or the cell size is not done here. The authors at the end, propose a scheme for attacking the large amount of machine-part matrix data. They suggest the formation of a matrix with the whole range of machines and a fraction of the parts in the beginning. The DCA is then reapplied to this matrix and every part family is treated like a new part. The machines and a new set of parts including the one from the previous iteration are subjected to the algorithm. The process continues for all parts. In the end, the original parts are reinstated into the matrix.

Chandrasekharan and Rajgopalan (1986) show some of the major limitations of ROC developed by King. These are:

1. Even in the case of a well-structured matrix there is no certainty that a block structure will emerge as a result of rank ordering.
2. The initial solution is not the best solution. This indicates that a method can disturb a block diagram which is initially in a block diagram form.
3. Results of the algorithm strongly depend on the disposition of the initial matrix.
4. While the top left-hand corner is grouped, the rest of the matrix is disorganized.

They propose a modified rank ordering procedure consisting of three stages. In the first stage, the ROC algorithm is applied to the initial data matrix. The second stage applies a search procedure for identifying a submatrix that contains only ones as it's elements. The search procedure starts with the first diagonal element (a_{11}) and continues through the second (a_{22}) to finally (a_{ii}), until a zero is encountered. The row subscript is then decreased by one and the search progresses along that row (i - 1) until a zero element is encountered at column (j). The column subscript is decremented by one (j - 1) and the block is identified with those new rows and column subscripts (i - 1, j - 1). Next the corresponding part family and machine cells are stored as partial output and ROC is applied again on a truncated matrix. This process continues with the identification of independent part families.

In the third stage, the cells obtained from the previous stage are regrouped. To do so, a measure of association between cells C_i and C_j, S_{ij}, is defined such that: S_{ij} = Number of common elements)/(Number of elements in smaller cell). This enables the union of subsets of a cell to the cell. S_{ij} values are computed for all the cell pairs and the one with the highest values are merged to form one cell. The corresponding families are also joined. The S_{ij} values are recomputed and the operation continues until the S_{ij} values are zero. This indicates independent cells. In order to prevent the formation of a single cell or numerous cells the algorithm permits the specification of a maximum or minimum number of machines, the number of cells, and a threshold values of S_{ij} at which clustering is terminated. Bottleneck machines are those which appear in more than one cell at the final stage.

This modification seems to remove all the deficiencies of the ROC algorithm. It also introduces a new concept of a similarity measure based on machine association between cells instead of parts.

A related work in clustering a data matrix is by McCormick et al. (1972). The Bond Energy Algorithm (BEA) is attributed to their work. The algorithm works on an input matrix data and arranges the rows and columns in such a way that numerically larger elements or elements possessing similar characteristics are lumped together. The bond strength is defined as the summed product over all the rows and columns in the array. The measure of effectiveness is the sum of bond strength in the array.

Another method of simultaneous machine-part grouping is by Khator and Irani (1986). In this method, clustering of the part-machine is done by first selecting a seed part. A seed part is the one which requires a minimum number of machines m not included in a cluster yet. The authors argue that this minimum machine criteria reduces combinatorial complexity. The seed part is also constrained to the current machine included in the cluster. At a further point, the authors include yet another criterion for seed selection. This is the selection of the highest numbered part having the minimum machine requirement. Thus, the disposition of the matrix is the governing factor in such a case. In discussing the case of bottleneck machines, the algorithm performs two tasks. It places the bottleneck machines in any one of the clusters already formed and eliminates them from further analysis. It then selects a seed part from those processed by the bottleneck machines. The next cluster is the one without any of the bottleneck machines as these machines are already removed at the beginning of the solution process. The efficiency of the method with a large data set is untested.

A revision of the above method (Khator and Irani, 1987) utilizes the part-machine matrix to determine the "occupancy value" for a part. The route of a part, p, consists of a set of machines I_1, and all the parts that use one or more of these machines are represented by a set J. Some of these parts might use additional machines represented by the set I_2. The machines in I_1 and I_2 and parts in J represent a machine-part matrix whose Occupancy Value (OV) is defined as $OV_p = \sum\sum a_{ij}/mxn$ where m is the number of rows and n is the number of columns and a_{ijs} are the individual cell entries. In conjunction with the minimum number of required machines M_j and OV, the seed part is selected and machines necessary for its production are determined.

The authors give examples citing the effectiveness of the method. The method is untested for large data sets and the authors stress the necessity of examining the heuristic for machine duplication under economic restraints, upper and lower limits of number of cells, total number of machines assigned to any cell, lower limit of overall utilization of machines after reallocation among cells, and trade-offs between material handling and set-up losses for machines shared between cells.

The similarity coefficient method is also the basis for the work by Seifoddini and Wolfe (1986). The machine-part grouping is accomplished by employing a bit level storage technique to decrease the storage requirements and computational effort. The authors determine the computer words required to store one row of a machine-part matrix chart as a binary stream by the relationship: NWORD = NPART/NBITS, where NWORD is the number of computer words, NPART is the number of parts and NBITS is the number of bits per computer word. They also define a machine vector (MV) as an array containing the information related to processing a part on a single machine (i). It is an NWORD dimensioned array. A machine vector MVO is constructed by combining two machine vectors MV_i and MV_j. This vector stores information related to parts visiting machines i or j. Thus, MVO = $MV_i.OR.MV_j$. A non-zero bit indicates that a part needs processing in either machine. In the same manner, MVA = $MV_i.AND.MV_j$ indicates information about processing a part on both machines i and j. Further, NOR and NAND are defined as the number of non-zero bits in MVO and MVA respectively. The similarity coefficient between the two machines i and j, S_{ij}, is calculated from S_{ij} = NAND/NOR.

The similarity coefficient matrix for all machine pairs is accessed by an average clustering algorithm to bring similar machines together. Once this group is achieved, a cell vector CV combines its machine vectors into one cell. Thus if there are two machine cells containing machine vectors (MV_1, MV_2 and MV_3) and (MV_4) and (MV_5) respectively then $CV_1 = MV_1.OR.MV_3$ and $CV_2 = MV_4.OR.Mv_5$. Thus, if these two vectors are combined the resulting vector will indicate the presence or absence of inter-cell movements. That is, if CVA = $CV_1.AND.CV_2$ is non-null then inter-cell transfers occur, and the number of non-zero entries yields the number of inter-cell moves.

Duplication of machines is based on the number of inter-cell moves. It starts with the machine creating the largest number of such moves and continues until no machine is creating more than the specified number. This limit is specified by the user. The effect of such cell formation on machine loading or cell size limit is not addressed here. Also, machine duplication may not always be viable. In such a case and with a large amount of data, numerous exceptional elements might result.

One heuristic developed by Ballakur and Stuedel (1987) attempts to form part families and machine cells simultaneously. A part is assigned to a cell such that the majority of its operations might be only in that cell. It indirectly attempts to minimize the intercell moves of parts, given the machine workloads and cell size restrictions. The authors define the workload fraction (WLF) of a workcenter S_i in a cell C_j as the ratio of within-cell workload on workcenter S_i due to parts already assigned to C_j to the total workload of the workcenter or WLF $= \sum W[S_i, P_k]/W[S_i]$, where $W[S_i, P_k]$ is the workcenter of part P_k that has already been assigned to cell C_j on workcenter S_i. $W[S_i]$ is the total workload on S_i due to all parts routed through it. The workload fraction of a workcenter has to be greater than a specified fraction known as the Cell Admission Factor (CAF) for it to be admitted into the cell. The within cell utilization (WCU) of a workcenter S_i in cell C_j is defined as the ratio of within-cell workload on workcenter S_i on account of all parts already routed through C_j to the available machine capacity of workcenter S_i. In other words, $WCU(S_i) = \sum W[S_i, P_k]/[CAP(S_i)/N(S_i)]$, where $CAP(S_i)$ is the total capacity of workcenter S_i and $N(S_i)$ is the number of machines in that workcenter. It is assumed that all machines are functionally identical, and they work same number of shifts per day. The cell size upper limit (CSUL) is the maximum number of machines that can be assigned to that cell.

The heuristic requires as an input the number of identical machines in a workcenter, its total capacity, the total number of operations required for each part, part demand, part processing time and workcenter processing location. Additionally, the values of CAF and CSUL need to be specified by the user.

The algorithm starts building a new cell by selecting the workcenter having the highest workload per machine. This workcenter is termed the key workcenter and is admitted to the cell. All parts routed through the workcenters are assigned to the cell if they have not already been assigned to a cell or if the number of operations for that part in the new cell is greater than those in its assigned cell. The individual operations of these parts on other workcenters is evaluated next. These workcenters are admitted to a cell if their WLF exceeds the CAF. The expansion of cells continues in this fashion until there are no workcenters left to be considered. Workcenters that are rejected first are considered for starting the subsequent cells. Parts routed through the workcenters are evaluated for their operational requirements. This and WLF dictate the admission of other machines to the cell. Thus subsequent cell building goes on. When all cells are built, statistics on number of inter-cell moves, total number of cells formed, maximum cell size, the percentage of operations performed within a cell for each part and the average number of operations that can be performed in a cell are computed. The authors show that the heuristic performs as well when compared to other available ones. The heuristic is also applied to industrial data for favorable results. The user can control cell parameters like CAF and CSUL, and it offers flexibility in cell design.

2.4 Summary

A number of cell formation techniques are discussed above. They were divided into three categories: (1) part family grouping, (2) machine grouping and (3) machine-part grouping. Part family grouping techniques create part families and then, assign machines to part families which require them for the successful completion of the parts in the family. Machine grouping techniques divide machines into cells and then, allocate parts to those cells. Machine-part grouping techniques form machine groups and part families simultaneously. Cell formation techniques in these three divisions are further divided into algorithmic and non-algorithmic.

Hence, this chapter presents the majority of the cell formation techniques in the literature. These techniques are described in terms of their working and special features. Special features include their primary use (e.g. use of classification and coding in design standardization) or ability to deal with special cases such as the ability to check the load on cells or the ability to deal with bottleneck machines.

3.0 METHODOLOGY FOR COMPARING GT TECHNIQUES

Implementation of theoretical concepts into practice is troublesome in most cases. Typically the reasons are: (1) lack of control of the variables, or (2) lack of prior knowledge of their performance. In the case of GT based cell layout, there are many techniques in the literature to form a cell. The performance of these techniques can not be determined without either implementing them or developing some method to analyze it before implementation. Thus, it is necessary to develop a method to compare layouts prior to physically building the system. In order to compare two cell formation techniques, it is important to compare their performance.

GT based cell formation techniques differ from each other in the ways in which they perform, but their objectives are similar; improving commonly noted performance measures such as reduction in material handling, reduction in setup time, increase in machine utilization, etc. The values of the performance measures determine the success of the cell formation techniques used. Hence, comparing the performance of cell formation techniques is best done by measuring the performance measures. This chapter presents a methodology that compares the performance of cell formation techniques on the basis of cell performance measures before the cellular system is actually built.

This methodology is a manual evaluative method. It has four steps;

1. Selection of performance measures.
2. Identification of data requirements.
3. Creation of GT cells using the known techniques.
4. Performance measures measurement.

The first step, selection of performance measures, determines the important PMs based on preselected criteria. There can be many criteria for the selection of performance measures in the manufacturing systems such as:

1. Importance of the PMS in terms of the cost of the product.
2. Data availability for the measurement of PMs in the cell.
3. Compatibility of the PMs with the type of cell formation techniques used to create the layouts.

Criteria for selecting PMs in this thesis include the importance of the PMs in operational performance of the cell, and the relevance of the PMs in respect to the GT techniques to be compared.

The second step, identification of data requirement, is dependent on the PMs selected and cell formation techniques selected. Data requirement is constrained by the availability and ability to measure the data in the system. The third step, creation of cells using GT techniques is the actual design of the system using the selected cell formation techniques. It should be noted that GT techniques to be compared should be similar in scope because it is suitable to compare the techniques which use similar data (e.g. processing similarity vs. design similarity), or similar mechanism to form families (e.g machine grouping type vs. machine-part simultaneous grouping type). The fourth step, PMs measurement, utilizes the PMs to provide a basis for comparison between GT techniques. In the following sections of this chapter, all four steps of the methodology are discussed in detail. A case study example is shown in Chapter Five to show the workings of the methodology.

3.1 Selection of Performance Measures

3.1.1 Scope of Performance Measures

Performance measures are defined as the parameters that represent the physical process of manufacturing. Performance measurement should provide a basis for the assessment of the efficiency of a company in carrying out the physical aspect of its production operations. A wide range of company activities exists about which management makes frequent decisions. These decisions affect such things as productivity, flexibility of production, quality, labor relations, and others. The measures used should provide a basis for decision making in the following areas:

1. Indicator to show when things are going wrong and if remedial action is required.
2. Means for monitoring the effects of changes.
3. Assistance in company integration.
4. Providing feedback information to the management and workers.

Performance measurement is concerned with assessing the outcome of company operations and with examining the actual achievement in operational terms at the different levels in the company. Control in operational performance can be achieved by comparing the measures with forecasts, historical values and average industry values. This determines whether each aspect of company operation is under control, or if it requires some management attention.

3.1.2 Assumptions for Performance Measures

The context of performance measurement can be expressed as a set of fundamental assumptions about the operating management and company environment.

1. Performance is measured in relatively independent manufacturing units, e.g. department or group which has the opportunity to perform, adapt and take initiative of its own.
2. Within the timespan of measurement, the resources available remain constant.
3. Performance measurement is related to a defined set of objectives.
4. Performance measurement must relate to individual responsibilities, current patterns of control and to available data.

A number of important ideas arise directly from these assumptions. Firstly, the independent unit can consist of a machine and/or worker and management which has defined boundaries to perform the work. An independent unit with defined boundaries is viewed as an independent entity in a set of entities. GT favors scenarios where the groups are created for specific purposes and perform a set of activities independently. Hence, performance measurement is likely to be easier and more productive with GT (DeBeer 1976). Secondly, the measurement of operating performance can be done in terms of the effectiveness in meeting the group's targets. This requires performance measurement to be done on a set of variables which can be termed as group objectives, thus satisfying the assumption of the PM being related to a defined set of objectives. Thirdly and finally, implicit within all these assumptions and interpretations, is the fact that none of the measures are entirely independent of all the other measures. Each measure reflects some aspects of the physical operations of the company, which are themselves heavily inter-dependent. For this reason all aspects of a company's operations should be monitored to ensure that no feature is allowed to dominate to the extent which detracts from overall company performance.

3.1.3 The Improvement of Performance Measures

One of the difficulties faced by a production manager is to separate the measures which can be improved, and for which he/she is responsible, from those which are essentially fixed for a period of time and which are controlled by the firm's environment. There is a tendency to avoid the definition of some measures, and so the management operation task appears to be an enormous problem. Hence, a suggested sub-division of performance measures can be done in these three sets:

1. Environmental Measures: These take a long time to change and are largely outside the control of the company.
2. System Design Measures: These measures can be controlled by company but also take a long time to change.
3. Operating Measures: These variables take a short time to change and are more directly controllable by the production management.

This is not the only way that these measures could be grouped. It also should be noted that some of the measures can appear in more than one set. The content of these measures will change at different levels in the organization. At each level of the organization, all measures with a time scale for change, which are equal to or less than the time scale of analysis, are controllable measures and those with a longer time scale may be considered as environmental measures. At any given level, the controllable measures can be characterized by performance measures and can be regulated, but the environmental measures can not be regulated. Environmental measures can typically be measured only. The scope of performance measures in this thesis is limited only to operating measures.

Performance measures, in most cases, are a combination of a large number of sub-measures. It is possible, however, to select a few significant sub-measures which will be sufficient to provide a basis for control. If the number of measures chosen is high, the cost of the analysis will be high. The need is to find a compromise between cost and comprehensiveness, and at the same time provide a simple scheme which may be added to when more experience is gained. A further criterion which should be followed in choosing PM is that the measure must be within the control of the manager concerned. Operational measures mainly are the performance measures which can be measured and controlled by the manager.

3.1.4 The Choice of Performance Measures

Performance measures are the yardsticks for cell productivity. Some of them, mentioned below, also act as the objectives of group technology applications. Hence, success of the design aspect of a group technology manufacturing cell can be determined through the study of these performance measures (Wemmerlov, Hyer 1987). The selection criteria in choosing the PMs are importance of PMs in cellular layout and compatibility with GT techniques.

3.1.5 Material Handling

The movement of material is a common denominator in all manufacturing activities involving physical goods. It has been said that for a manufacturing activity of any kind, whether it is a single machine, a group of machines, or an entire plant, it is possible to identify three basic functions which define the total activity. These functions are:

1. Work performed,
2. Material handling, and
3. Control (Apple 1982).

Ever since the beginning of the time, man has been faced with the problem of moving himself and the material needed for his existence. Man himself frequently acts as material handler in his daily life. However, over a period of time, he has realized that material handling is an art of implementing movement economically and safely. In material handling, the concern is with parameters like; motion, time, quantity and space. The proper application of material handling knowledge will result in smooth integration of all the processes and resources in an efficient production system.

3.1.5.1 Importance of Material Handling

With the industrial revolution and the rise of the factory system, man continued to develop material handling systems to do the jobs where human and animal muscles were insufficient, either in capacity, speed or efficiency. With the development of the society and industrial era, the cost of labor became overwhelming, and it was desirable to reduce material handling labor, which usually added to the production cost but contributed little, if anything, to product value.

The actual size of the handling "task" is difficult to measure but, can be measured in several terms. From the literature, it is possible to conclude, by averaging all of the estimates made by all of the experts, that material handling accounts for about 25 to 30 percent of production costs (Apple 1982). Although, the sources of such figures are lost in their repetition, it might be wiser to recognize that they could range from a low of 5 to 10 percent, to a very high of 85 to 90 percent, depending upon the nature of the activity (Apple 1982). Other opinions draw conclusions such as the fact that one out of ten people in the labor force is occupied in handling; or, in a specific plant, fifty tons of material may be handled for each ton produced (Apple 1982). A real estimation can only be determined by an individual company devoting enough effort and attention to material handling to permit an equitable determination of the number of people or dollars involved.

Cost reduction through changing the material handling system is done in two different ways:

1. Improving Layout: By analyzing the flow of materials and the volume involved between operations, it is usually possible to reduce travel time and space needs. Rearranging equipment and providing handling systems that reduce the distance material must travel are useful practices.
2. Equipment Utilization: Many pieces of expensive equipment do not operate at their potential capacity because they are limited by the rate at which materials are supplied to, or removed from, the equipment or the work area. A proper handling system, or an efficient control of an existing handling system, can greatly increase equipment utilization.

3.1.5.2 Material Handling Measurement

One of the most confusing aspects of determining material handling requirements is that of classifying them into logical groupings as a basis for study and analysis. The handling tasks which are usually within some other area of activity are usually classified as an inseparable portion of the other activity and are therefore difficult to measure. Classification of distinct material handling activities can be done in the following two categories:

1. Work-place handling and
2. Inter-work-place handling.

Work-place handling includes preparatory handling on machines. Inter-work-place handling includes handling from one work area to another, or one work station to another. With a change in plant layout organization, performance of material handling measures changes only in the inter-work-place category. Hence the performance measures for material handling will primarily be in terms of the distance travelled by the material between two work areas or two work stations.

3.1.6 Setup Time

Setup time is defined as the time required to change and/or adjust the tooling on the machine between the processing of two different jobs. The average amount of time required for a setup has an impact on many shop performance measures (Porteus 1985). For example, it affects average flow time, due date performance and machine utilization. The capacity of a shop is often defined relative to the output of the shop. It refers to the maximum theoretical rate of productive conversion capability (Adam and Ebert 1982). Schmenner(1984) lists a number of factors which may affect output capacity, including lot sizes (by altering the number of setups required), scheduling (by reducing the number of setups required), process improvements and the quantity and quality of labor involved. Hence, reduction in setup time contributes towards an increase in output as well as increased shop capacity.

Reduction in setup time can be achieved in many ways, two of which are:

1. Creating family of parts which are similar in nature, and
2. Doing setup time based scheduling.

In the first case, group technology concepts are used to create part families. The techniques such as classification and coding can be used to identify the geometric or operational similarities, and then shop layout can be designed based on the sequence in which family parts are manufactured. The second case of setup time based scheduling requires two assumptions; (1) setup times are not independent of the sequence, and (2) there is an availability of data to construct a matrix to show the actual setup time required between every possible pair of machines and parts. Clearly the time required to change a machine over is a function of the degree of similarity between two parts which are processed in sequence on that machine. If two parts, processed in sequence, are identical, there should be no setup time required to prepare the machine for the second part. For cellular manufacturing, both techniques of reducing setup time are possible because of the inherent nature of GT to group like things together.

Although, the implementation of a GT based cell, in and of itself, has been shown to lead to reduction in setup time, further reduction may be possible through scheduling (Foo and Wager 1983). In this scheduling study, setup time has been assumed to be independent of the sequence in which jobs are processed. This simply is not realistic, especially in a cellular environment where family grouping is used (Flynn 1987). However, determining what the setup time will be for a given changeover is no simple task. Aggrawal (1972) argued that actually a new setup may require:

1. Complete dismantling of the old setup plus time for changing to the new setup,
2. Partially dismantling of the old setup plus additional time for the new setup to be done, or
3. Quick loosening of the old setup plus additional timing for finalizing the the new setup.

Thus, the degree of similarity between jobs processed in sequence is important. Using GT techniques for cell layout and family grouping will enhance the the possibility of a favorable result.

3.1.6.1 Setup Time Measurement

Measurement of setup time is usually very simple. Measurement of setup time can be done for each part as well as for the whole family of parts. In the case of GT based part family grouping, measurement of setup requirements for individual parts may not be sufficient or desired, and under the circumstances, setup requirements for the whole family are measured in order to determine overall improvement in setup performance. Setup time measurement is done in terms of the amount of time required per part or batch of parts.

3.1.7 Machine Utilization

Machine utilization is defined as the time a machine is engaged in productive work. This consists of processing time and setup time. Machine utilization is a parameter that partially represents shop productivity.

There exists a substantial amount of literature dealing with shop or cell capacity utilization. The focus here is on the overall facility utilization. Considering the overall facility, performance measurement has to be done on a group of machines which function together to produce a family of parts. Machine utilization typically depends upon the type of organizational layout in more than one way. Product layout normally has lower utilization due to interdependence of the machines to carry out the processes for a product. Creation of bottleneck machines or line imbalance are common occurrences and result in low machine utilizations. In the case of process layout, machines with similar functions are grouped together. Such a group of similar machines should allow the load to be distributed on machines with similar processing capabilities within the group. Such efforts allow higher machine utilization. However, there are some associated problems with process layout such as high average flowtime for all parts, substantial capital invested in work-in-process inventory, poor quality control for one functional group to another, etc.

Cellular layout developed using GT principles offers partial solutions to the above problem. By forming part families and having sequence related scheduling, reduction in cycle time and higher machine utilization can possibly be achieved. By grouping into cells, material flowpaths are simplified and higher machine utilizations can be achieved.

3.1.7.1 Machine Utilization Measurement

Machine Utilization measurement can be done in two ways: (1) by recording the time that a machine is engaged in productive work or (2) by the quantity of parts processed in a fixed time period. The amount of time a machine is engaged in work constitutes three different activities: setup time, processing time and machine loading and unloading time. Of these, setup time is the only element that is variable and can be reduced by the application of GT principles. With a reduction in setup time, the machines are available for a greater amount of time for processing other parts, thus, increasing the quantity of parts produced for a fixed period of time.

3.1.8 Work-In-Process

Work-in-process is defined as the average amount of material waiting to be processed or to be moved at any given time. Due to very stringent cost reduction efforts, work-in-process is gaining increasing interest in today's industry.

Work-in-process inventory is proportional to the average time a part spends in the system. Such a time consists of setup time, processing time, waiting time and time spent in transportation. Reduction and simplification of setup time and transporting time results in shorter average time spent by a part in the system and a reduction in the work-in-process inventory. Using GT based layout, the between machines movement is simplified and GT based family grouping and scheduling help bring down the work-in-process inventory.

3.1.8.1 Work-In-Process Measurement

Work-in-process measurement, though difficult, is done regularly in industry. The reason attributed is the capital cost tied up with the inventory. The measurement of work-in-process is either in terms of the amount of dollars worth of inventory, or quantity of parts. Quantity of inventory is tied closely with the flowtime in the system (Flynn 1984). Flow time dictates the time material spends in the system. The average amount of time spent by material in the system is directly proportional to the average amount of inventory. Hence, for the measurement of work-in-process, we shall use the percentage reduction in flowtime to determine reduction in inventory.

3.1.9 Flexibility

The flexibility of a production system is defined as the measure of its capability to adjust to changing environmental conditions and process requirements (Vinod Kumar 1984). As a result of growing pressures to produce more and more variety at less expense, there is a growing demand for higher productivity, improved quality and at lower costs. In short, higher levels of effectiveness as well as increased life of a production system is desired. Development of science and technology and the steady rise of production costs call for the adaptation of systems which require a high degree of flexibility.

There are several ways measures of flexibility can be defined. One measure of production system flexibility can be observed as the facility design adequacy, which is the probability that a given structure of a production system will adapt itself to the changing environmental conditions and to process requirements within the limits of given design parameters (Zelenovic 1982). If environmental and process requirements exceed the determined limit of the system, the flexibility of the system is inadequate, and the plant layout will have to be changed to suit new conditions. Another measure of flexibility may be observed as the time needed for system transformation or adaptation from one job task to another (Zelenovic 1982).

Flexibility, in some ways, affects some of the other performance measures in the manufacturing system. The most important being machine utilization; they bear a very close relationship, and are antagonistic in nature. In other words, one can design and produce a highly flexible system which carries out a wide range of tasks, but the degree of utilization and effectiveness of such a system in relation to simple tasks could be very low and visa versa. Investigation into the design of flexible production systems, therefore, points to a search for the appropriate ratio between flexibility and utilization.

Considering what various researchers have written about manufacturing flexibility, it is evident that different researchers emphasize different types of flexibility. For example, Zelenovic (1982) discusses strategic planning flexibility, design flexibility and adaptation flexibility. Stecke (1984) discusses machining flexibility and assembly system flexibility. Browne (1984) attempts to classify eight types of flexibility using different terminology. Buzacot (1982) discusses state flexibility, action flexibility, job flexibility and machine flexibility, and Yao (1986) focuses on routing flexibility. One can also talk of loading flexibility, material handling flexibility, information-flow flexibility, set-up time flexibility, data handling flexibility and so on. All of these types of flexibility are not independent and many still need precise definitions.

3.1.9.1 Measurement of Flexibility

Irrespective of the various types of flexibility stated by the researchers, the general consensus is that there exists a lack of a single measure of flexibility (Vinod Kumar 1984). Flexibility, in general, depends upon the decision options available and the freedom with which these decision options can be pursued. As mentioned earlier, performance measurement should relate to the objective of the problem at hand. Also, performance measurement depends upon the definition of flexibility. Group Technology and Cellular Manufacturing concepts advocate forming cells of machines and part families in such a way that processing of part families is done completely in the cell dedicated to that family. Definition of flexibility in our case can be given as the number of alternatives the group offers in the manufacturing of a part. Hence the measurement of flexibility is done by determining the alternate processing routes offered by the machines in the group.

3.1.10 Summary of PMs Selection

There are many other performance measures in the cell that are not considered here. The reasons behind that goes back to the criteria for selection. One of the criteria for selection of PMs is their importance in GT applications. Many performance measures like due date performance, cell control, labor utilization, etc. were not considered because GT principles do not have a direct effect on these PMs, or there are other performance measures are more significant measures of cell performance.

3.2 Identification of Data Requirements

The identification of data requirements step involves identifying data requirements necessary to calculate selected performance measures. Note that identification of data requirement is primarily dependent on the selection of performance measures. From the selection of the performance measures for this research, the following are the data requirements:

1. Initial machine-part matrix.
2. Initial layout organization and cell measurements.
3. Setup and processing time for all parts.
4. Similarity coefficient among all parts.

The identification of data requirement is constrained by the availability of the data in the system. It also indicates the types of data that need to be recorded and the extent of their detail.

3.3 Analysis of GT Techniques

The next step in the methodology is analysis of the GT techniques which are to be compared. This analysis gives the method by which machine-part matrix data can be decomposed to create part families and machine groups. From the machine groups, cell layouts can be created. In case of special cases such as bottleneck machines or exceptional parts, it can be resolved according to the recommendation given by the technique. From the layouts created and using initial data, PMs can be calculated.

3.4 Summary

An outline of the methodology for comparing GT techniques is given in this chapter. The first step of the methodology, selection of performance measures is discussed by defining performance measures for the cell, establishing their criteria of selection and their measurement methods. Other parts of the methodology including identification of data requirement are discussed and data requirements for the case are established. The last step in the methodology is analysis of GT techniques, and it is given in detail in Chapter Four.

4.0 CASE STUDY

The workings of the methodology described in Chapter Three is demonstrated with the use of a case study example. In the following sections of this chapter, the initial system description for the case study example is given. Discussion of performance measures selected and data required is given in Chapter Three. Here, the analysis of the selected GT techniques, ROC and PFA is given first and then how the measurement of PMs is performed. Justification for selecting ROC and PFA is also given with the analysis of both techniques.

4.1 System Description

The manufacturing system, presented here, consists of twelve machines to manufacture eighteen parts. These twelve machines are of four different types. There are four lathes, three milling machines, three shaping machines and two drills. One of the lathes, denoted by L2 is a specialized lathe and is not interchangeable with the other lathes. All the other machines of one type are interchangeable, which means one machine can be replaced by another machine of the same type to perform all the functions of the other machine. Most of the parts, typically, visit three to four machines before completion. Part routings are such that they can not be altered without altering the part design. All parts have similarities of varying degree among them in terms of processing similarity. Note that the system described here is only a part of the whole manufacturing system, and hence does not include other supporting operations like heat treatment or inspection which are necessary for successful part completion.

The above mentioned data is given in the form of initial part-machine matrix (Figure 1), setup time and processing time for each part on each machine they visit (Table 2, 3, 4). Machines arranged in functional layout are shown in Figure 2.

4.1.1 Initial Layout Arrangement

The initial layout arrangement is based on a functional layout. The shop area that is occupied by the machines is 60 feet long and 30 feet wide. Due to the nature of the functional arrangement, this area is divided in the four different areas to accommodate four different types of machines. These four functional areas perform different types of operations in each. Two of the areas have three machines each, one has four and the last one has two machines. Each machine roughly occupies 32 sq. ft. of space. These four areas are served by a separate material handling system for incoming and outgoing material from the system. The layout in areas is arranged in such a way that the material travelling distance is minimized.

Parts

M/Cs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1		1	1	1					1							1	
2	1											1			1			1
3		1					1		1		1					1		
4	1		1		1												1	1
5	1		1	1	1					1							1	
6								1				1	1	1	1			
7												1	1	1	1			
8								1				1			1			
9		1				1	1		1									
10		1					1				1					1		
11			1	1						1								1
12		1				1			1		1					1		

Figure 1. **Initial Part-Machine Matrix**

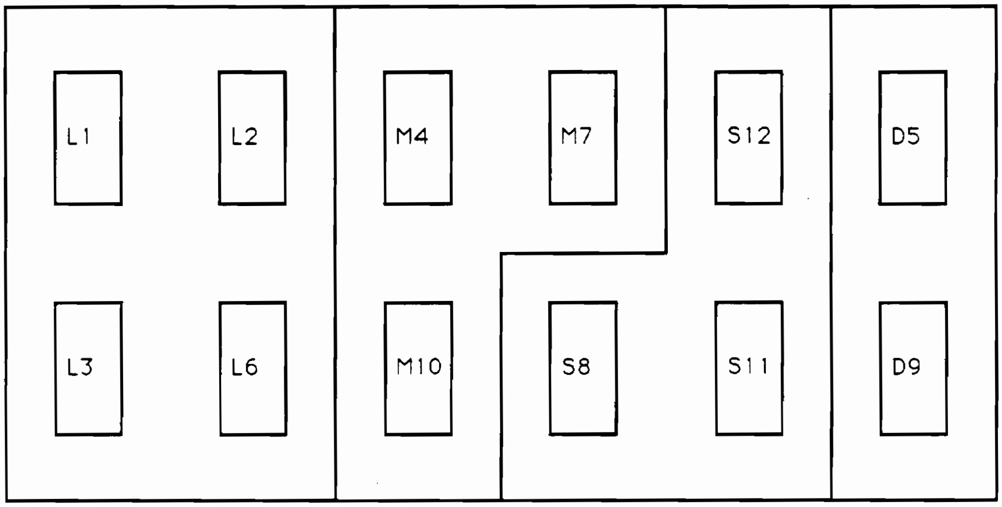


Figure 2. Functional Layout

Table 2. Setup-Processing Time Data

M/C #	Part #	Setup Time	Proc. Time	Total
1	1	4	9	13
1	3	2	6	08
1	4	4	8	12
1	5	3	7	10
1	10	4	7	11
1	17	5	10	15
2	1	4	7	11
2	12	7	10	17
2	15	4	6	10
2	18	8	9	17
3	2	7	10	17
3	7	5	9	14
3	9	4	6	10
3	11	5	9	14
3	16	4	8	12
4	1	3	8	11
4	3	5	10	15
4	5	8	11	19
4	17	5	9	14
4	18	5	8	13

Table 3. Setup-Processing Time Data

M/C *	Part *	Setup Time	Proc. Time	Total
5	1	5	8	13
5	3	4	7	11
5	4	6	9	15
5	5	6	9	15
5	10	4	6	10
5	17	5	8	13
6	8	7	10	17
6	12	4	8	12
6	13	5	10	15
6	14	8	12	20
6	15	5	9	14
7	12	6	9	15
7	13	4	8	12
7	14	5	9	14
7	15	5	8	13
8	8	4	8	12
8	12	3	6	9
8	15	4	7	11

Table 4. Setup-Processing Time Data

M/C #	Part #	Setup Time	Proc. Time	Total
9	2	4	8	12
9	6	9	12	21
9	7	7	10	17
9	9	7	11	18
10	2	5	7	12
10	7	5	7	12
10	11	7	10	17
10	16	5	8	13
11	3	6	9	15
11	4	5	8	13
11	10	7	11	18
11	18	5	10	15
12	2	6	9	15
12	6	5	9	14
12	9	6	9	15
12	11	3	7	10
12	16	5	9	14

4.2 The Two Cell Formation Techniques

In this section, both cell formation techniques, Rank Order Clustering (ROC) algorithm and Production Flow Analysis (PFA), are discussed in detail. These two techniques, though different from each other in more ways than one, group machines and create part families simultaneously. These two techniques were selected to demonstrate the working of the methodology because of following reasons;

1. ROC and PFA are two of the most popular techniques in the literature.
2. The techniques to be compared should have common data requirements for suitable comparison e.g. techniques like the graph-theoretic approach require qualitative relationships such as part similarity compared to quantitative relationships needed for ROC and PFA.

PFA is a manual but very comprehensive technique. While PFA groups machines and creates part families manually and heuristically, ROC does it with help of a computer based algorithm and also offers special capabilities of handling bottle-neck machines and exceptional parts scenarios.

4.2.1 Rank Order Clustering Algorithm (ROC)

There are several algorithm based procedures for machine-part grouping. One such example is the Rank Order Clustering Algorithm by King (1980). This method of simultaneous machine-part grouping needs a machine-part matrix as an input. A positive entry, usually a value of one, indicates the requirement of a machine for that part; a zero indicates otherwise. For each row and column of the matrix, the entries are read as a binary word. The row entries are then ranked in a decreasing order of their binary values. Such a reordering process continues until two successive iterations yield the same row order. The process is then continued with columns. At termination, the authors claim, a diagonalized set of clusters should emerge. This algorithm first assigns binary values to a cell entry. The clustering algorithm is given as follows:

1. For each row of machine-part matrix in turn read the pattern of cell entries as a binary word. Rank the rows in order of decreasing binary value. Rows with the same values should arbitrarily be ranked in the same order in which they appear in their current matrix (reading from top to bottom).
2. Are the current matrix row order (numbering from top to bottom) and the rank order just calculated the same?

   If yes, go to 6.

   If no, go to 3.
3. Re-form the machine-part matrix starting with the first row, by rearranging the rows in decreasing rank order.

   Rank the columns in order of decreasing binary value. Columns with the same values should arbitrarily be ranked in the order in which they appear in this current matrix (reading from left to right).
4. Are the current column order (numbering from left to right) and the rank order just calculated the same?

   If yes, go to 6.

   If no, go to 5.
5. Re-form the machine-part matrix starting with the first column, by rearranging the columns in decreasing rank order.

   Go to 1.
6. Stop.

It is assumed that the algorithm would normally begin with the original machine-part matrix, but it does not matter, the procedure is iterative, and it is possible to start with any rearranged form of the matrix. Thus, the ROC algorithm rearranges rows and columns in an iterative manner that will, ultimately, and in a finite number of steps, produce a matrix in which rows and columns are arrange in order of decreasing value when read as binary words.

There are situations when either a component may require processing in two different groups or there may be machines which are required by many components. The first situation is the case of exceptional parts and second is that of a bottleneck machine.

4.2.1.1 Special Cases

The Case of Exceptional Elements: In this algorithm, once an exceptional part is detected, it is temporarily deleted from the matrix. The 1 entries in machine-part matrix are replaced with an * symbol and are considered as a blank entry for computational purposes. Then ROC is applied to this revised matrix. Once the groupings are achieved, deleted entries are re-entered.

The case of bottleneck machines: This approach initially involves the use of the ROC algorithm in the manner already described. If this leads to an overlap of requirements between potential groups, then constraints of the problem are fully relaxed by a decomposition that provides duplication of these machines to the extent that each part operation is performed by one such machine. The ROC is applied to this new decomposed problem and a solution is obtained. A further operation may be required to recompose, where possible, the duplicate machines in the group.

As a further extension to this method, King and Nakornchai (1982) refined the above technique by the use of a computationally efficient sorting procedure. Here, starting from the last column, a row reordering is done. The rows with entries are located and moved to the head of the row list. This is done for all rows. The same procedure is repeated for columns. The final row and column order yields the part-machine grouping. The new procedure for dealing with bottleneck machines is to ignore them during the shifting process. After the shifting process is complete, the required number of bottleneck machines are added to the group. This is done on an interactive basis. This procedure does not consider machine or cell loadings, cell size limits, or cost restrictions for machine duplications. This raises questions about its effectiveness where such factors come into play.

4.2.1.2 Advantages of ROC

There are several distinct advantages associated with ROC:

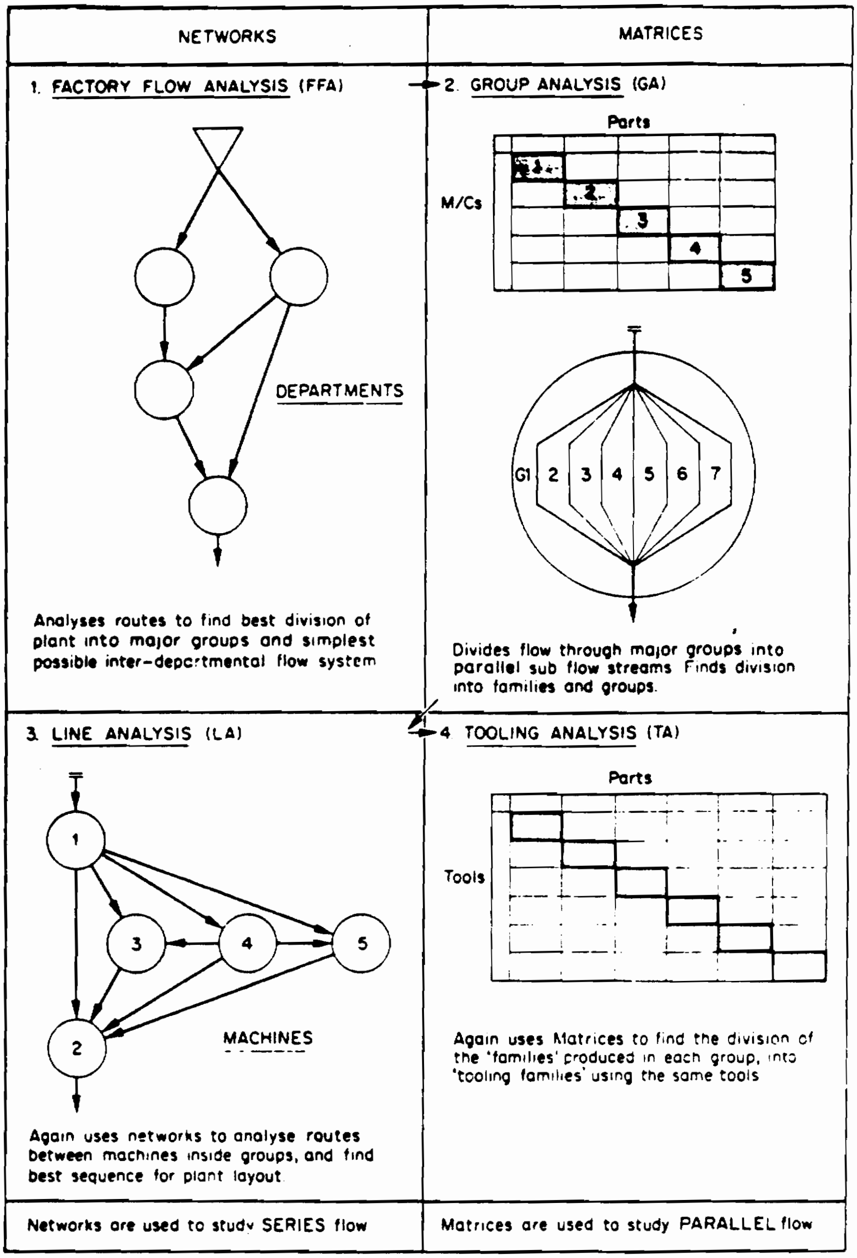
1. This method is iterative, so it does not depend upon the initial matrix.
2. The major advantage claimed for ROC is in its ability to deal easily with the problems of exceptional elements and bottleneck machines which frequently arise in practical problems.

4.2.2 Production Flow Analysis (PFA)

Production Flow Analysis, introduced by Burbidge (1963), is one of the earliest and most comprehensive approaches to cell formation. PFA is a technique devised for finding families of components, and associated groups of machines for a group technology layout. PFA is a technique used to simplify material flow and to find families of parts and groups of machines for group layout. The technique is applied in four successive stages as illustrated in the Figure 3. The main information needed is an accurate route card for every part produced. It is particularly applicable for identifying less similar parts that require common operations. The technique is applied in four successive stages. By a progressive analysis of information contained in the route cards of parts and assemblies, PFA looks for a natural division of groups and families into which parts will fall on the basis of similar routes in terms of machines used. It sets out to use only existing equipment, tooling, and processing methods. It also identifies any exceptional components which do not fit the solution for the majority. The four stages of PFA are discussed below.

The first stage called "Factory Flow Analysis" (FFA) studies the way in which material flows between different production processes. The primary aim of FFA is to find a simple and therefore, efficient material flow system between major groups. The list of machines used to carry out each process are called "Processing Units" or PUs. Within limits imposed by the need to separate the incompatible processes, FFA analysis combines PUs doing processes on the same parts into larger units called "Major Groups". The major groups found by this analysis contain the largest possible groups of compatible machines, which can complete all the parts in their major families without intermediate visits to other groups, or outside contractors. The change simplifies the material flow system.

Exceptional parts with routes which do not fit the new simplified material flow system are then examined and modified individually. The second stage is called "Group Analysis". It uses a matrix to divide all the parts assigned to a major group into smaller 'families' and all the machines into 'groups' in such a way that each family can be completely processed in one 'group'. The third stage is called "Line Analysis". It again uses network analysis to analyze the routes between the machines in a group, taken by the parts in its family, in order to find the best arrangement for cell layout. The fourth stage is called "Tooling Analysis". Again using a matrix, it finds the division of parts processed on each machine into 'tooling families' and also finds their optimum loading sequence. The four stages of PFA are discussed in more detail in the next subsections.



Analyses routes to find best division of plant into major groups and simplest possible inter-departmental flow system

Divides flow through major groups into parallel sub flow streams. Finds division into families and groups.

Again uses networks to analyse routes between machines inside groups, and find best sequence for plant layout.

Again uses Matrices to find the division of the 'families' produced in each group, into 'tooling families' using the same tools

Networks are used to study SERIES flow

Matrices are used to study PARALLEL flow

Figure 3. Stages in PFA : (Burbidge 1975)

4.2.2.1 Factory Flow Analysis (FFA)

The first stage of Factory Flow Analysis is essential in all but the simplest of companies. The limitation is that one can not successfully introduce group layout in a processing department where 20% or more of the parts are routed to outside contractors or to other departments for intermediate operations and then return to the department for further work to be done on them. This kind of complexity must be eliminated by before an attempt is made to find groups and families inside the departments. If the parts to be made in the department can not be made in the department without visiting other departments for intermediate work, it will be impossible to divide them into families which are completely processed in a particular group.

In small factories, carrying out several different processes, the major groups found by FFA will be small, and will themselves have the quality of groups. In larger factories Group and Line Analysis provide a simple method for finding the further divisions into smaller groups and families inside these major groups and the most efficient layout of the machines in each group.

The primary aim of FFA is to find a simple and therefore efficient material flow system between major groups. There are certain conditions which may be desirable in order to simplify the analysis. They are:

1. If processing in successive stages is desirable for economic reasons, policy reasons, or due to incompatible processes, the number of successive stages should be kept to a minimum.
2. Each part must be fully processed in one major group during a single visit. It should not leave the major group for intermediate operation and then return.
3. Each machine should exist as far as possible in one major group only.

4. Major groups should have minimum valency, drawing materials from fewest possible sources, and issuing them to fewest possible destination.

FFA is done in ten major steps as follows:

1. Divide into processing units
2. Allocate machines into processing units
3. Determine "Process Route Number" (PRN)
4. Analyze by PRN
5. Draw basic flow chart
6. Simplify the basic flow chart and find the major groups
7. Determine which parts are exceptions
8. Eliminate exceptions
9. Check machine loads
10. Specify the standard inter-major group material flow system.

The way in which processing machines are divided into P.U.s for analysis can affect the efficiency of FFA. There are certain conditions which may be desirable to apply in order to simplify the analysis. The main conditions are:

1. Facilities which may have to service several major groups should not be included as a part of one processing unit (like a forging department).
2. Departments which carry out two or more incompatible processes should be divided into separate processing units for analysis.
3. Providing that they are not incompatible, two departments may be combined to simplify the analysis, if one takes all or most of its input from the other.

If the existing division into departments is used, the existing lists of machines in the departments give information needed for the analysis.

Process Route Number (PRN) is a code number formed by listing, in correct sequence, the code numbers for all the PUs visited by a part. The PRNs are found by drawing a thick line on the route card between any two following operations done on machines allocated to different departments. The department numbers are then written at the right hand side of the route, and these numbers are listed in sequence to form the PRN code number. Process route numbers are added to all the route cards and the number of different parts with a PRN are counted and tabulated in a "PRN Frequency Chart".

A basic flow chart is then drawn to illustrate the material flow system. Material flow paths, discovered by analyzing PRNs, are established and the number of parts using each flow path is determined using the PRN frequency chart. These basic flow charts are simplified to find major groups. The first step in simplification is to specify the constraint, or in other words to specify which processing units may not be joined together, due to incompatibility of the process, economic reasons, or company policy.

The exceptions with complex PRNs, which do not fit the simplified basic flow chart, can be eliminated by either one of the following: reallocation, change in method, change in design or outside purchase. At this stage of FFA, it is possible to determine on what types of machines it will be necessary to check the machine loads. For any machine types required in more than one department, it is necessary to determine whether machines of these types should be divided between the departments. Having found the optimal material flow system between major groups, it is necessary to issue specifications and instructions so that it can be maintained. The system can be specified by publishing the simplified basic flow.

4.2.2.2 Group Analysis

The second stage of PFA is called Group Analysis. It uses a matrix to divide all the parts assigned to a major group into smaller "families" and all the machines into "groups", in such a way that each family can be completely processed in one "group". The primary aim of group analysis is to find the most efficient division of a major group into groups of the required size. To help in achieving this objective, the following secondary objectives are adopted. As far as possible:

1. Each part should be processed in one group only and
2. Each machine type should exist in one group only.

Group analysis takes place in eight main steps as follows:

1. Renumber operations on route cards
2. Sort routes into packs
3. Draw pack-machine charts or component-machine charts
4. Find families and groups
5. Check loads and allocate parts
6. Investigate and eliminate exceptions
7. Specify groups and families
8. Draw final flow system network.

For FFA it is only necessary to know the series of departments visited by each part. For group analysis it is now necessary to know which machines are visited by each part in each major group. The operations done on any part are numbered consecutively. This numbering method provides all the information needed to find groups and families and simplifies analysis by reducing the number of operations. All the components which use the same machines in the same sequence are collected together in "packs". These packs are then divided into sub-packs according to machines used for the second operation. The process is continued until no additional packs are found. The number of packs can be reduced by combining all the packs which use the same combination of machines.

From the initial machine-part chart, families and groups are formed by changing the sequence in which parts and machines are listed on the chart. Rearrangement is done by calculating usage frequency. If a functional layout is being converted into a group layout, then it is only essential to check the load on the types of machines which are required in more than one group. Next eliminate exceptions by rerouting, changing methods, redesigning or by purchasing. Further load checks may be necessary on the machines where new work is routed. When all the departments have been divided into groups and families, a final flow system network is produced showing the flow of material between all the groups in the facility.

Group analysis is primarily a method for dividing a flow stream into a number of parallel streams. There may be occasions, however, when the matrix will indicate the desirability of a measure of a series flow into a department. If, for example, all first operations are done on the same machines, or a group of machines, there may be advantages in forming a "preparation group" The same may apply to all last operations, where one machine performs a common "finishing operation" for two or more major groups. To obtain the advantages of group technology, however, the intermediate common operations, ideally should only be accepted as a temporary expedient.

4.2.2.3 Line Analysis

The third stage is called "Line Analysis". The task is to plan the layout of the machines inside the groups. The main information needed to achieve this aim is concerned with the sequence in which the different parts in the family use the machines in the group. By a further analysis of the information contained in the part route cards, it finds the best sequence in which to layout the machines. In other words, it finds the relative machine positions which will give nearest approximation to line flow. Each group is considered separately and in turn. With simple groups containing very few machine types, full analysis is unnecessary. For more complex groups and families, the analysis takes place in following seven steps:

1. Renumber operations.
2. Prepare a machine operation number frequency chart for group.
3. Adopt a single digit symbol for each machine.
4. Determine Operation Route Numbers (ORN).
5. Analyze by ORNs.
6. Draw the group flow network diagram.
7. Simplify the flow system.

For line analysis it is necessary to number all the operations. Each part processed in a group is given a separate number in series starting at operation number 1. Separate numbers must be used for all the operations, eventhough the same machine type is used for more than one operation. A machine-operation frequency chart is now prepared for every group showing the number of times each machine or other work center is used for operation no. 1, 2 and so on. Then it is necessary to adopt a single digit symbol for each machine or work center, and these numbers can be numerical or alphabetical.

The Operation Route Number (ORN) is found for every part in the family by listing the symbols for the machines and other work centers in the sequence in which they are used to make each part. Different ORNs, discovered after examining all the route cards in the family, are listed in number (or letter) sequence. The number of times each ORN used is counted, and an ORN frequency chart is prepared. The flow network diagram is then drawn for the group using the data contained in ORN frequency chart. An examination of this network gives an immediate guide to the sequence in which the machines should be laid out.

4.2.2.4 Tooling Analysis

The fourth stage is called "Tooling Analysis". Using a matrix, it finds the division of the parts processed on each machine into "tooling families", and also finds their optimal sequence for loading.

4.2.2.5 Advantages of PFA

There are several distinct advantages associated with PFA:

1. Considers route card information so parts having different shape and material but similar processing requirements can be grouped together.
2. It analyses the problem at more than one level such as between groups, within group and also at the individual machines.

Applying ROC and PFA on machine-part matrix, machine-part matrix is decomposed to create part families and machine groups (Figures 4, 5). Layouts were created based on machine groups and they are shown in Figure 6 and Figure 7.

4.2.3 Gantt Charts

Gantt charts were drawn to allow graphic analysis of machine and part processing. Machine gantt charts keep records for setup time and processing time of parts visiting that machine. They also register the time a part reaches and leaves the machine and hence, records the travel time for the machine. Using these records, flow time for all the parts in the system were calculated. Flowtime was used in calculation of two performance measures, machine utiliza-

Parts

m/cs	1	3	5	17	10	4	18	15	12	14	13	8	2	9	6	7	11	16
1	1	1	1	1	1	1												
5	1	1	1	1	1	1												
4	1	1	1	1			1											
2	1						1	1	1									
11		1			1	1	1											
6								1	1	1	1	1						
7								1	1	1	1							
8								1	1			1						
9													1	1	1	1		
12													1	1	1		1	1
3													1	1		1	1	1
10													1			1	1	1

Figure 4. **Final ROC Matrix**

Parts

m/cs	1	3	5	17	10	4	18	15	12	14	13	8	2	9	6	7	11	16
1	1	1	1	1	1	1												
4	1	1	1	1			1											
5	1	1	1	1	1	1												
11		1			1	1	1											
2	1						1	1	1									
6								1	1	1	1	1						
7								1	1	1	1							
8								1	1			1						
3													1	1	1	1		
9													1	1	1		1	1
10													1	1		1	1	1
12													1			1	1	1

Figure 5. **Final PFA Matrix**

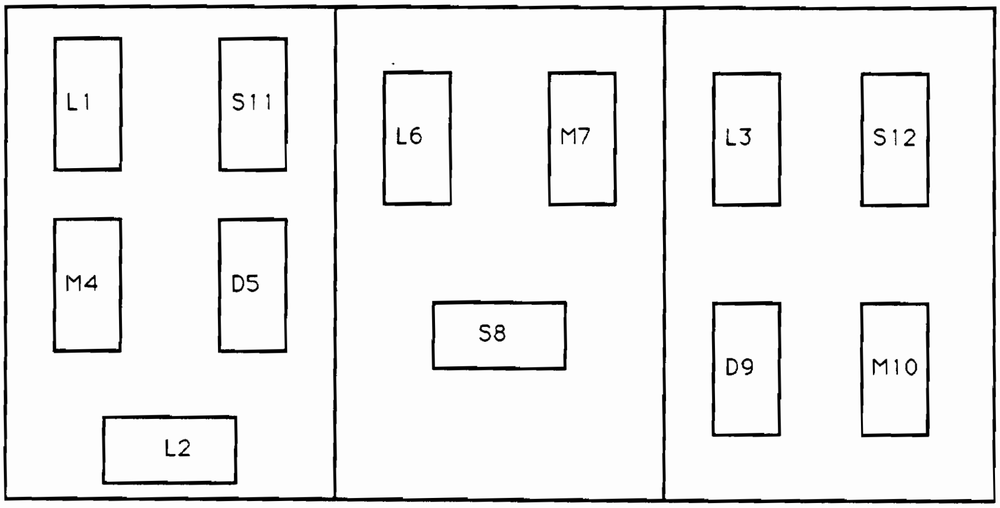


Figure 6. ROC Layout

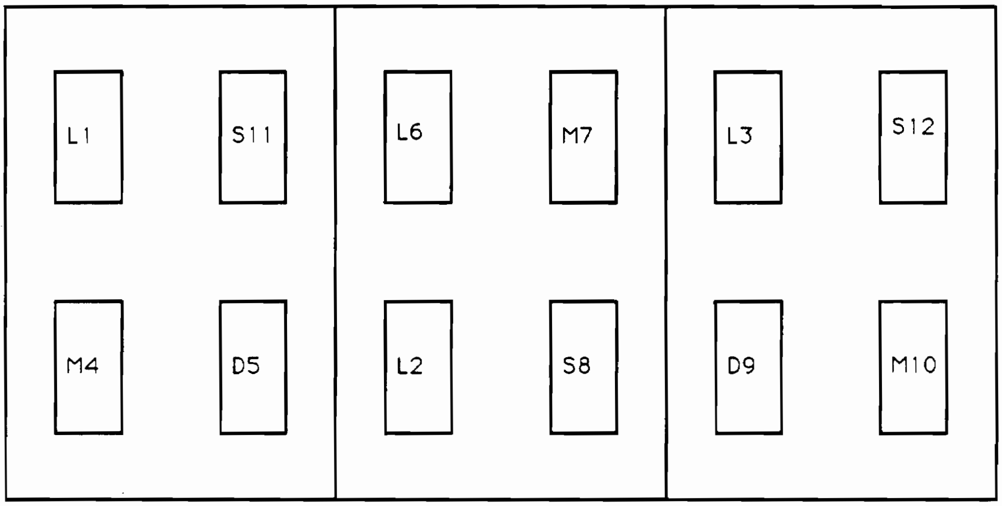


Figure 7. PFA Layout

tion and work-in-process. Gantt charts for functional, ROC and PFA are shown in Figures 8 to 15.

4.3 Performance Measurement

Physical performance measures selected here are based on their impact on the performance of a manufacturing cell. The selection process for performance measures selection and their merits and demerits are discussed in Chapter Three of this thesis. In the following sections, it is shown how each performance measure is calculated.

4.3.1 Material Handling

Material handling is defined as movement done by the material in the system during the process of its transformation into finished product. Material handling is the art of implementing motion economically and safely. It deals with parameters like space, time, motion and quantity. Scope of the material handling activity in a company will frequently fit one of the two following levels: (1) system level, (2) cell level.

System Level: Material handling at system level requires the analyst to visualize the material handling problems, the physical distribution activities and all closely related functions as one, all encompassing the system. The extent to which total system concept is carried out depends upon the importance of material handling activity to individual company as well as the economics of extending the overall handling system.

Cell Level: At this level of material handling activity, primary emphasis is on the movement of material between two location, more likely than not, within the confines of the cell. The concern of material handling engineer at this stage is to find the best mode of handling the

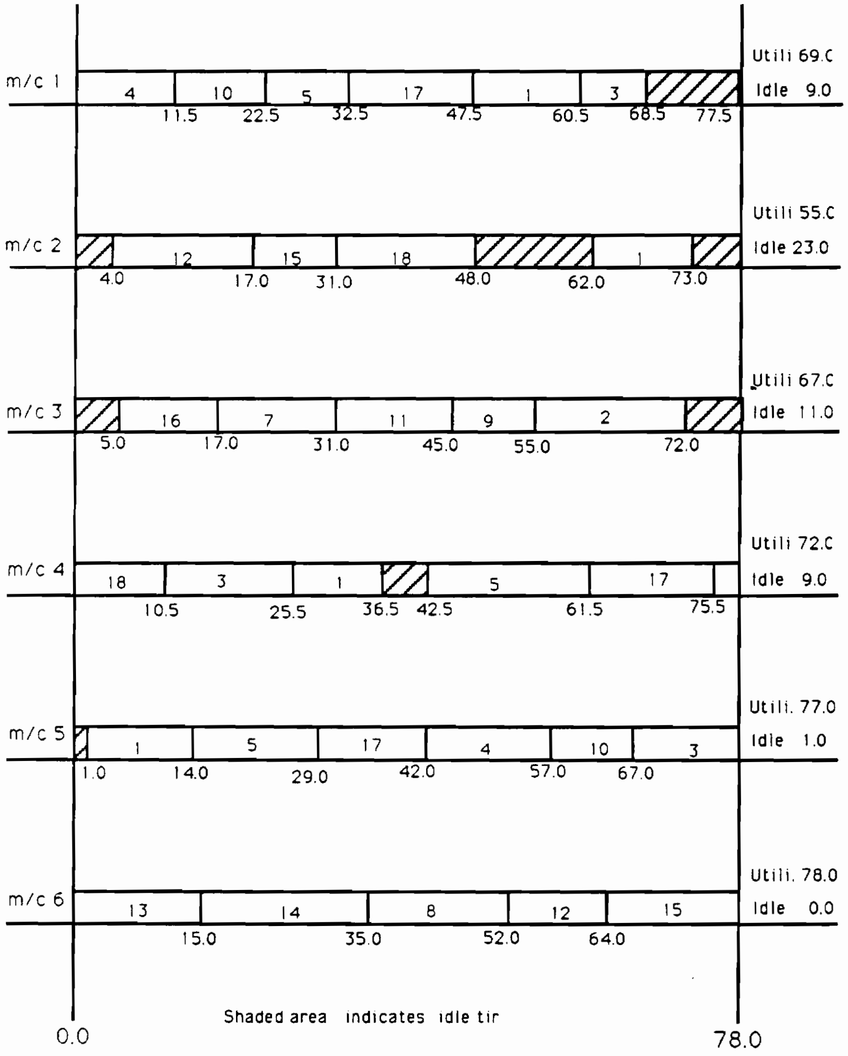


Figure 8. **Functional Schedule Gantt Charts**

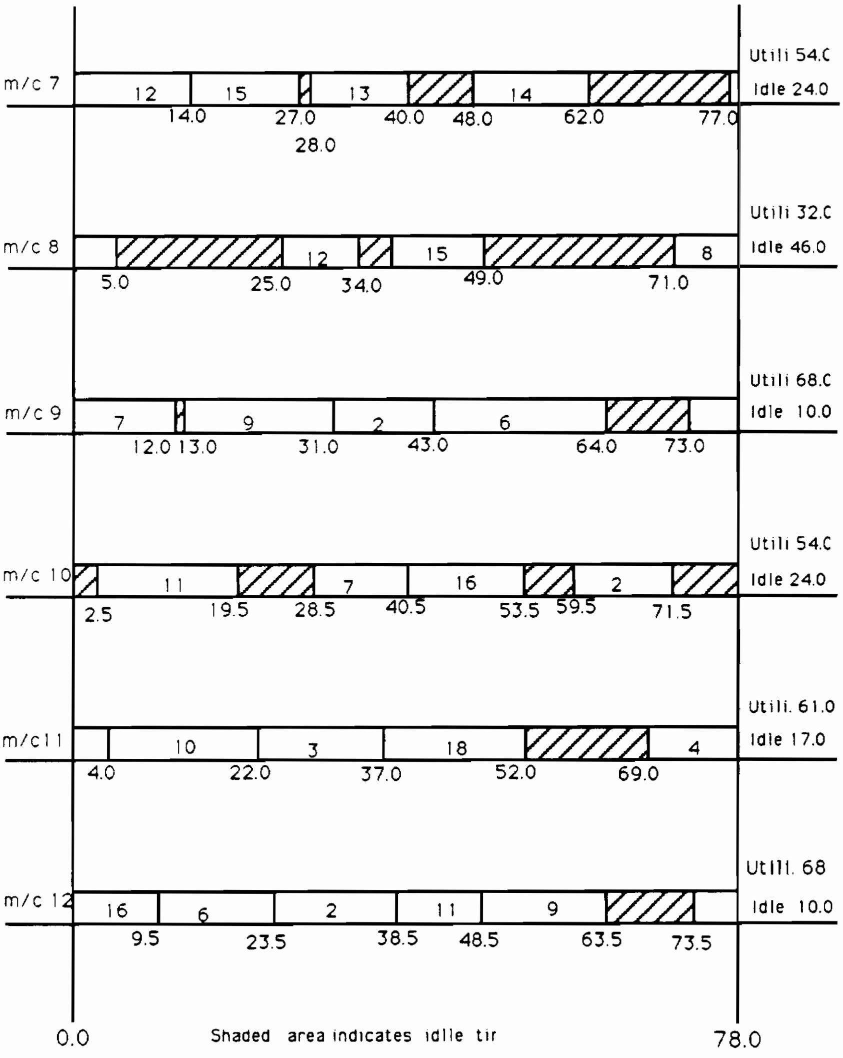
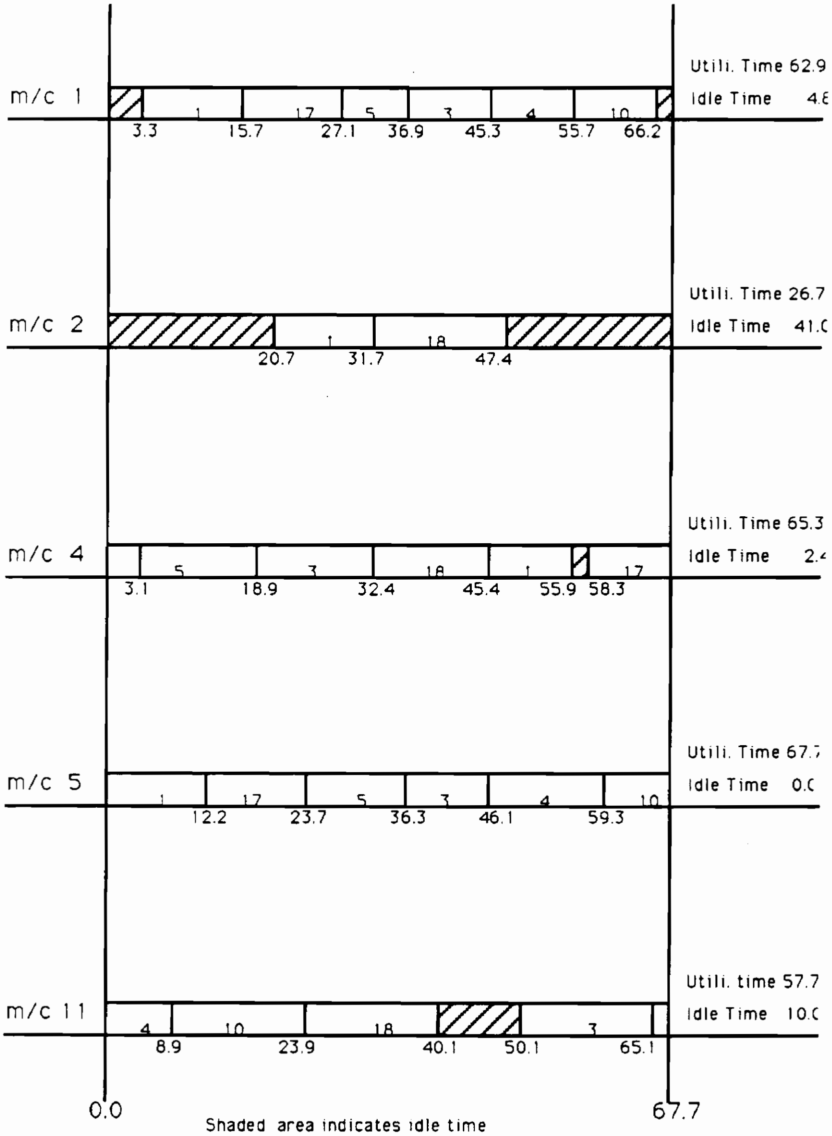


Figure 9. Functional Schedule Gantt Charts



Shaded area indicates idle time

Figure 10. ROC Group 1 Gantt Chart

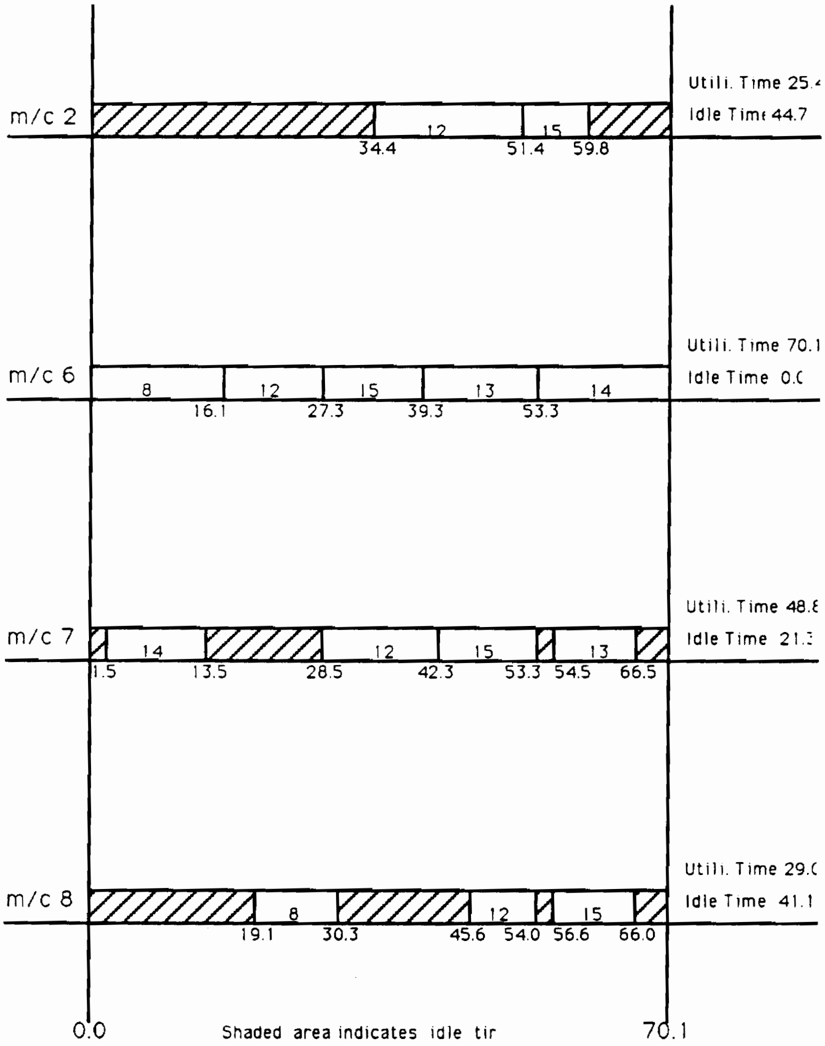


Figure 11. **ROC Group 2 Gantt Chart**

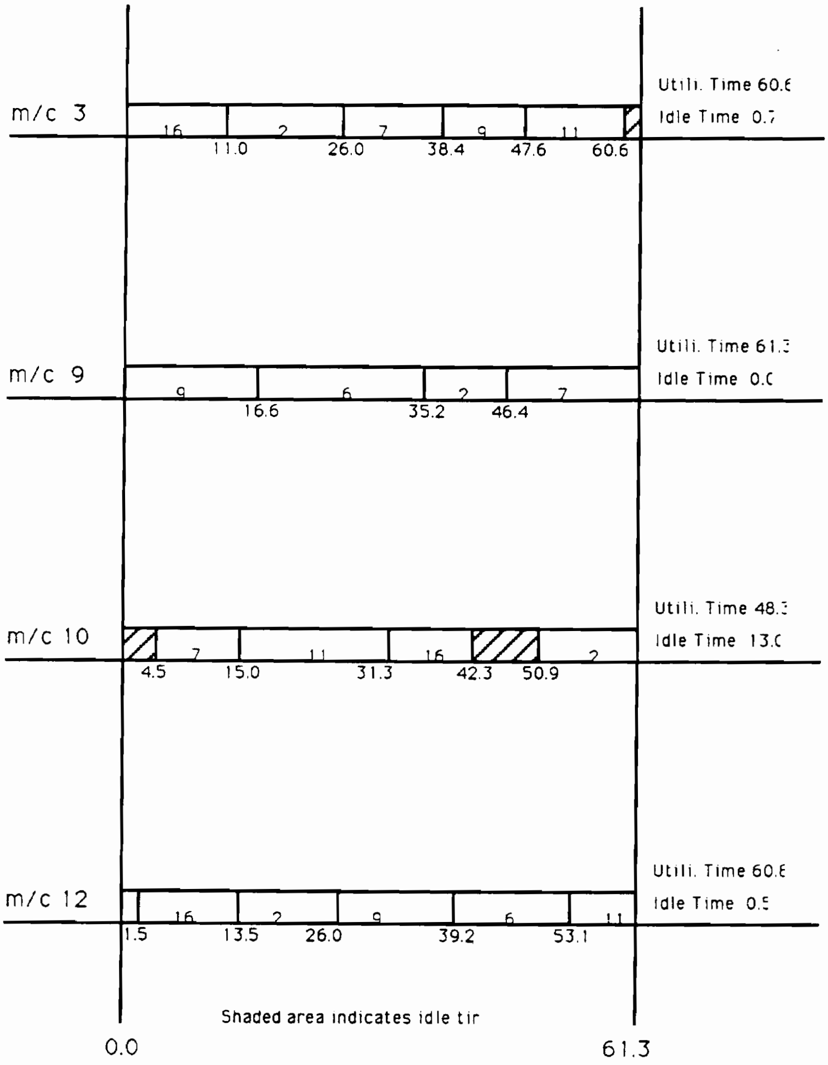


Figure 12. ROC Group 3 Gantt Chart

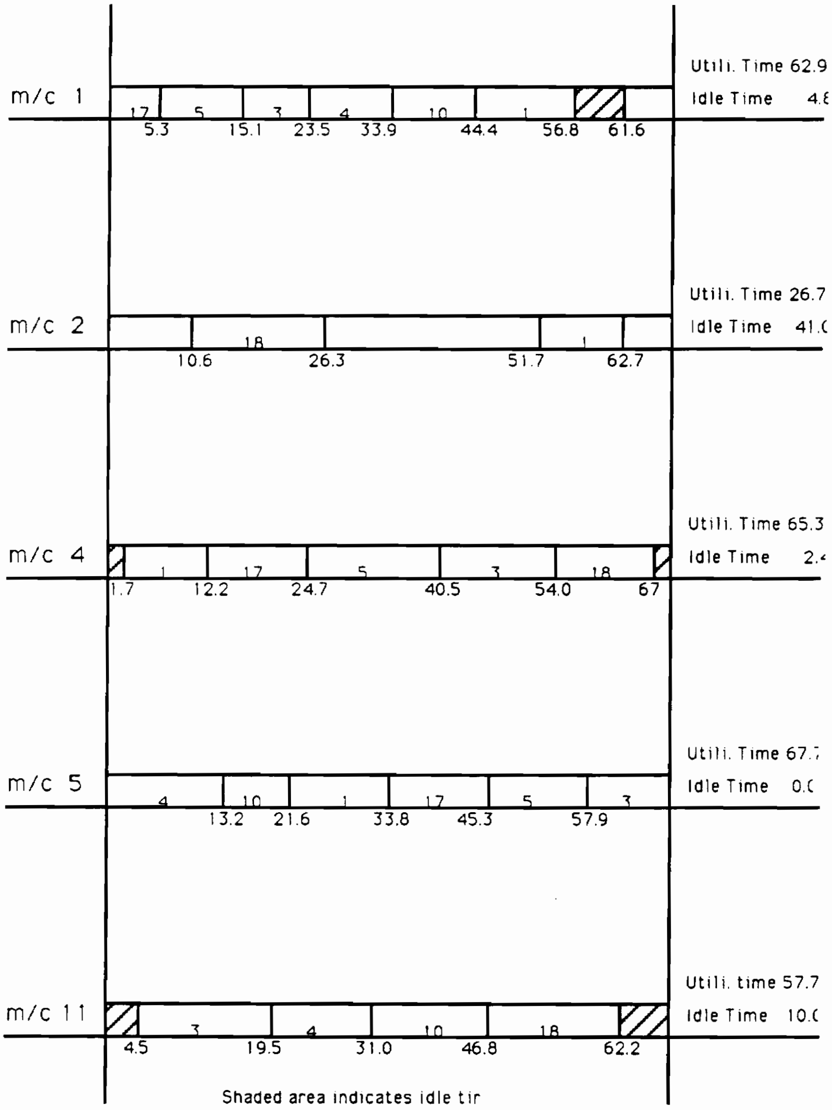


Figure 13. PFA Group 1 Gantt Chart

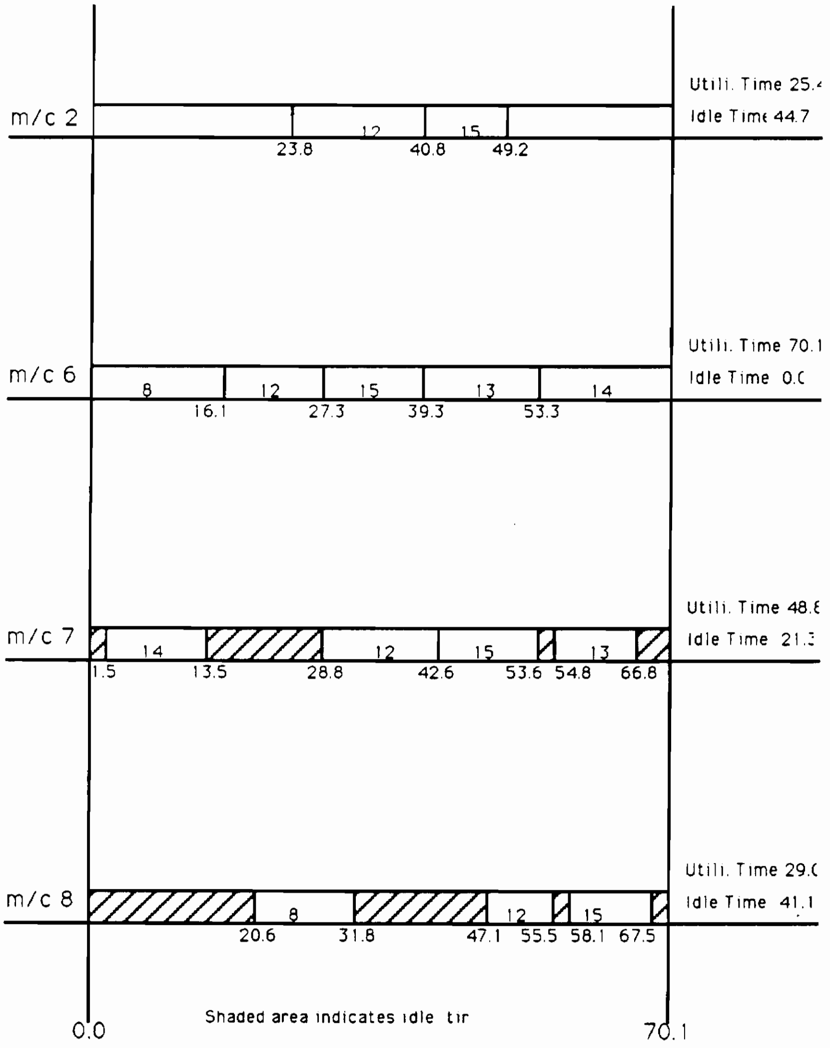


Figure 14. PFA Group 2 Gantt Chart

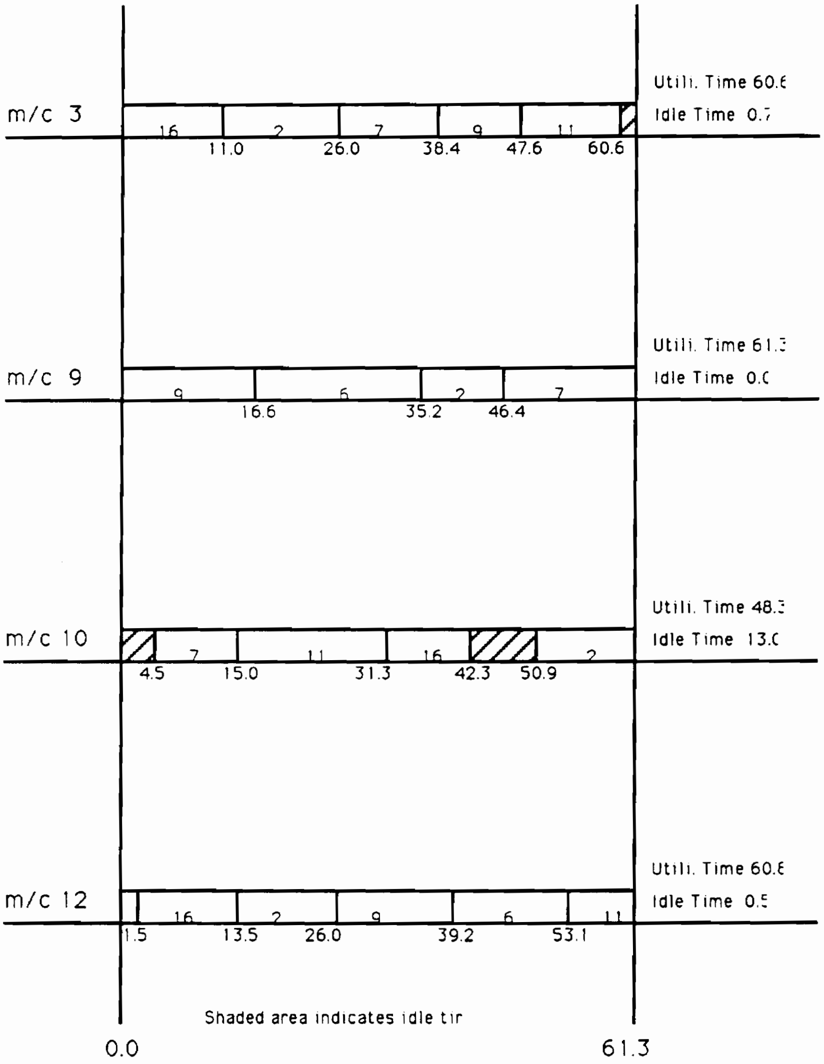


Figure 15. PFA Group 3 Gantt Chart

material at the station and the best way of moving it from one station to another. The natural division of material handling in such a process is done in following two categories:

1. Material handling at the station.
2. Material handling between the station.

Group technology based layout will allow rearrangement of the facility and hence, the only portion that changes due to rearrangement is material handling between the stations

As discussed earlier, the scope of the handling activity in our case is measurement at cell level only. By the definition of material handling given earlier, it is equivalent to the distance the material moves in the system. Each part has a defined route through which it travels in the system for processing on the machines appearing in its route. This distance is measured for each individual part in the system to determine material handling for each part and summed for all the parts in the system Tables 5 and 6.

In order to analyze the effect of layout of different types material handling distance is divided into two different categories;

1. Type A: distance travelled to and from machines while entering and leaving the system.
2. Type B: distance travelled between machines during its transformation process.

It is shown later that by changing the layout, Type B material handling distance is reduced greatly while reduction in Type A material handling distance is relatively marginal. All the distances measured are in feet. For the sake of comparison, average material handling distance per move is calculated for Type A as well as Type B material handling in the functional, ROC and PFA layouts.

Table 5. Distance Travelled By Material Between Processes

Part No.	Routes	Distance Travelled in Feet	
		Functional	ROC
1	1-2-4-5	112	68
2	3-9-10-12	242	68
3	1-4-5-11	166	58
4	1-5-11	144	52
5	1-4-5	106	52
6	9-12	82	56
7	3-9-10	210	62
8	6-8	130	42
9	3-9-12	172	62
10	1-5-11	144	52
11	3-10-12	152	62
12	2-6-7-8	158	118
13	6-7	92	28
14	6-7	92	28
15	2-6-7-8	158	118
16	3-10-12	152	62
17	1-4-5	106	52
18	2-4-11	124	62

Table 6. Distance Travelled By Material Between Processes

Part No.	Routes	Distance Travelled in Feet	
		Functional	PFA
1	1-4-5-2	112	132
2	3-9-10-12	242	68
3	1-4-5-11	166	68
4	1-5-11	144	62
5	1-4-5	106	62
6	9-12	82	56
7	3-9-10	210	62
8	6-8	130	56
9	3-9-12	172	62
10	1-5-11	144	62
11	3-10-12	152	62
12	2-6-7-8	158	96
13	6-7	92	28
14	6-7	92	28
15	2-6-7-8	158	96
16	3-10-12	152	62
17	1-4-5	106	62
18	2-4-11	124	125

4.3.2 Setup Time

Setup time is defined as the time required to change tooling between the processing of batches. By organizing the machines in a plant into cells which are dedicated to processing families of parts, a number of benefits are expected to occur (Gupta and Tomkins 1982). Among these is the reduction of time which is required to change the tooling on a machine between the processing of batches of parts (setup time). Since the parts in a family are similar in terms of manufacturing characteristics, the average amount of time required to change a machine over to work on another batch should be lower when a machine is dedicated to processing similar parts, as in cellular manufacturing.

The degree of similarity between parts processed in sequence is important. This degree of similarity between parts processed on a machine dedicated to processing a family of parts is high. The value of the degree of similarity between parts of the family will determine the value of total setup time required for the whole family. This is done by using the values in the matrix given in Table 7. The matrix gives degree of similarity between two parts and hence by scheduling the parts with greatest degree of similarity together, a lowest overall setup can be achieved.

A part requires one setup on each machine it visits. Therefore the number of setups required by a part is equal to the number of machines visited by the part. Similarly, a machine will have the same number of setups performed on it as the number of parts visiting that machine. Setup time for one part is the sum of all the setups required on the machines on its route. For example, in our case, eighteen parts together have 55 operations performed on twelve machines. Hence, total number of setups required for the system are 55.

Setup time in the case of ROC and PFA are calculated in the following manner. First, using the similarity coefficient matrix, the optimal scheduling sequence is generated in such a way

Table 7. Similarity Coefficient Matrix

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0	.60	.40	.75	0	0	0	0	.40	0	.14	0	0	.14	0	.75	.40
2	-	0	0	0	.50	.75	0	.75	0	.75	0	0	0	0	.75	0	0
3		-	.75	.75	0	0	0	0	.75	0	0	0	0	0	0	.75	0
4			-	.50	0	0	0	0	1	0	0	0	0	0	0	.75	.5
5				-	0	0	0	0	.50	0	0	0	0	0	0	1	.25
6					-	.25	0	.66	0	.25	0	0	0	0	.25	0	0
7						-	0	.50	0	.25	0	0	0	0	.25	0	0
8							-	0	0	0	.50	.33	.33	.50	0	0	0
9								-	0	.50	0	0	0	0	.50	0	0
10									-	0	0	0	0	0	0	.50	25
11										-	0	0	0	0	1	0	0
12											-	.50	.50	1	0	0	.16
13												-	1	.50	0	0	0
14													-	.50	0	0	0
15														-	0	0	.16
16															-	0	0
17																-	.25
18																	-

that total setup for the group is minimized. This is done by scheduling parts having the highest degree of similarity together and creating a sequence of parts for the part family. Using this scheduling sequence for a group, the scheduling sequence for any machine in that group is determined depending upon the parts visiting that machine. For example, group 3 in the ROC as well as the PFA method has a schedule of sequence of parts no. 11-16-2-7-9-6. Hence, schedule on machines 3 and 9 are 11-16-2-7-9 and 2-7-9-6 respectively. Given the schedule for a machine equivalent setup in the case of ROC or PFA is calculated by multiplying the similarity coefficient between two machines and the setup time of the machine that follows the first machine. Thus, in the case of ROC and PFA equivalent setup times are calculated. All setup times are calculated in minutes. Average setup time per setup is given in Table 11 in Chapter Five.

4.3.3 Machine Utilization

Machine utilization is defined as the time a machine is engaged in productive work. By this definition, machine utilization refers to the percentage of the time a machine is busy. Another approach to determine machine utilization is the amount of work done by a machine in a given time. When the cycle time of the parts is reduced due to a change in the layout, a greater amount of time is available for processing of other parts. Under such a scenario, eventhough the percentage utilization in terms of the time machines are engaged in work may be the same for both layouts, a greater amount of work is done per time when cycle time is reduced due to change in layout. From the second approach, machine utilization is improved in terms of a greater amount of work done by the machine rather than the percentage of time the machine is busy. Machine utilization results are expressed using both approaches in Chapter Five. Applying the first definition, it is expressed in terms of percentage usage of the machines and using the second approach, it is expressed in terms of the cycle time which is in minutes.

4.3.4 Work-In-Process

Work-in-process is defined as the average amount of material in the system. In practice, the work-in-process can be directly related to average flowtime of the system. The average amount of material in the system depends upon the average time the parts spend in the system. The longer the flowtime, the longer the material stays in the system and the higher is the work-in-process. Hence, average work-in-process for the system is expressed in terms of average flowtime for the system. Percentage change in flowtime can be directly related to the percentage change in work-in-process. The elements of flow time are setup time, processing time, wait time and travel time. By changing the layout from functional to GT based layouts, setup time and travel time are affected. Setup time is reduced due to setup related scheduling and travel time is reduced due to flow path simplification. Average flowtime is calculated from Gantt charts and expressed in terms of minutes. Average flowtime for all parts in all three layouts is shown in Table 8.

4.3.5 Flexibility

From the many definitions of flexibility, the definition given here is based on routing flexibility. It is defined as the number of alternate routing offered by the group. Routing flexibility becomes significant when a machine breakdown or overloading of the system occurs. Each part visits different smaller cells depending upon its operational requirements. Here, similar machines are grouped together, so a part has more than one machine available if that cell contains more than one of same type of machines available. Hence, if a part visits more than one smaller cell, then different combinations of routes are possible among all the cells is the part routing flexibility. Thus, flexibility for a part is expressed in terms of the number of alternate routes available for that part.

Table 8. Flowtime in Minutes For All Three Layout Configurations

Part No.	Routes	Flowtime for different layouts		
		Functional	ROC	PFA
1	1-2-4-5	175.0	86.4	138.9
2	3-9-10-12	203.0	92.3	92.3
3	1-4-5-11	279.5	136.8	92.2
4	1-5-11	90.5	148.3	103.7
5	1-4-5	112.0	110.5	66.4
6	9-12	110.0	61.6	61.6
7	3-9-10	130.5	84.8	84.8
8	6-8	95.0	36.8	40.3
9	3-9-12	150.0	105.5	105.5
10	1-5-11	108.5	163.3	119.5
11	3-10-12	135.0	129.1	129.1
12	2-6-7-8	120.5	134.1	137.6
13	6-7	48.5	71.5	71.8
14	6-7	70.5	88.6	88.6
15	2-6-7-8	135.5	146.1	149.6
16	3-10-12	96.0	79.8	79.8
17	1-4-5	125.0	97.7	121.5
18	2-4-11	138.5	183.5	138.4

GT cells are created based on some principles such as, a part should be processed to the point of completion in one group only and the group contains machines which are dedicated to produce family of parts assigned to the group. Hence, alternate routing is restricted only to the group, otherwise a violation of the GT principles occur. Another aspect is that machines dedicated to process parts of one family may not have capability to satisfy the processing needs of the parts from another family, so alternate routing outside the group will have a penalty associated with it (increased material handling and time constraint) and in some cases may not even be possible.

Measurement of flexibility for all three layouts is done by evaluating the alternate routes possible for a part in the system. This measure is a single numerical value that represents the number of alternate routes for the parts in a group, and it is shown in Table 9.

Table 9. Flexibility By Number of Routes

Part No.	Routes	Flexibility by * of Routes		
		Functional	ROC	PFA
1	1-2-4-5	18	1	1
2	3-9-10-12	54	1	1
3	1-4-5-11	54	1	1
4	1-5-11	18	1	1
5	1-4-5	18	1	1
6	9-12	6	1	1
7	3-9-10	18	1	1
8	6-8	9	1	1
9	3-9-12	18	1	1
10	1-5-11	18	1	1
11	3-10-12	27	1	1
12	2-6-7-8	27	1	1
13	6-7	9	1	1
14	6-7	9	1	1
15	2-6-7-8	27	1	1
16	3-10-12	27	1	1
17	1-4-5	18	1	1
18	2-4-11	9	1	1

5.0 RESULTS

The following are the results achieved during the analysis of the example system. Results are expressed in terms of the selected performance measures.

5.1 Material Handling

Material handling was calculated by measuring the distance a part travels in ROC and PFA layouts (Tables 5, 6). As described in Chapter Four, material handling is divided into two categories;

1. Type A: distance travelled to and from machines while entering and leaving the system.
2. Type B: distance travelled between machines during its transformation process.

The reason behind dividing material handling in two categories like this is to show that type B distance for material handling is reduced considerably. The results are summarized in the following Table 10.

Table 10. Material Handling Results

Layouts	Functional	ROC	PFA
Type A-Total MH distance in feet	634	474	565
Type B-Total MH distance in feet	1908	628	706
Type A-Ave. distance/move in feet	17.61	13.16	15.69
Type B-Ave. distance/move in feet	51.57	16.97	20.54
Total distance/move in feet	34.82	15.10	17.12
Percentage Savings		56.63	50.83

Material handling distance for ROC and PFA is greatly reduced compared to functional layout because both these methods analyze part routes as they construct the cells and therefore, bring together the parts that use the same machines. These machines then are arranged in close proximity to each other and hence, reduce the distance parts need to travel in the system. As regards to the distance travelled by parts once they are within a cell, ROC and PFA layouts are not very different. The reason is that although both methods are different in their mechanism to achieve layouts, they both basically consider machine-parts processing data. Hence, using both methods creates part families and machine groups that are similar.

A reduction in material handling distance by as much as around 50% is considerable change in the distance travelled by the parts. The reduction in distance is mainly due to the machine proximity for ROC and PFA. In regards to types of movement, the Type A category, material movement while entering and leaving the cell, average distance per move are: functional 17.61, ROC 13.16 and PFA 15.69. The amount of reduction in material handling distance of Type A category does not seem be significant. In the Type B category, material movement between machines is considered. Average distance per move in this category are: functional

51.57, ROC 16.97 and PFA 18.51. This indicates that the savings in material movement costs are achieved primarily due to the proximity of the machines in the group.

In some cases, the resulting machine groups and part families from ROC and PFA may not be similar. This occurs when, in a sufficiently large system, a few of the machines are visited by a large number of parts, or a few of the parts are visiting a large number of machines. In the case of bottleneck machine in PFA, during the analysis, bottle-neck machines were handled as independent "Processing Units (PUs)". While applying ROC, in cases of exceptional part or bottleneck machines, such entries are removed from the analysis. These entries are added, at the end, to the final matrix. Thus, due to difference in approaches of both techniques, they will result in two different layouts altogether.

5.2 Setup Time

The similarity coefficient matrix data (Table 7) is used to determine the schedule for each part families in the group. Effective setup time is calculated for each part using schedule of parts and similarity coefficient data. Reduction in setup time requirement is achieved due to the creation of families of similar parts, and machine groups that process those parts in one group. Part families and machine groups are created by identification of similarities among parts as well as machines. Due to similarities among the parts of the same group, these parts are scheduled in such a way that overall setup is reduced for the group. For two parts having some similarity between them, the part that follows can take advantage of the setup of preceding part. Hence, in the example total setup required is reduced by about 25 percent for ROC as well as PFA. Based on scheduling sequences generated by similarity coefficient data, setup time results are given in Table 11.

Table 11. Total Setup Time for All Three Layouts

Group No.	Functional	ROC	PFA
Group 1	113min.	86.3min.	86.3min.
Group 2	71min.	53.3min.	53.3min.
Group 3	99min.	73.0min.	73.0min.

Using cell formation techniques like ROC and PFA, the goal is to form families of parts and groups of machines such that parts can be processed together using machines from one group. In the case of PFA, part families are created according to the similarities among the parts. Similarity is established by the number of common machines featured in the process routes of the parts. In the case of ROC, part families are created by the use of an algorithmic procedure which tends to bring parts together which have common machines in their processing routes. ROC and PFA are different in their mechanism to determine families of parts and groups of machines. Reduction in setup time is totally dependent on the part families and similarities among the parts in that family. In our case, part families in ROC and PFA are the same, so the setup time reduction is also the same. If part families created by two different techniques are different, then setup time reduction may be different.

5.2.1 Gantt Charts

Gantt charts were drawn to provide graphic analysis of machine and part schediles. Machine Gantt charts keep records for setup time and processing time of parts visiting that machine. They also register the time a part reaches and leaves the machine and hence, records the travel time for the machine. Using these records, flow time for all the parts in the system were calculated. Flowtime was used in calculation of two performance measures, machine utilization and work-in-process. Gantt charts for functional, ROC and PFA are shown in Figures 8 to 15.

5.3 Machine Utilization

Using setup time and processing time data, Gantt charts were drawn to determine flowtime for each part in all three layouts (Figures 8-15). Flowtime values are given in Table 8. From flowtime machine utilization was calculated. Machine utilization is a function of each machine's schedule. The machine schedule is dependent on a number of parameters such as setup time, processing time, travel time and machine and part availability. Gantt charts, using the above mentioned parameters were drawn to determine cycle time and flowtime. As discussed above, machine utilization is defined using two approaches. In Table 12, the results using both approaches are given.

Applying group technology principles setup time and travel time are normally reduced. This will contribute to a reduction in cycle time, and in turn an increase in machine output. On the other hand, part and machine availability tend to suffer in a group technology layout compared to a functional layout because groups may contain only one machine of a particular type and hence, load sharing can not be practiced. Part and machine availability also suffers when the part schedule is generated to take advantage of setup time based scheduling. Due to reasons given above, machine utilization in terms of percentage of time a machine is busy may not always produce favorable results, and in some cases can actually be worse. However, expressed in terms of output of the machine, reduction in setup time and travel time tend to be more prominent thus reducing the cycle time. Reduction in cycle time typically will produce greater output.

Table 12. Machine Utilization Results

Layouts	Functional	ROC	PFA
% Machine Utilization	80%	81.4%	81.4%
Cycle Time in Minutes	78.0	70.1	70.1
% Reduction in Cycle Time		10%	10%

Referring to the results, shown in Table 12, it appears that machine utilization in terms of time is increased marginally from 80% in functional case to 81.4% for the cases of ROC and PFA. In terms of machine output, machine utilization is increased by about 11% from functional to ROC and PFA. Note that there is no difference in the results between ROC or PFA because data used to calculate machine cycle time, like setup time and processing time, are the same. Travel time in both cases will be different but the difference is very negligible, so the machine schedule in both cases are the same. Thus, results are same. Results as regards the machine utilization is concerned, for ROC and PFA will be the same as far as groups of machines and part families are the same.

5.4 *Work-In-Process*

Work-in-process is expressed in terms of the average flow time for the parts in the system. Average flowtime is a function of setup time, processing time and idle time. Reduction in setup time and move time contribute towards a reduction in average flow time in the system. Idle time is dependent on part or machine availability. As described in the previous section, machine availability actually may be decreased going from functional to group technology layout, and it may result in an increase in idle time. However, reduction in other factors like move time and setup time will offset the reduction in machine availability. As per the description given above, work-in-process is expressed in terms of average flowtime. In Table 13, average flowtime for all three layouts and the percentage change in average flowtime from functional layout to ROC and PFA are given.

Table 13. Work-In-Process Results

Layouts	Functional	ROC	PFA
Total Flowtime in Minutes	2333.5	1956.9	1821.6
Average Flowtime in Minutes	129.6	108.7	101.2
% Reduction in Flowtime		16.14%	21.96%

For our example, reduction in average flow time is about 20% going from functional to group technology layouts. In precise terms reduction in average flowtime from functional to ROC layout is 16.14% where for PFA it is 21.96%. This difference between ROC and PFA in terms of average flowtime can be attributed to the fact that PFA groups parts based on processing similarities of parts. When grouping parts according to the processing similarities, parts having a number of common machines in their routes come together. Whereas the ROC algorithm does not necessarily bring parts having highest degree of processing similarities together.

5.5 *Flexibility*

Flexibility is calculated by determining the number of alternate routes for different layouts (Table 14). As per the definition of flexibility given previously, flexibility is expressed in terms of the number of the routes a part can take to satisfy all its processing requirements. The number of the routes a part can take in each layout are given in Table 14.

Table 14. Flexibility Results

Layouts	Functional	ROC	PFA
Total No. of Routes	384	18	18
% Average No. of Routes/Part	6.98	1	1

This is one performance measure where the functional layout has a decided advantage over the group technology layouts. Flexibility, here, is defined in terms of routing flexibility. For a functional layout there typically is a greater number of similar machines in one group, simply because of the nature of the functional layout where similar machines are grouped together. With proper planning and scheduling of the load on each machine in the group, flexibility may not be critical in a normal operating system. Also, unlike this case, in a bigger system there will be some degree of flexibility for GT based layouts. The difference between ROC and PFA in terms of flexibility is purely the function of the machine grouping. If there is some difference in any case then, it will be a minor one.

6.0 CONCLUSIONS

6.1 Summary

The methodology applied to evaluate the performance of manufacturing cells is a manual evaluative methodology. It is a straight forward and easy to implement. The first step of the methodology is selection of performance measures. This allows the users to define their own need for performance measures, so it is flexible. The data requirements step gives the kind of data needed to measure the selected PMs. Analysis of cell formation techniques demonstrate how these techniques are applied to the raw data. The measurement of PMs involve measurement of flowtime from the Gantt charts. It may be noted that flowtime values are dependent on the scheduling sequence. Scheduling criteria in our case was maximum machine utilization. With a different scheduling criteria, a different schedule may generate, however, in principle flowtime for GT layouts will be lower with respect to functional layout. The drawback of the methodology is in the lack of consideration for qualitative performance measures. For a more practical application, performance measures should be assigned a weight.

On the basis of the study of five prominent physical performance measures of the manufacturing cell and the single example case study analyzed, it can be concluded that GT based layouts are better in all categories except flexibility. The philosophy of group technology, just as the name suggests, seem to provide a group solution to group problems where group problems are the improvement of the selected performance measures. As most of the performance measures are either interrelated or dependent on each other, solution to one performance measure has a multi-dimensional effect. For example, setup time and machine utilization are related such that setup time is a part of cycle time and cycle time determines the machine utilization.

Application of group technology principles results in a streamlined flow of material through the system reducing the material handling distance, and in turn material travel time. Formation of part families creates the opportunity to take advantage of the similarities among the parts in terms of setup time. Reduction in these two parameters has contributed to a reduction in cycle time and average flowtime for the parts in the system. Cycle time reduction for all the parts improves machine utilization in terms of output and average flowtime reduction reduces the average amount of work-in-process. In the case of flexibility, ROC and PFA machine groups normally have only one machine of each kind in the group, so flexibility is very limited.

ROC and PFA, two cell formation techniques created on GT based principles, function to achieve the above discussed objectives. Through GT based cell formation techniques, machines working on a family of parts come together. Once in a group, these machines are arranged in close proximity to reduce material handling distance. Similarly, formation of part families permits the advantage of sequence dependent scheduling. This results in reduced setup time. The importance of these two performance measures and their effect over other performance measures such as machine utilization and work-in-process has already been established in the earlier discussion. However, it is observed that the effects of the former two performance measures have not been transfered on the latter two in the same magnitude. The possible explanation for this is that cycle time and flowtime are dependent on other parameters too, mostly being idle time generated by observing a specific schedule. Sequence dependent scheduling can, sometimes, result in increased idle time and in turn increased cycle time and flow time. Reduction in move time of one part, sometimes, results in no subsequent reduction in cycle time or flowtime because the machine is not available anyway. These are the possible scenarios for cycle time and flowtime not being so reflective of the reduction in setup time and move time, the common advantages of GT based layouts.

The difference between ROC and PFA is not always very apparent. The difference in performance between them is when resulting machine groups and part families are different in both cases. A performance measure such as setup time is totally dependent on part families. If part families for ROC and PFA are the same, then setup time performance will be same. On the other hand, material handling performance depends on machine groups and layout of machines in the group. The performance of machine utilization and work-in-process depend on both machine groups as well as part families. Though work-in-process which is proportional to average flow time for parts shows greater impact travel time reduction and hence, machine groups are more important. Whereas machine utilization shows greater impact of setup time reduction and hence, part families are determinant factor.

Flexibility depends on the number of any one type of machine in the group so, it tends to depend on machine groups. Otherwise, the difference between ROC and PFA is in terms of techniques of application. ROC, is an algorithmic approach, which is very easy to implement, even on a sufficiently large data. PFA on the other hand is a manual, heuristic technique. ROC carries the merit of being very efficient in dealing with situations like bottleneck machines or exceptional elements. PFA is a very comprehensive procedure and performs analysis up to determination of a schedule on a single machine and associated tooling requirements. Studying both techniques, it is observed that, when a machine figures in the majority of the parts process routes, ROC will tend to eliminate the machine from analysis as a bottleneck machine initially and then will duplicate the machine in the groups that require it. Whereas PFA will establish such machines as a "Processing Unit (PU)" and treat it as one department by itself. Hence, for large data, if ROC fails to establish mutually exclusive groups, the first stage of PFA, Factory Flow Analysis (FFA) can be used to establish major PUs. Once, major PUs are established, ROC can be applied to some of the major PUs which are larger in size.

6.2 Conclusions

Following are the key conclusions of this research based on the methodology developed and the single case study analyzed:

1. ROC and PFA have better performance in material handling, setup time, machine utilization and work-in-process than functional layout. This is due to simplification of material flow and identification of similarity among parts.
2. Flexibility, in terms of routing flexibility reduces considerably when using cellular layout.
3. Performance measures such as material handling and flexibility are dependent on machine groups, whereas setup time is dependent on part families and machine utilization and work-in-process show mix dependency.
4. PFA has the ability to suggest plant layout in the group and scheduling sequence through analysis as opposed to ROC. This will give a decided advantage for a complex problem, having a wide variety of parts in terms of machine capability and tooling requirements.
5. For a more complex system, where many bottleneck machine and exceptional parts occur, PFA will create more streamlined flow in the system due to its comprehensiveness at the same time being very tedious.
6. ROC can be implemented on computers easily, thus making its application very simple.
7. ROC can be applied to a complex problem with much ease, if machine duplication is possible. In such a situation, while applying ROC, if there are machines required by more

than one group, machine duplication will ensure that all parts can be completed in one group only.

8. Although, there are hardly any examples of comparisons of cell layouts in the literature, one study suggests that GT cell layouts do not have better performance in terms of machine utilization and work-in-process which is contrary to the results shown here. Their study is based on stochastic data and results in the formation of queues at the machines which result in longer flowtime and smaller machine utilization. However, with proper measurement of data such as setup time, processing time, etc. and predetermined schedule, performance measures like flowtime and machine utilization can be measured accurately.

6.3 Future Research Recommendations

1. Study of some other cell formation techniques in the literature will give a pool of knowledge that can be used to build an expert system to determine the choice of a cell formation technique, given the performance measures.
2. Study of ROC and PFA with respect to other nonphysical parameters such as due date performance, information flow time lag or controls in the manufacturing system will enable the designer to determine the performance of the whole system instead of just cell performance.
3. Assigning weights to different PMs can result in a multi-attribute decision model to handle a wide variety of performance measures.

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Vita

Rajul Tank was born on July 18, 1964 in Jeera, Gujrat, India. He graduated from M. S. University of Baroda, Baroda, India in Jan 1987 where he received his Bachelor of Engineering degree in Mechanical Engineering with specialization in Fluid Power. Upon graduation he started graduate studies at Virginia Polytechnic Institute and State University.

He will be working in the industry for few years.

He is a member of Alpha Pi Mu, AIIE and SME.

Rajul Tank