

**SOLUTION TO LARGE FACILITY LAYOUT PROBLEMS USING
GROUP TECHNOLOGY**

A Thesis by

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DEDICATION

Dedicated to my parents and my dear friends

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ABSTRACT

In this work, a systematic methodology to construct cellular layouts using GT technique for large size problems has been developed. Previous researches in this field have addressed heuristics that can be used to solve only medium size problems. A mathematical model that uses reduced intercellular count as a criterion for cell formation is developed. The developed model includes details like machine sequence, production volume and machine revisits for formation of cells. A performance measure that is used to evaluate the cells being formed is proposed after some modifications in the existing method from Nair & Narendran (1998). Once the cell configurations are evaluated, separate layouts are developed for each cell depending on the amount of flow between machines within their respective cell. The best configuration is selected based on the least material handling cost that a configuration accounts for. This process defines entire steps of the proposed approach.

The validity of the proposed approach was verified using small, medium and large case studies. From the case study results, it is concluded that the proposed methodology can be used to solve large facility layout problems using GT. The developed model proved to be efficient irrespective of the size of the problem considered, even after inclusion of details such as machine sequence, production volume and machine revisits along with the performance measure for the cells formed. By restricting the number of cell configurations between an upper and lower limit, the model eliminated the possibility of unwanted configurations that increases the complexity of the problem. So for a large size facility layout problem, the proposed method can be used to get the actual number of intercellular movement between cells and also can be used to select the best configuration for a given production plan using reduced material handling cost as the criteria.

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CHAPTER 1

INTRODUCTION

The location and arrangement of departments on the shop floor can be considered as a typical facility layout problem. One of the primary objectives of a facility layout problem is to reduce the material handling cost associated with the manufacturing. An effective facility layout tries to reduce product cost, lead time and enhance product quality there by increasing market share and profitability of any industry. All the existing research on facilities planning try to address material handling costs reduction as an important aspect because, the material handling cost contributes to 20-50% of the manufacturing cost of a product (Tompkins, 1997). Since 20-50% of operating expenses in the manufacturing facility depend on the material handling costs, it is proven that 10-30% of these expenses can be reduced by efficient facility layout design (Tompkins and White, 1984). The material handling cost is directly related to the flow cost, which is the cost spent for moving the material from one location to another. By changing the locations of workstations/machines in the layout, reduction in material handling cost could be obtained by minimizing the distance traveled by the material-handling carriers between the facilities. In addition to reduction of material handling costs, other objectives include reduction of in-process inventory, cycle time and lead time and the effective utilization of resources.

1.1 Typical size of problems handled in Layout

Since the late 1950s, a number of algorithms have been developed to solve the facility layout problem. These algorithms may be classified as optimal or suboptimal algorithms. During the early 1960's, a considerable amount of research was done in developing optimal algorithms for the Quadratic Assignment Problem (QAP). To model the facility layout problem using optimization approach, QAP and mixed integer programming had been used. The

disadvantages of the optimizing algorithms are that the memory and CPU time requirements are high, so that large-scale problems cannot be solved optimally. Most approaches have assumed the department to be of equal area and that the departments are fixed. In recent years, several authors have used heuristics such as simulated annealing, genetic algorithms and tabu search for solving large facility layout problems. Heuristics are problem specific, take relatively smaller run times and give solutions close to optimal solutions. Heuristics are preferred over optimization techniques to solve NP-hard problems that cannot be modeled using optimization techniques. Some of the earlier heuristics developed to solve facility layout problems have ignored geometric constraints such as shape and area of departments which are crucial for facility layout. Further, researchers have used Centroidal or Euclidean distance in calculating the material handling cost without taking aisle space into consideration. Meller and Gau (1999) used an iterative approach in which both GA and MIP were considered but the computation time was large as the size of the problem increases. Azadivar and Wang (2000) developed a new approach in which GA package, simulation package, an automatic simulation model generator and a graphical user interface was used. This approach failed to preserve the feasibility of the solution. As a result, researchers have concentrated on developing suboptimal algorithms for solving the layout problem. Some of the earlier methods used flowcharts, process charts, experience and knowledge of the facility analyst to determine layouts. All these algorithms have high computational time and memory requirements. Picard and Queyranne (1981) reported that facility layout problem with a size of 11 required less than a second of CPU time and 100k memory on an IBM 360/75. But for larger size problems, i.e. for a 20 machine problem, they indicated that the dynamic programming algorithm would require excessively high computational time. The maximum size of facility layout problem solved using GA is a 32

department problem by A.A.Isler (1998). One of the methods by which large facility layout size problems can be resolved is to use a divide and solve approach that reduces the complexity of the problem and increase the possibility of getting an optimal solution with less computational time. Group Technology (GT) is one such technique that can be used effectively in solving large facility layout problems.

1.2 What is GT?

Group Technology (GT) seeks to obtain the economies of scale of mass production in a batch production environment (Brandon, 1992). The attractions for the pioneers of GT were, however based on cost directly but rather indirectly as a result of having more effective control over the manufacturing systems. GT can be one critical element in the rejuvenation of outdated and unproductive plant. GT addresses the following issues as a single coherent problem,

- Components are aggregated into families with similar production requirements
- Small groups of machines are matched to the component families
- Groups of operatives are assigned to cells

The basic idea of part families manufacture originally consisted of grouping parts with similar machining characteristics together to form so-called ‘additive batches’ and routing them through the functional machine layout with the assistance of the production control. The basic idea of the GT cell is to split the manufacturing area into machine groups in which all the machining operations required for the manufacture of a certain parts spectrum can be accomplished. Within the GT cell itself all the forms of work can be employed with the advantage that the task area is limited in such a way that the members of the group also have the feeling of belonging to a team. GT can be an effective tool in addressing large size facility layout problems.

1.3 Literature in GT

Several researchers have contributed to the growth of the application of group technology to cell formation. Comprehensive reviews of these methods were provided by Singh (1993), Offodile, Mehrez, and Grznar (1994), and Selim et al. (1998). Cellular manufacturing utilizes group technology to identify similarities in process sequence, processing requirements or quality of a group of products to identify machines that can be clustered together into a cell. The machines assigned to each cell may be functionally dissimilar. However, the group of products (part family) assigned to the cell have similar process sequence or other characteristics that enhances the overall efficiency of the system.

There are typically two approaches when considering the types of input used for cell formation. Most researchers use a binary machine-component incidence matrix to form cells. Other researchers have used the production sequence and production volumes as well to form cells. The machine component incidence matrix $A = \{[a_{ij}]\}$

$$\text{Where, } a_{ij} = \begin{cases} 1 & \text{if component 'i' visits machine 'j'} \\ 0 & \text{otherwise} \end{cases}$$

When using the machine-component incidence matrix, the objective is often to form cells and assign parts to these cells such that a high density of '1' is maintained in each individual diagonal block matrix. The '1' entries that are outside the diagonal block represents the need for intercellular flow of parts. The component incidence matrix does not reveal the volume of intercellular flows (Nair and Narendran, 1998). It does not take into consideration the processing sequence or revisits to the same machine.

Harhalakis et al. (1990) incorporated the processing sequence as an input for the formation of cells by having a component-machine incidence matrix (CMIM) of ordinal data. Non-zero entries in the CMIM represent the operation number for a component. Sofianopoulou

(1997) presented a GT method formulated as a linear integer program which uses operation sequence and tries to minimize the inter-cellular flow between cells. It gives a better performance for small size problems than larger ones. Askin & Zhou (1997) developed an approach for forming assembly lines from individual cells of the cellular layout using a similarity measure that is based on operation sequence. Certain approaches went one step ahead by considering alternative routings or additional operation sequences. Jeon & Leep (2005) presented a methodology considering alternative machine routes in the event of a machine failure and demand changes across different periods. Ramabhata& Nagi (1998) developed an integrated approach to the GT problem by considering alternate machine routings and capacity considerations. Malakooti & Yang (2004) presented yet another integrated approach in the field of GT by addressing process, production planning in addition to the fundamental idea of cell formation. Sofianopoulou (1999) uses alternative production sequences and replicate machines in arriving at an optimal cellular layout by formulating the problem as a non-linear integer programming model. Kim, Baek & Jun (2005) arrived at an approach that simultaneously minimizes inter-cellular movements and workload imbalances. The problem is formulated as a binary integer program that uses alternative part routings to form machine cells.

Network flow procedure or graph theory is another approach used in GT that deals with cell formation and minimizing inter-cellular movement. Lee & Garcia-Diaz (1995) introduced a network flow procedure to solve cell formation problems, formulated as a linear/quadratic programming model using operation sequence as the input information. Mukhopadhyay, Babu, Sai (2000) used a modified Hamiltonian chain to form cellular layouts using a binary machine/part matrix that serves as the basis for developing the graph. The network approach discussed by Wu (1998) is concurrent and establishes both cell formation and allocation of

duplicate machines simultaneously. It uses the operation sequence of parts to distinguish machines of same type from each other. The approaches discussed above are sequential based in which either the machine grouping or part grouping is done first, followed by the other.

There are some approaches which follow a different procedure by forming both machine and part groups simultaneously. Sarker & Li (1997) formulated a mixed integer programming model which simultaneously identifies part routings and form machine cells. Chen (2003) used a data mining based cell formation technique using association rule induction. The part families that can be processed inside these machine cells are simultaneously assigned.

Certain grouping method use sorting based techniques to form cellular layout by rearranging the binary input matrix which eliminates two dimensionality restrictions between machine and part by sorting them separately. Li & Parkin (1997) presented a GT algorithm referred to as a “sorting algorithm”. To finally add to the list of operation sequence based approaches, Genetic Algorithm (GA) can be used to group machines/parts into cells. Cheng, Gupta, Lee & Wong (1998) solved the GT problem as a traveling salesman problem using a solution methodology based on a GA. Wicks & Reasor (1999) developed an approach to handle a dynamic production environment where the product mix and volume changes across multiple periods are accounted using a GA based heuristic.

Dunker, Westkamper and Radons (2002) proposed a new algorithm called co evolutionary algorithm for arrangement and placement of machines within cells using GA. The algorithm also arranges cells with respect to each other by including another GA. This algorithm can be used only when the part families and machine cells are identified using some heuristics. The size of problem tackled was a 62 department problem. Though the authors account for

reduced computational time for arranging, it actually increases when the number of machines in a particular cell or number of cells is increased.

The different operation sequence based approaches yield solutions which have to be validated by a suitable grouping measure to determine their quality. Several grouping measures are discussed in the literature. Jaccard (1908) presented a similarity coefficient based on the common operations performed. McAuley (1972) modified Jaccard's similarity coefficient and redefined it as the number of parts visiting both machines to the number of parts visiting at-least one of the two machines. Vakharia & Wemmerlov (1990) introduced a similarity measure considering sequence of operations within cell and machine loads. Kusiak & Cho (1992) proposed a similarity measure considering alternate process plans. Islam & Sarker (2000) carried out an analysis on existing measures and introduced a new similarity coefficient referred to as the relative matching coefficient. While the above measures are based on dimensionless parameters there are measures using distance as the main dimension to validate the cellular approach. Kim, Baek & Jun (2005) presented a similarity distance measure between part routings. While similarity coefficients are mainly pre-grouping measures, there are certain measures to be used after grouping known as the post-grouping measures. Chandrasekharan & Rajagopalan (1989) introduced a Grouping Efficiency (GE) measure to measure the quality of clusters. Kumar and Chandrasekharan (1990) presented a grouping efficacy measure to evaluate the performance of cellular manufacturing systems. Harhalakis *et al.* (1990) presented three evaluation criteria using operation sequence referred to as global efficiency, group efficiency and group technology efficiency.

1.4 Research Objectives

Most of previous researches in this area were focused on methodologies where, grouping of machines/resources were done based on similarity, production volume and operation sequence. Also in the previous researches none have addressed the number of cells to be formed, given a set of information like number of machines, number of parts, operation sequence and production volume. Though the previous researches were able to attain an optimal solution by considering all the above factors, the complexity of problem increased due to increase in the size of problem. The size of problem considered for a facility layout problem using GT was limited to 13 machine problem which accounts for a large computational time. In order to address all these current issues, the research objectives are focused on developing a methodology for large size facility layout problem which is detailed below,

- Develop a systematic methodology for large size facility layout problem using GT.
- Propose an algorithm to calculate the number of cells to be formed and also number of machines/parts to be placed in each cell formed.
- Develop a mathematical model that minimizes the number of intercellular moves (which in turn reduces Material Handling cost) based on the number of cells to be formed.
- Evaluate the effectiveness of the cells formed using performance measures like Bond Efficiency and Compactness.
- Develop an algorithm for arrangement of cells and arrangement of machines inside cell so as to reduce the total material handling cost.
- Validate the model using small, medium and large case studies.

CHAPTER 2

LITERATURE REVIEW

This chapter discusses the literatures published by researchers so far in the area of Facility Layout and GT. Section 2.1 discusses researches in the area of Facility Layout design. Section 2.2 discusses various approaches for solving facility layout problems. Section 2.3 discusses the concept of GT. Section 2.4 discusses various GT approaches used for solving facility layout problem. Section 2.5 discusses the various grouping measures used in GT and finally. Section 2.6 gives the conclusion of this chapter.

2.1 Facility Layout

Facility Layout Problem (FLP) is defined as the physical arrangement of the specified departments or machines in a predefined area. According to Heragu (1992), the machines or the workstations should be placed in such a manner that the material handling distance be reduced between the departments. According to Immer (1953), 40% of the industries production cost is associated with the cost of material handling or the transportation of materials between the departments. This cost can be reduced using two techniques, fitting and moving facilities. Fitting is the process of allocation of unequal shaped departments into large objects by optimizing the given goals. Moving the facilities involve changing the facility with respect to time to preserve the fitness of the facility. Multi-criteria decision making techniques are used in FLP to find the feasible layout of given departments which fulfills the multiple objectives. The objectives are referred as overall integration of all functions, minimum material movement, smooth work flow, employee satisfaction, safety etc. The cost of the flow between departments can be declared in two forms either by quantitative measure like weighted flow of the materials or by qualitative adjacency requirement.

According to Azadivar and Wang (2000) along with the material handling the other important factor that should also be considered is the time taken for the material to be transported. The total productivity of an industry depends on the total actual time than the cost. There are some other factors which will strongly affect the layout design. The factors are minimal cycle time and the minimal delivery time without ample number of inventory. According to Tam and Li (1991), the flow cost between departments can be reduced by maintaining the given constraints. The constraints include avoiding the facility overlap, defining the boundaries for the areas of individual departments and the floor area in advance. Kusiak and Heragu (1987) divided the facility layout problem approaches in to two types of algorithms which are suboptimal algorithms and optimal algorithm like branch and bound or cutting plane algorithms. According to Welgama and Gibson (1993), these two algorithms can only be used to smaller problems like 15 facilities which ended up in finding the heuristic algorithms.

According to Chiang (2001), the heuristic algorithms can be divided into five methods like construction, improvement, hybrid, knowledge-based and graph-theory. The construction method is divided into two steps in which, the first step involves finding the best sequence with the allocation of the departments within the given dimension of the floor. The second step deals with fixing the departments in the above sequence until it satisfies all the constraints. Improvement method deals with interchanging the position of the departments arbitrarily in the existing layout so that it can improve the solution quality. This process of interchanging stops until the process gets saturated with no other best solution. The method which unites the optimal and suboptimal algorithms or unifies the construction and improvement method is known to be Hybrid method. The graph theory method starts initially with a predefined weighted unidirectional network which results in developing a dual maximal planar that establishes a best

feasible solution of the facility. The knowledge based method uses the expert systems or the fuzzy logic which deals with the multi-criteria nature of the layout. This method is also called as artificial intelligence method which contains Simulated Annealing (SA), Genetic Algorithm (GA) etc. Being the top ranked problem among all other problems in the combinatorial optimization field, the facility layout problem can be solved with various mathematical approaches. The approaches are quadratic assignment problem (QAP), quadratic set covering problem, linear integer programming problem, mixed integer programming problem, and the graph theoretic problem.

Chittrantawa et al presented a non-linear mixed integer program to solve the facility layout design problem. An integrated model that describes the importance of the material handling system and facility design for its production support role and cost impact was proposed. There are two common factors that are seen in both facility and material handling system design which shows that these two are directly related to each other. Those factors are 'material flow' and 'distance'. An effective facility design is obtained by minimizing the material handling cost. Mostly the facility layout problem is divided into facility layout and material handling system design from which it is very easy to obtain an optimal solution. It is very clear that the main objective of a facility layout problem is to minimize the relocation costs. Here with a non-linear mixed integer model they have integrated the facility layout, material handling with P/D location. The author had proposed a model to minimize the equipment operating cost, fixed cost of conveyors and fixed cost of vehicles. This shows the impact of facility layout design on a production environment.

2.2 Approaches for solving Facility Layout Problem

In this section researches regarding various approaches for solving the facility layout problem are discussed. According to Tompkins et al (1996), layout solutions are developed to reduce the material handling costs, this can be achieved by reducing the material handling distance objective or by maximizing the adjacency based objective. Francis et al (1992) in solving the facility layout problems used the cost of the material flow between the departments. The optimal layout is obtained by minimizing the cost. Peters and Yang (1998) in solving the facility layout problems also considered the uncertainty in the market demand. Fuzzy approach has been used by many authors to solve the market uncertainty and product mixes. Shore and Tompkins (1980) have developed a stochastic model and they found out that in an uncertain environment solving the problem by an analytical approach using probability distributions and stochastic variables are very complex.

Evans et al (1987) used a Fuzzy logic approach in solving the facility layout problems in which a heuristic based on fuzzy relations was used to generate the layout. The author also developed a ranking method to rank the designed layout based on the similarity index referred to the departments. Grobenlyn (1987) approached the problem of facilities layout by using fuzzy logic in which the grade of satisfaction for the optimality criteria relating to the position of the departments was considered. Dweiri and Meier applied the analytical hierarchical process in which factors were assigned according to the order of importance and a fuzzy decision making method was developed to generate activity relationship charts. The authors used CORELAP to handle these charts and to develop the layout. Aiello et al (2001) developed an optimal layout that minimizes the material; handling cost by using fuzzy logic approach. Here the material flow between the departments and the centroid between the departments is considered. The

interdepartmental flow is obtained by summing all the fuzzy requested from department i to department j . It should be noted that the demand for all the products in each department is smaller than the maximum capacity for production. Different layouts are developed by using fuzzy logic approach and the material handling costs for different layouts are compared and the lowest material handling cost layout is chosen as the best alternative.

Azadivar and Tompkins (1999) presented a simulation model generator with a GA based algorithm to optimize the simulation models whose performances are functions of qualitative and structural decision variables of the system. Azadivar et al (2000) developed an optimization technique that takes dynamic characteristics and operational characteristics of the system into consideration. This procedure is able to solve the facility layout problem based on the performance measures such as cycle time and productivity. The model is first simulated and then genetic algorithm is applied to the model. A simulation model is considered to evaluate the performance measure of the layout.

Langevin et al (1994) discussed a two step heuristic procedure to solve the facility layout problems. Linear ordering of the departments was found in the first step and a mixed integer programming approach was done in the second step in order to locate the departments over or under the main aisle and also their respective dimensions. Montreuil (1993) used mixed integer programming (MIP) approach to solve the general facility layout problem and the solution was possible only for 5 department problems, Meller et al. (1998) developed a mixed integer programming approach by which 10 department problems could be solved. MIP is unsolvable for realistic problems and hence it is used with some heuristic approaches like Simulated Annealing and Genetic Algorithms. Gau et al (1999) have used an approach in which the facility layout problem is solved by using slicing tree presentation approach in MIP and then the solution

is fed into the genetic algorithm to generate the initial population. The MIP approach is very good in representing the layout and low cost solutions are obtained by using the Genetic algorithm.

According to Azadivar and Wang (2000) the lead times in a production process can be reduced by designing an optimal facility. The facility layout problem is very simple when there are very less number of equal area departments and the difficulty level increases with increase in number of departments. This type of problems can easily be solved by using QAP. If we consider departments of unequal area the distance between the departments can be obtained by their given dimensions and the clearance requirements between the departments. In this problem it is not an easy job to find the feasible solution because the distances between the departments are not the same. To acquire an optimal solution for this problem, many heuristics approaches were found which has a major drawback in developing ample number of physical layouts and poor local solutions. To overcome these drawbacks the search techniques can be done in different ways instead of traditional approaches. Serial search methods can be replaced by parallel search techniques and the enumerative and randomized search methods can be replaced by randomized search techniques. Genetic Algorithm uses the above said techniques in a parallel, stochastic heuristic approaches. With this optimization technique, Genetic Algorithms were successfully implemented in different fields of industrial engineering like group technology, vehicle routing and scheduling, job shop scheduling etc. According to Tate and Smith (1995), Cheng and Gen (1996), Meller and Gau (1996), Tam (1992) Genetic Algorithm techniques can also be applied to facility layout problems.

Delmaire et al (1997) used a genetic algorithmic approach to solve the facility layout problems, two main models were made to solve the layout. First model was that all departments

are of equal sizes and the centroid distances between the departments are taken into consideration. The first model was solved by using QAP approach. The second model considers different department sizes and distances are measured from their respective input/output points. Genetic algorithm was used along with linear programming to solve second model and different shapes like T shape and O shape of the layout was generated.

Kirkpatrick et al (1983) used simulated annealing method to solve facility layout problems. Annealing refers to the process of cooling material slowly till it reaches the stable system. The main features of simulated annealing are Temperature, Equilibrium the conditions which the process is maintained at a stable system and annealing schedule which determines when and how much the temperature is to be reduced. Heragu et al (1991) used the hybrid SA algorithm in solving facility layout problems, in which a core algorithm is used to solve the facility layout problem then SA algorithm is again used to the obtained initial solution to increase the efficiency of the layout obtained. Jajodia et al (1992) has used the simulated annealing algorithm to solve cellular layout problems. Cellular layout involves the determination of machines that have to be represented in each cell. The author has considered both the intracellular problem and intercellular problem. The main objective of this paper was to minimize the material flow in the facility. The method used by the author is called CLASS. CLASS stands for Computerized Layout Solutions using Simulated Annealing. Kouvelis et al (1992) discussed the single row layout problem in flexible manufacturing systems. The problem is solved by arranging all the machines in a straight line so that there is free movement of material handling distance from one machine to another. The difficulty arises when variety of products has to be manufactured and because of this there is a change in operation sequence.

Kouvelis et al (1992) has solved the facility layout problems by using the concept of zoning constraints along with simulated annealing. These constraints are restrictions on the arrangement of machines. Positive constraints allow some machines to be placed close together and negative constraints do not allow some machines to be placed close together. The objective is to place the machines in such a way within the constraints to obtain a reduction in the cost function. The author has used two algorithms namely Compulsion method and penalty method to handle the zoning constraints within the simulated annealing. Meller et al (1991) discussed Simulated Annealing Based Layout Evaluation algorithm (SABLE) in solving single and multi floor facility layout problems. The SABLE method developed was compared with other approaches and it was found that better solutions were obtained when compared to other layout problems. Burkard et al (1984) and Wilhelm et al (1987) used simulated annealing approach to solve quadratic assignment problem. Laursen (1993) described the process of simulated annealing algorithm by varying two parameters the number of simulations and simulation length.

2.3 Group Technology

In 1940's classification and coding systems that were widely used in sciences and libraries were yet to find their entry in the manufacturing of products. The situation began to change in late 1940's and in early 1950's fundamental coding systems were created. It was during late 1950s GT enthusiasts started to develop the concept that parts grouped together by common manufacturing attributes could be manufactured in a manner similar to mass production. Their idea was that, creating a large family of similar parts would help the manufacturers to allot groups of machine tools to manufacture the parts, develop common tooling and comfortably reduce setup times.

In simple terms, GT can be defined as grouping of parts with similar operations and machines corresponding to these operations, which makes GT to be recognized as one of the key factors to improve productivity in any manufacturing system. GT have got different definitions such as (Ranson, 1972).

1. Identifying and grouping similar or related machines, parts in a production process in order to make use of their similarities by considering the inherent economies of flow-production methods.
2. Logical arrangement and sequence of all facets of company operation to bring in the benefits of mass production to high variety, mixed quantity production.
3. Development of technological processes, efficient setting up of machine tools and equipment planning, so as to insure the most profitable technical planning of production in the shortest time.
4. By realizing that many problems are similar and that by grouping similar problems, a single solution can be found to a set of problems, there by saving time and effort.
5. Classification of parts or machines into groups in order to increase the efficiency in the field of design as well as in production.

When viewed from a manufacturing perspective, GT can be defined as the decomposition of manufacturing system into various subsystems by categorizing parts into part families and machine into machine cells depending on the similarity of part manufacturing characteristics. The advantage of grouping machines into cells will reduce the number of production centers that must be scheduled. Also grouping of parts into families reduces the complexity and number of parts for scheduling purposes.

Implementation of GT may result in the following benefits (Hall, 1975),

1. 30% reduction in new shop drawings
2. 10% reduction in number of drawings through standardization
3. 42% reduction in raw material stocks
4. 53% reduction in new part designs
5. 62% reduction in work-in-process inventory
6. 82% reduction in overdue orders
7. 70% reduction in throughput time
8. 60% reduction in industrial engineering time
9. 69% reduction in setup time
10. 20% reduction in production floor space required

Implementing GT in general will yield benefits in areas such as productivity, effective machine operation, component standardization, accuracy in cost prediction, reliability of estimates, customer service and sales potential. GT will focus on reducing unnecessary variation intensity by using part family formation scheme and also simplify design and process planning of new products by making use of similarities in part design and manufacturing characteristics.

The main aim of classification in any manufacturing environment is to provide an efficient and rapid method of information retrieval for decision making. But still today in most companies, production decisions are solely based on guess work. The need for GT classification can be for the following purposes (Burbidge, 1975)

1. To find the parts for tooling and material families
2. To find the optimal components for parts
3. To find the optimal scheduling sequence for loading

Part classification is a method by which slightly dissimilar parts are identified and grouped together to take advantage of their basic similarities in manufacture and design. Once the parts have been organized, GT cells can be designed around the part family; with each cell handling one or more part families and all parts in a given family are expected to be more or less identical and able to be processed by a standardized process plan. Some of the recent papers discussed in this review give an idea on different methodology for part family formation by grouping them into several categories of importance.

2.4 Group Technology Classification

This section discusses various approaches that were used for solving group technology.

2.4.1 Part family grouping (No machine cell formation)

Part family grouping recognize similarities in terms of shape, size, design characteristics in-order process all parts belonging to the same family within a single cell. A. Lee-Post (2000) developed an approach where design attributes of parts are used to generate part families using genetic algorithms (GA). The design attributes are coded into a classification system which serves as input to a GA. Grouping technique can be extended for use in other areas of manufacturing such as process planning, part design, DFM etc. Comparisons of results from other heuristics are not provided. No criterion for evaluating the effectiveness of grouping is utilized. Hence the effectiveness of GA cannot be determined.

2.4.2 Cell formation with no operation sequence

In cases where an optimal solution cannot be reached researchers have come up with their own approaches. These are commonly referred to as heuristics or rule of thumb methods. Among several heuristics genetic algorithm has always been applauded for its ease of application and power to carry out an extensive search. Dimopoulos & Mort (2001) presented a hierarchical

clustering methodology that is coupled with a genetic algorithm (GA). This GA searches the solution space to provide a closest sub-optimal solution. In this approach genetic algorithm is responsible for guiding cell formation by itself. The input is taken from a binary machine/part matrix and a cluster analysis is performed on it. Machine similarities are established through Jaccard's similarity coefficient (Jaccard 1908) based on common operations performed.

The parts are then assigned to respective machine cells and the final solution is evaluated by a fitness values. The effectiveness of the GA approach is validated by using two grouping measures namely grouping efficacy and weighted grouping efficacy. No provisions for including product volume, operation sequence which questions its availability to practical applications. There are no constraints included in the approach to place restrictions on size of cell, no of cells formed creating problems of spatial relevance. The theory behind GT justifies that inter-cellular movements can only be minimized but cannot be reduced to zero except in rare cases. While many approaches find ways to eliminate singletons cells there is an outrageous argument supporting singleton cells which deprives the theory of cell formation of its stated purpose.

2.4.3 Operation Sequence based approaches

Most GT methods use binary machine part/matrix and do not have operation sequence information. The approaches reviewed under this section further have operation sequence as part of the input data. Sofianopoulou (1997) presented a GT method formulated as a linear integer program. It tries to minimize the inter-cellular flow between cells. This method does not pre-specify the number of cells to be formed. The linear integer programming model formulated is an NP-complete problem. The heuristic used is a simulated annealing procedure. The test

results from the heuristic are compared to optimal solution from an enumeration algorithm (Balas' additive). The performance is better for small cell size problems than larger ones.

Askin & Zhou (1997) developed an approach for forming assembly lines from individual cells of the cellular layout. A similarity coefficient measure identifies the longest common subsequence (LCS) in the given operation sequences. This is followed by a hierarchical clustering procedure to yield part families. The optimal machine sequence for the part families is first established to form assembly lines. The solution is provided by a model formulated as a shortest path problem. It is coupled with a greedy heuristic to handle real-time problems. The similarity measure used here is based on operation sequence and does not include other factors such as product volume, machine capacities, etc. Even for mid-size problems the greedy heuristic is used in lieu of the optimal approach. The solution becomes worse when extended to large size problems. The model with primary focus on creating assembly lines sacrifices compactness and utilization to keep inter-cell movements under control.

2.4.4 Alternative Routings/Process Sequence

Jeon & Leep (1998) presented a methodology considering alternative machine routes in the event of a machine failure and demand changes across different periods. The problem is solved in two phases. The first phase identifies part families using a similarity coefficient measure taking two parts at a time. It is based on the number of alternative routes taken in the event of a machine failure. The part families are formed using genetic algorithm as the search technique. In the second phase machine cells are identified using mixed integer programming models. The change in demand across periods is also considered. The objective function reduces manufacturing costs that includes inventory holding cost, operating cost and other overhead expenses. Though the model is effective in reducing cost, the computational

difficulties faced have not been discussed. The question of whether it can be extended to large size problem is unstated.

Ramabhata & Nagi (1998) presented an integrated approach to the GT problem by considering alternate machine routings and capacity considerations. However the main objective is to reduce material handling costs due to inter-cell movements. The problem as such is NP-Hard and therefore formulated as a mixed integer linear programming model. This MILP formulation works well for small size problems but industrial size problems cannot be handled due to computational hindrances. In such cases using a heuristic will yield a quicker solution but of sub-optimal quality. The output of the model is improved by solving it through a branch and bound algorithm which gives slightly a better solution than the heuristic. Even though the solution quality improves there is no guarantee of getting an optimal solution all the time which sometimes can also be sub-optimal.

Malakooti & Yang (2004) presented yet another integrated approach in the field of GT by addressing process, production planning in addition to the fundamental idea of cell formation. The problem by inclusion of operation sequence, alternative production plans and product volume translates into one of non-linear integer programming type and is therefore NP-complete. The above formulation is decomposed into two sub problems - one to identify optimal process plan for each part and the other to form machine-part cells. These are solved in an iterative fashion using a heuristic one after the other. The methodology is implemented in a real time scenario involving an emergency room application to signify its practical importance. However in dealing with conventional cell formation it fails to handle large size problems due to computational limitations. Though the idea of decomposing the formulation looks good one

cannot avoid complete escape from the condition of being NP-complete. Further integration to consider other factors like capacity, set up times will make the problem still worse.

GT methods discussed in literature finally bring up with a cell configuration that reduces inter-cellular movement to the best possible extent. Though resources are made use of in a judicious manner it is hard to satisfy all constraints without trade-off of some kind or the other. The model developed by Sofianopoulou (1999) uses alternative production sequences and replicate machines in arriving at an optimal cellular layout. The problem is formulated as non-linear integer programming type forming cells in two stages. It starts by grouping machines together into cells with each part getting assigned to an appropriate sequence. Parts are identified together as part families using an integer LP model in the next stage. The complexity of the model presents computational limitations and cannot be solved using the optimization approach. A two-dimensional simulated annealing heuristic is therefore used to provide a sub-optimal solution even for mid-sized problems which clearly is an indication that the model cannot be extended to higher cases. Though use of replicate machines seems to be a great idea in reducing inter-cell movement there should have been a way to present cost justification to management for easy decision making.

Kim, Baek & Jun (2005) presented an approach that simultaneously minimizes inter-cellular movements and workload imbalances. The problem is formulated as a 0-1 integer program which uses alternate part routings to identify form machine cells. The inclusion of multiple objectives makes the problem NP-Hard and hence solved using a two-staged heuristic. The first stage determines representative part routings equal to the number of part families. These representative part routings are identified by associating each part routing with a potential function which keeps track of similar part routings based on the number of shared machines.

The second stage involves assigning part routings to these families and satisfying constraints for controlling inter-cellular movements and workload balancing. The model is tested against the method suggested by Won (2000) and gives better results in terms of reducing workload imbalance but not intercellular movement. The number of part families is decided by the model and is not user-specified. The input matrix in binary form makes it convenient to handle problems of larger dimensions even with multiple objectives.

2.4.5 Network Flow Procedure/ Graph Theory

Under this category where potential/existing relationship between machines, parts are traced out using graphical procedures. These are easier to use in smaller dimension problems and they offer higher visibility in identifying the right solution. Lee & Garcia-Diaz (1995) introduced a network flow procedure for solving cell formation problems. It is formulated as a linear/quadratic programming model using operation sequence as the input information. The methodology is carried out in three different phases. It begins by identifying similarities between machines through a network model. This is followed by partition of network to form machine cells to take advantage of machine utilization. Finally part families are created and assigned to these machine cells. The model is quite flexible as it allows cell parameters like cell dimension and number of cells to be specified by the user. The network based solution procedure used for solving the linear/quadratic model reduces computational inadequacies for small to medium size problems and not for large size problems.

Mukhopadhyay, Babu, Sai (2000) used a modified Hamiltonian chain to form cellular layouts. In this graphical approach the vertices represent machines and edges represent components. A binary machine/part matrix serves as the basis for developing the graph. The chain comprising of vertices and edges starts by including stronger relations and grows weaker

when proceeding down the hierarchy. Dummy edges are included in between to maintain continuity in the linking process and represent points with no or insignificant relationship. These can be easily disintegrated to form separate cells. Thus the name “modified Hamiltonian chain” as it includes dummy edges in its configuration. This method is simple as it uses only the number of parts to decide on strength of relationship between machines instead of using similarity coefficients/indices. The dummy edges included in between facilitate breaking up of chain into cells –an edge over other graphical methods. The model uses a binary machine part matrix with no room for operation sequence, production volume, etc. No information on computing package used or time taken for solution convergence is provided and so extensibility to large size problems is unknown. In some cases manual intervention is needed to complete the chain formation which is impossible at higher problem levels. Overall there is no significant or a breakthrough performance realized from end results except in certain cases where marked changes are noticeable.

GT methods work on improving the efficiency of cell formation by controlling cell parameters, using mathematical models and so on. Yet another approach to this is to duplicate machines that are shared heavily. Among other parameters to be controlled, machine capacity plays a significant role when machine duplication is involved. Majority of the approaches solve cell formation problem and allocation of multiple replicated machines separately like a staged approach. This leads to failure in recognizing machines with or without replicates and sometimes leads to replicating machines that don't have to be. The network approach discussed by Wu (1998) is concurrent and establishes both cell formation and allocation of duplicate machines simultaneously. The idea is to use operation sequence of parts to distinguish machines of same type from each other. The network model uses simple node for single replicate

machines and complex node for multiple replicates. Simple and complex nodes are determined by calculating capacity requirements for each machine type leading to an undirected graph. The graph is further partitioned into sub-graphs which represent cells using Wu and Salvendy (1993) algorithm. Machines with replicates are assigned to respective cells based on capacity requirements of each cell. The model is tested on two cases and results prove to be satisfactory. The difficulty in forming an undirected graph arises when extended to large size problems with operation sequences, production volume considered. Though machine replicates improve solution quality there should have been a way to justify it by using some form of evaluation criteria.

2.4.6 Simultaneous/ Concurrent cell formation techniques

The conventional method of performing cell formation is to group machines first followed by grouping of parts as families or vice versa. Certain techniques perform these operations in a single stage providing more dependence on each other. Sarker & Li (1997) formulated a mixer integer programming model which simultaneously identifies part routings and forms machine cells. The objective function uses operating cost and material handling cost as the basis for justifying benefits of cell formation. Due to inherent complexity of the model it cannot be used to handle large size problems. Constraints included handle capacity concerns and alternate process plans. The machines assumed are generic to facilitate the selection of alternate process plans.

Chen (2003) used a data mining based cell formation technique using association rule induction. Data mining uses association rules to group machines based on similarity using a priori algorithm. The input to the algorithm is a binary machine-part matrix from which relationships are figured out through induction to form machine cells. The part families that can

be processed inside these machine cells are simultaneously assigned. The solution is qualified using grouping efficacy as the measuring criteria. The approach performs efficiently and can be used for large size problems with binary data as input. The power to identify possible relationship between machines completely lies on functionality of association rules and needs to be framed carefully. The cell grouping measure discussed is also based on binary information and will not be effective when other manufacturing parameters are considered.

2.4.7 MIP/LP Models

In arriving at an optimal solution mathematical programming based approaches are found to be better in comparison to the rest. Srinivasan & Mahesh (2002) presented an approach to GT problem by considering cell formation as incremental rather than comprehensive. This is done to reflect the real time scenario where industries go with implementing one cell after the other. The problem is formulated with an objective to minimize the cycle time for a fixed number of workstations. Each part family is reduced to an equivalent part to ensure unidirectional material flow containing all operations pertaining to the part family. The problem like most other LP models is found to be NP-Hard. It is therefore solved separately using branch and bound technique and a heuristic based on multistage programming approach. They work well for small size problems but when it comes to large size problems there is a trade-off between computational time and quality of the solution yielded.

Vakharia & Chang (1997) constructed a non-linear integer programming model with an objective to minimize the total system cost comprising of material handling cost with cost of machines allocated to various cells. The non-linearity of this programming model and use of integer variables make the system worse by turning it into an NP-Hard problem presenting computational hindrances. The situation is handled by using two combinatorial search heuristics

that yield a near-optimal solution. Simulated annealing heuristic is one of them and it tries to search for an optimal solution in the immediate neighborhood of an initial solution. This initial solution is randomly generated and must prove to be feasible satisfying model requirements. The other combinatorial search technique used is a tabu search heuristic. Using this heuristic avoids getting entrapped in a local optimal region by maintaining a tabu list which keeps track of prior solutions and improves on them. For both of these combinatorial search heuristics the numbers of iterations need to be fixed accordingly. Running these heuristics over test cases indicate simulated annealing to show a better performance than tabu search in terms of solution quality and computation time. Though simulated annealing performs better it cannot be totally relied as it fails to produce near-optimal solution on a uniform basis. The number of iterations in both heuristics has been randomly set with low values for simulated annealing and higher values for tabu search and would be better to handle them within the model instead of having them user specified. As mentioned earlier there exists a trade-off between cost of inter-cellular movements and cost of available number of machines. This will impact resulting cell configuration and can be addressed through constraints which give priority based on situational demands.

2.4.8 GT using Sorting Technique

Certain methods identify cell grouping by using a sorting procedure to rearrange either rows or columns of machine/part incidence matrix. Arranging the cells in a diagonal form helps to visualize and identify inter-cell moves.

Li & Parkin (1997) presented a GT algorithm referred to as a “sorting algorithm”. It is an improvement over the work done by Boe, Cheng (1991) and eliminates two dimensionality restrictions, interdependency between machine and part arrangement by sorting them separately. The sorting operation uses matrix manipulation to perform rearrangement of rows and columns

to achieve the best cellular layout with minimum inter-cellular flow between cells. Like other GT algorithms it uses a binary machine/part as the input. This is followed by the use of permutation methods to form matrices, one for row and another for column called as permutation matrices. The matrix multiplication of these permutation matrices and binary input matrix yields the sorting matrix. It has non-zero and zero entries grouped together to represent a cellular layout with few exceptional elements as inter-cellular flows. A grouping efficiency measure is developed here to take into account inter-cell transfer and to show how intact the cell configuration is. The results are compared with other sorting algorithms found in literature and indicate higher group efficiency obtained using this algorithm.

2.4.9 GA based approaches

Cheng, Gupta, Lee & Wong (1998) solved the GT problem as a traveling salesman problem. The solution methodology for this problem is based on a GA. A binary machine-part incidence matrix is used as the input to the TSP formulation. The decision criterion used here is a distance measure which relates to the similarity between the machines in processing common parts. The final quality of the solution is validated using measures like grouping efficiency, grouping efficacy. As the operation sequence is represented in a binary form it does not account for the actual inter-cellular travel from and to a specific machine in the sequence. The results are compared with other similar approaches and indicate that uniform performance cannot be guaranteed under all conditions.

Group Technology mainly deals with cell formation under static scenario. Wicks & Reasor (1999) developed an approach to handle a dynamic production environment where the product mix and demand volume changes across multiple periods. The mixed integer programming problem formulation is solved using a genetic algorithm heuristic. Material

handling cost is reduced over the planning horizon by reducing inter-cellular moves, duplicating machines or re-locating machines from one cell to other. Input parameters to the model like demand, planning horizon are predicted by relying on forecasts which does not guarantee a reliable performance. The number of cells to be formed is also constrained in the model which holds good for a static case but not for a dynamic one. Even small size problems cannot be solved to optimality using the mathematical model. The quality of the solution deteriorates when extended to large size problems.

2.4.10 Other Relevant Approaches

Islam & Sarker (2000) carried out an analysis on existing measures and a new similarity coefficient is developed. This is referred to as relative matching coefficient. The similarity coefficient is embedded inside a linear zero-one integer programming model which gives an optimal solution. The new similarity coefficient identifies relative similarities between machines and uses this information to build up a machine similarity matrix. The matrix is the input to a mathematical model and grouped into machine cells by proceeding from a higher to a lower level of similarity values. The process is repeated again and parts are grouped together into part families using part similarity matrix fed to the mathematical model. The solution quality is analyzed using a grouping efficiency measure – the one suggested by Chandrasekharan and Rajagopalan (1986). To eliminate computational problems an alternative solution methodology is provided by a heuristic using the same logical sequence followed above. New similarity coefficient developed here works well and is based upon information from a binary machine/part matrix. This makes it difficult to handle real time manufacturing issues like capacity planning, scheduling/routing. The model can be enhanced by modifying or developing a grouping measure

that complements for both mathematical model as well as the heuristic instead of using one already presented in the literature.

2.5 Grouping Measures

This section discusses various grouping measure approaches that were used in GT.

2.5.1 Pre-Grouping/ Similarity Coefficient based approaches

This section reviews similarity measures used for forming machine/part families. Jeon & Leep (2005) introduced a similarity coefficient measure based on number of alternative routes taken in the event of a machine failure.

$$S_{ij} = \frac{(\sum_{mp} t_{ijp}^{(m)}) / 2}{\sum_m (\sum_k r_{ik}^{(m)} + \sum_l r_{jl}^{(m)}) - (\sum_{mp} t_{ijp}^{(m)}) / 2}$$

Where,

S_{ij} : Similarity coefficient between part types i and j

r_{ik} : k th alternative route for part type i

r_{jl} : l th alternative route for part type j

t_{ijp} : p th alternative route of new arrangement between part types i and j

$r_{ik}^{(m)} = 1$, if the k th alternative route for part type i still exists when machine type i

fails=0, otherwise

$r_{jl}^{(m)} = 1$, if the l th alternative route for part type j still exists when machine type m

fails=0, otherwise

$t_{ijp}^{(m)} = 1$, if the p th alternative route of a new arrangement for part types i and j still

exists when machine type m fails = 0, otherwise.

Jaccard's similarity coefficient (Jaccard 1908) based on common operations performed is given as

$$S_{ij} = \frac{a_{ij}}{a_{ij} + b_{ij} + c_{ij}}$$

Where,

S_{ij} is the similarity between machines i and j .

a_{ij} is the number of parts processed by both machines i and j .

b_{ij} is the number of parts processed by machine i but not by machine j .

c_{ij} is the number of parts processed by machine j but not by machine i .

McAuley (1972) modified Jaccard's similarity coefficient and redefined it as the number of parts visiting both machines to the number of parts visiting at least one of the two machines.

$$S_{ij} = \frac{\sum_{k=1}^n X_{ijk}}{\sum_{k=1}^n Y_{ijk}}$$

Where,

S_{ij} = the similarity coefficient between machines i and j

n = number of parts

$$X_{ijk} = \begin{cases} 1 & \text{if part } k \text{ visits both machines } i \text{ and } j \\ 0 & \text{otherwise} \end{cases}$$

$$Y_{ijk} = \begin{cases} 1 & \text{if part } k \text{ visits one of machines } i \text{ or } j \text{ or both} \\ 0 & \text{otherwise} \end{cases}$$

Seifoddini & Djassemi (1991) modified Jaccard's similarity coefficient to incorporate production volume. The modified similarity coefficient measure is given below.

$$S_{ij} = \frac{\sum_{k=1}^n N_k X_{ijk}}{\sum_{k=1}^n N_k Y_{ijk}}$$

N_k = production volume for part k and n

Gupta (1990) extended this similarity coefficient to include operation time and operation sequences as well as production volume. The extended similarity coefficient is given as

$$S_{ij} = \frac{\sum_{k=1}^N \left[\gamma_k \cdot X_{ijk} \cdot t_{ijk} + \sum_{l=1}^{n_k} \gamma_{kl} \cdot Z_{kl} \right]}{\sum_{k=1}^N \left[\gamma_k \cdot X_{ijk} \cdot t_{ijk} + \sum_{l=1}^{n_k} \gamma_{kl} \cdot Z_{kl} + Y_k \right]}$$

Where,

S_{ij} = the similarity coefficient between machines i and j

N = number of parts

γ_k = production volume for part type k

n_k = number of trips in which part type k visits both machines i and j

$$X_k = \begin{cases} 1 & \text{if part } k \text{ visits both machines } i \text{ and } j \\ 0 & \text{otherwise} \end{cases}$$

$$Z_{kl} = \begin{cases} 1 & \text{if part } k \text{ visits both machines } i \text{ and } j \text{ in a row} \\ 0 & \text{otherwise} \end{cases}$$

t_{ijk} = Portion of total processing time that part type k spends on both machines i and j (ratio of total smaller unit operation times to higher unit operation times for machine parts i and j for part type k during visits to machine i and j)

$$y_k = \begin{cases} 1 & \text{if part } k \text{ visits either machine } i \text{ or } j \\ 0 & \text{otherwise} \end{cases}$$

Vakharia & Wemmerlov (1990) & Choobineh (1988) introduced a similarity measure considering sequence of operations within cell and machine loads. It makes use of Jaccard's similarity coefficient and is presented as follows,

$$S_{jk}(L) = \frac{1}{L} \left[JAC_{jk} + \sum_{r=2}^L \frac{C_{jk}(r)}{N-r+1} \right]$$

Where,

L = the order of the similarity coefficient

Sequence of operations of length 1 through L are used to calculate

$$S_{jk}(L) \quad L \leq N$$

JAC_{jk} = the Jaccard similarity coefficient between parts j and k

N_i = number of operations of part i

$$N = \text{Min}_i(N_i)$$

$C_{jk}(r)$ = the number of common sequences of length r between parts j and k

Kusiak & Cho (1992) proposed a similarity measure considering alternate process plans.

For any two parts (process plans) referred to column k and l in the incidence matrix $[a_{ij}]$, the zero-one similarity measure is defined by

$$S_{kl} = \begin{cases} 1 & \text{if } a_{ik} \geq a_{il} \quad \text{or } a_{ik} \leq a_{il} \quad \text{for all } i \\ 0 & \text{otherwise} \end{cases}$$

$S_{kl} = 1$ indicates that part vector (process plan) l is a subset of part vector (process plan) k

or vice versa, where

Part vector $k = [a_{1k}, a_{2k}, \dots, a_{mk}]^T$ and

Part vector $l = [a_{1l}, a_{2l}, \dots, a_{ml}]^T$

Islam & Sarker (2000) carried out an analysis on existing measures and a new similarity coefficient is developed. This is referred to as relative matching coefficient defined as follows,

$$S_{ij} = \frac{a + (ad)^{1/2}}{a + b + c + d + (ad)^{1/2}}$$

a = Number of parts processed on both machines i and j

b = Number of parts processed only on machine i

c = Number of parts processed only on machine j

d = Number of parts processed neither on machine i nor on machine j

Offodile (1991) presented a similarity measure S_{ij} between parts i and j to accommodate alphanumeric part coding defined as follows,

$$S_{ij} = \frac{\sum_{k=1}^K S_{ijk}}{K}$$

$$S_{ijk} = \begin{cases} 1 - \frac{|a_{ik} - a_{jk}|}{R_k} & \text{if attribute } k \text{ is numeric} \\ 1 - \frac{\delta(a_{ik}, a_{jk})}{L_k} & \text{if attribute } k \text{ is alphanumeric} \end{cases}$$

Where,

S_{ijk} = similarity measured between parts i and j on attribute k

K = total number of attributes considered

a_{ik} = part coding for part i on attribute k

a_{jk} = part coding for part j on attribute k

R_k = range of possible part coding for all parts on attribute k

$\delta(a_{ik}, a_{jk}) =$ number of codes along the entire length of the code that are different between parts i and j

$L_k =$ number of different codes used to describe attribute k

2.5.2 Distance based similarity measures

Kim, Baek & Jun (2005) presented a similarity distance measure between a part routing (r) and a representative part routing (r_f) defined as

$$d(r, r_f) = \left(\sum_{m=1}^{|M|} \{s_{rm} - s_{r_fm}\}^2 \right)^{1/2}$$

$d(r, r_f) = 0$ if two part routings require the same machines

where,

$R =$ set of part routings

$F =$ set of part routing family indices

$M =$ set of machines

$m =$ index of machine ($m = 1, 2, \dots, |M|$)

$f =$ index of the part routing family ($f = 1, 2, \dots, |F|$)

$r =$ index of part routing ($r = 1, 2, \dots, |R|$)

$r_f =$ index of the representative part routing of the part routing family f

$(s_{r1}, s_{r2}, \dots, s_{r|M|}) =$ information about part routing r where,

$$s_{rm} = \begin{cases} 1 & \text{if an operation of part routing } r \text{ is performed on machine } m \\ 0 & \text{otherwise} \end{cases}$$

2.5.3 Post-Grouping Measures

Chandrasekharan & Rajagopalan (1989) introduced a grouping efficiency (GE) measure to measure the quality of clusters.

$$GE = \frac{qn_1 + (1 - q)n_2}{n_1 + n_2}$$

where, n_1 = Number of entries '1' in the diagonal blocks

Total number of elements in the diagonal blocks

n_2 = Number of entries '0' in the off-diagonal blocks

Total number of elements in the off-diagonal blocks

q = a weighting factor having a value between 0 and 1

Performance of a cellular manufacturing system can be evaluated using another measure called grouping efficacy. Kumar (1990) presented a grouping efficacy measure defined as

$$\Gamma = \frac{1 - \frac{e_0}{e}}{1 + \frac{e_\gamma}{e}}$$

Where,

Γ = grouping efficacy

e = total number of 1's in the machine-component chart

e_0 = total number of 1's in off-diagonal blocks

e_γ = number of 0's in diagonal blocks

A weighted grouping efficiency measure presented by Ng (1993) gives realistic importance to the presence of exceptional or off-diagonal elements. It is defined as

$$\gamma = \frac{q.(e - e_0)}{q.(e + e_\gamma - e_0) + (1 - q).e_0}$$

Where, $0 \leq q \leq 1$

The grouping measures discussed above are suitable only for binary data and cannot be used when information on operation sequence is provided. Harhalakis *et al.* (1990) presented three evaluation criteria using operation sequence.

Global efficiency is defined as ratio of total number of operations performed within suggested cells to total number of operations in the system.

$$\text{Global Efficiency} = \frac{\sum_{j=1}^n rc_j}{\sum_{j=1}^n r_j}$$

rc_j is the number of operation in the route of component j performed in its cell.

Group Efficiency is defined as the ratio of the difference between the total of the number of external cells that can be visited and the total number of external cells actually visited by all the components to the total of the maximum number of external cells that can be visited by them (only applicable when number of cells is more than one).

$$E_w = \sum_{j=1}^n \min[(q_j - 1), (c - 1)]$$

Where,

q_j is the number of different machines belonging to component j routing.

The total number of cells actually visited by all the components is

$$A_w = \sum_{j=1}^n \sum_{k=1}^c (x_{jk} - 1)$$

Where,

$x_{jk} = 1$ if component p_j visits cell c_k , $k=1, 2, \dots, c$

= 0 otherwise

$$\text{Grouping Efficiency} = \frac{E_w - A_w}{E_w}$$

2.6 Conclusion

Most of previous researches that addressed Facility Layout using GT, were focused on methodologies where grouping of machines/resources were done based on similarity, production volume and operation sequence. Also in the previous researches none have addressed the number of cells to be formed, given a set of information like number of machines, number of parts, operation sequence and production volume. Nair & Narendran (1998), Won & Lee (2001) used most of the above factors for the formation of cells using GT technique. But the solution they obtained lacked optimality for formation of cells. So the next chapter discusses the inefficiencies of both Nair & Narendran (1998), Won & Lee (2001) methods for cell formation followed by a new method of cell formation technique that overcomes all the drawbacks of those two methods along with a performance measure for the cells being formed. The new method also includes an algorithm for placement of cells and placement of machines within cell. A test case study to validate the proposed methodology is also explained.

CHAPTER 3

METHODOLOGY

For any algorithm in GT, the main objective is to reduce the intercellular flow of parts and at the same time provide an efficient grouping of machines and parts. So far the similarity based method developed by Nair & Narendran (1998) and an optimization based approach developed by Won & Lee (2001) have been considered as the efficient algorithm for cell formation using GT. Section 3.1 and 3.2 discuss the shortcomings of Nair & Narendran (1998) and Won & Lee (2001) method for cell formation. Section 3.3 discusses a new method of cell formation technique to minimize intercellular count along with a performance measure for the cells formed. Section 3.4 explains a proposed layout development strategy that combines GT and layout development once the cells are being formed. Section 3.5 details the entire new methodology along with the proposed layout development strategy using a small case study. Section 3.6 discusses the conclusion of this chapter.

3.1 Nair & Narendran (1998) Model

Nair & Narendran (1998) proposed a similarity measure based GT approach in dealing with cell formation called weighted machine sequence similarity.

3.1.1 Notations used in Nair & Narendran (1998)

m	Number of machines (rows)
n	Number of components (columns)
B	$[b_{ijp}]$ Input component-machine incidence matrix
n_{ji}	number of times the 'j' th component visits the 'i' th machine ($n_{ji} \geq 0$)

- b_{jip} the operations sequence number if the ' j '_{th} ($1 \leq j \leq n$) component visits the ' i '_{th} ($1 \leq i \leq n$) machine for the ' p '_{th} ($0 \leq p \leq n_{ji}$) time; zero otherwise
- W_j Weight of component ' j '
- r_j Maximum number of operations for component ' j '
- $s(i, l)$ Pair-wise similarity between machines ' i ' and ' l '
- $TOTOP_k$ Total number of operations in the ' k '_{th} cell
- NOP_k Total number of non-operations (voids) in the ' k '_{th} cell
- c maximum number of machine-cells
- β Bond Efficiency

3.1.2 Methodology for Cell Formation

For a pair of machines i and l the similarity measure is given by the following equation.

$$s(i, l) = \frac{C_i + C_l}{T_i + T_l} \quad (3.1)$$

Where,

$$T_i = \sum_{j=1}^n \sum_{p=1}^{n_{ji}} w_j t_{jip}$$

$$C_i = \sum_{j=1}^n \sum_{p=1}^{n_{ji}} w_j c_{jip}$$

Where,

$$t_{jip} = 0 \text{ if } b_{jip} = 0$$

$$= 1 \text{ or } r_j$$

$$= 2 \text{ otherwise}$$

$$c_{jip} = 0 \text{ if } b_{jip} = 0 \text{ or } b_{jlp} = 0$$

$$= 1 = 1 \text{ or } r_j$$

$$= 2 \text{ otherwise}$$

This is a sequential approach with machines/parts grouped into cells in two different stages. The first stage forms machine cells based on the above similarity measure and the second stage assign part families to these cells.

Using equation (3.1) the similarity index matrix showing the relationship between a pair of machines is formed. Some machines exhibit a strong relationship with each other (high value of similarity) while some are totally disjoint (zero similarity) from each other. Each disjoint machine is chosen as a potential seed for a machine group or cluster. The machines that are chosen as seeds for clustering are referred to as centroids. Having a set of centroids, the machine-cells can be formed around these seeds by allotting other machines to these seeds based on highest similarity index value.

After forming machine cells, the components have to be assigned to the cells to form part families. Each cell formed is transformed into a component seed vector. The travel count of each component vector with every component seed vector is calculated using equation (3.2) and the component vector yielding the largest value is assigned to the corresponding component seed vector.

The component vector is represented as $(P_j = \{P_{1j} P_{2j} \dots P_{ij} \dots P_{mj}\})$, $1 \leq j \leq n$.

The travel count (sc_{kj}) of each component vector with every component seed vector is calculated using equation (3.2).

$$sc_{kj} = w_j \sum_{i=1}^n X_i \quad (3.2)$$

Where,

$$X_i = 0 \text{ (if either } P_{ij} \text{ or } CS_{ik} \text{ is 0)}$$

$$= 1 \text{ (if } P_{ij} \text{ is 1 or } r_j, \text{ and } CS_{ik} \text{ is 1)}$$

$$= 2 \text{ (if } P_{ij} \text{ is not 1 or } r_j, \text{ and } CS_{ik} \text{ is 1)}$$

The component vector with the highest travel count (sc_{kj}) is assigned to the component seed vector thus completing the component allocation to cells. The component incidence matrix does not reveal the volume of intercellular flows (Nair and Narendran, 1998). It does not take into consideration the processing sequence or revisits to the same machine.

3.1.3 Test Case (7 machines X 4 products)

Table 3.1 shows the sequence and production volume details for 7 machines and 4 products case.

Table 3.1 Product Machine matrix with sequence and production volume

		Machines							
		1	2	3	4	5	6	7	P.V
Products	A	1	2	3	4				800
	B		3	2	1		4		200
	C			2	1		3	4	250
	D				1	2	3	4	1000

Calculating the similarity index between machines using equation 3.1,

Table 3.2 Similarity index matrix (for machines)

	1	2	3	4	5	6	7
1	-	0.8571	0.7272	0.5245	0	0	0
2		-	0.8888	0.7058	0	0.1276	0
3			-	0.7894	0	0.3076	0.2
4				-	0.7058	0.8383	0.7142
5					-	0.851	0.923
6						-	0.9663
7							-

From Table 3.2 centroids are identified as, (1, 5) (1, 6) (1, 7) (2, 5) (2, 7) and (3, 5).

To start with (1, 5) and allotting other machines to these seeds based on highest similarity index value for a 2 cell configuration,

$$\text{Cell 1} = \{1, 2, 3\}$$

$$\text{Cell 2} = \{5, 4, 6, 7\}$$

Centroid (1, 6),

$$\text{Cell 1} = \{1, 2, 3\}$$

$$\text{Cell 2} = \{6, 4, 5, 7\}$$

Centroid (1, 7),

$$\text{Cell 1} = \{1, 2, 3\}$$

$$\text{Cell 2} = \{7, 4, 5, 6\}$$

Centroid (2, 5),

$$\text{Cell 1} = \{2, 1, 3\}$$

$$\text{Cell 2} = \{5, 4, 6, 7\}$$

Centroid (2, 7),

$$\text{Cell 1} = \{2, 1, 3\}$$

$$\text{Cell 2} = \{7, 4, 5, 6\}$$

Centroid (3, 5),

$$\text{Cell 1} = \{3, 1, 2, 4\}$$

$$\text{Cell 2} = \{5, 6, 7\}$$

The two different types of cell configuration possible from the above method of machine grouping are,

1) $\text{Cell 1} = \{1, 2, 3\}$

$$\text{Cell 2} = \{5, 4, 6, 7\} \text{ and}$$

2) $\text{Cell 1} = \{1, 2, 3, 4\}$

$$\text{Cell 2} = \{5, 6, 7\}$$

After having formed machine cells, the components have to be assigned to the cells to form part families. The travel count (sc_{kj}) of each component vector with every component seed vector is calculated using equation (3.2).

For cell configuration 1 machines and parts are assigned as shown in Figure 3.1,

	Cell 1	Cell 2
Machines	1,2,3	4,5,6,7
Parts	A,B	C,D

Figure 3.1 Machine-Part grouping

The product-machine matrix with production volume can be represented as in Table 3.3.

Table 3.3 Product-Machine matrix with production volume

		Machines						
		1	2	3	4	5	6	7
Products	A	800	1600	1600	800			
	B		400	400	200		200	
	C			500	250		500	250
	D				1000	2000	2000	1000

Total inter-cellular flow = $800+200+200+500 = 1700$.

For cell configuration 2, machines and parts are assigned as shown in Figure 3.2.

	Cell 1	Cell 2
Machines	1,2,3,4	5,6,7
Parts	A,B	C,D

Figure 3.2 Machine-Part grouping

The machine-part matrix with production volume can be represented as in Table 3.4.

Table 3.4 Product-Machine matrix with production volume

		Machines						
		1	2	3	4	5	6	7
Products	A	800	1600	1600	800			
	B		400	400	200		200	
	C			500	250		500	250
	D				1000	2000	2000	1000

Total inter-cellular flow = 200+250+1000=1450.

Since Cell configuration 2 gives a minimum inter-cellular flow compared to Cell configuration 1, we select the second grouping.

Nair and Narendran's (1998) method is sensitive to the initial centroids selected and may not always return the best solution especially when production volumes are considered, which is proved from the above case study. Also the number of centroids to be considered will be large with increase in the problem size. So the calculation becomes tedious and may result in a sub-optimal solution and sometimes even a worst solution. So Nair and Narendran's method cannot be applied for large size problem.

3.2 Won & Lee (2001) Model

In addition to operation sequence, Won & Lee (2001) considers production volume while grouping machine/parts into cells. This method is suited for medium size problem i.e. problem with machines/parts up to 13.

3.2.1 Notations used in Won & Lee (2001)

n	number of parts
m	number of machines
p	number of cells
i	index of part type, $i = 1, \dots, n$
j	index of machine type, $j = 1, \dots, m$
k, l, q	index of cells (families), $k, l, q = 1, \dots, p$
L_f	Lower limit on part family size
U_f	Upper limit on part family size
L_c	Lower limit on machine cell size
U_c	Upper limit on machine cell size
A	$= [a_{ij}]$, binary PMIM
E	$= \{(i,j) a_{ij} = 1\}$
n_i	Total number of operations required by part i
r	index of operation sequence number, $r = 1, \dots, n_i$
R_{ij}	Set of the operation sequence number along which part i visits machine j
d_i	Production volume of part ' i '
B	$= [b_{ij}]$, type I production data-based PMIM

3.2.2 Methodology for Cell Formation

To begin with, the binary PMIM, operation sequences and production volumes are given. The actual flows to or from machine 'j' by part 'i' accompanied by the production volumes of each part can be calculated using,

$$b_{ij} = \sum_{r \in R_{ij}} f_{ijr} d_i \quad (3.3)$$

Where,

$$f_{ijr} = \begin{cases} 1 & \text{if } r \text{ is } 1 \text{ or } n_i \\ 2 & \text{if } r \text{ is neither } 1 \text{ nor } n_i \\ 0 & \text{otherwise} \end{cases}$$

If a part visits any intermediate operation other than the first and the last operation, the production volume should be multiplied by a factor 2, in order to give importance to the middle operation while grouping. This is because Won & Lee (2001) suggested that a part requiring middle operation requires intercellular flow two times than first and the last operation, where the intercellular flow was considered only once. The sum of part flows is defined by,

$$\sum_{i=1}^n \text{Max}(n_i - 1, 1) d_i \quad (3.4)$$

Equation (3.5) is used to arrive at the type I production data-based PMIM which considers both the operation sequence as well as the production volume. The inter-cell flows or the sum of the binary exceptional elements are minimized using a mathematical model. The formulation of the model is shown below.

$$\text{Min} \sum_{(i,j) \in E} b_{ij} \left[\sum_{k=1}^p |x_{ik} - y_{jk}| \right] / 2 \quad (3.5)$$

The non-linear term in equation (3.5) can be linearized using the following constraint.

$$x_{ik} - y_{jk} + u_{ikj} - v_{ikj} = 0, \quad k = 1, \dots, p; (i, j) \in E$$

Therefore equation (3.5) is modified as,

$$\text{Min} \sum_{(i,j) \in E} b_{ij} \left[\sum_{k=1}^p (u_{ikj} + v_{ikj}) \right] / 2 \quad (3.6)$$

$$\sum_{k=1}^p x_{ik} = 1, \quad i = 1, \dots, n.$$

$$L_f \leq \sum_{i=1}^n x_{ik} \leq U_f, \quad k = 1, \dots, p$$

$$\sum_{k=1}^p y_{jk} = 1, \quad j = 1, \dots, m$$

$$L_c \leq \sum_{j=1}^m y_{jk} \leq U_c, \quad k = 1, \dots, p$$

$$x_{ik} \geq 0, \quad i = 1, \dots, n; k = 1, \dots, p$$

$$y_{jk} = 0 \text{ or } 1, \quad j = 1, \dots, m; k = 1, \dots, p$$

$$u_{ikj}, v_{ikj} \geq 0, \quad k = 1, \dots, p; (i, j) \in E$$

The method proposed by Won & Lee (2001) provides a cell formation technique, but does not provide a good measure for the efficiency of grouping. The concept of multiplying the production volume by 2 for the intermediate operation does not have any significant effect while forming cells. Also the Won & Lee (2001) methodology has the drawback of erroneous intercellular count, which might even lead to poor grouping in the case of medium and large size problem. Won & Lee (2001) method can be explained with the same case study as discussed for Nair & Narendran (1998).

3.2.3 Test Case (7 machines X 4 products)

Table 3.1 shows the sequence and production volume details for 7 machines and 4 products case.

Table 3.1 Product Machine matrix with sequence and production volume

		Machines							
		1	2	3	4	5	6	7	P.V
Products	A	1	2	3	4				800
	B		3	2	1		4		200
	C			2	1		3	4	250
	D				1	2	3	4	1000

Applying equation 3.3, the modified Part Machine Incidence matrix can be viewed as in

Table 3.5.

Table 3.5 Product-Machine matrix

		Machines						
		1	2	3	4	5	6	7
Products	A	800	1600	1600	800			
	B		400	400	200		200	
	C			500	250		500	250
	D				1000	2000	2000	1000

The above table is taken as the input for cell formation, with the minimum number of intercellular count as the criterion for cells to be formed. The formula for minimizing the intercellular count is,

$$\text{Min } \sum_{(i,j) \in E} b_{ij} \left[\sum_{k=1}^p (u_{ikj} + v_{ikj}) \right] / 2, \quad (3.6)$$

The results obtained after using the equation (3.6) for cell formation is detailed in Figure 3.3,

	Cell 1	Cell 2
Machines	1,2,3	4,5,6,7
Parts	A,B	C,D

Figure 3.3 Machine-Part grouping

The part-machine matrix with production volume can be represented as in table 3.6.

Table 3.6 Product-Machine matrix

		Machines							
		4	5	6	7	1	2	3	
Parts	C	1		3	4			2	
	D	1	2	3	4				
	A	4				1	2	3	
	B	1		4			3	2	

Accounted intercellular count = **1450**.

Actual intercellular count = **1700**.

From the above case study we can conclude that Won & Lee (2001) method of cell formation using PMIM I, results in erroneous intercellular count. This might sometimes lead to poor grouping of cells (in case of medium and large size problems), leaving the actual optimal solution for grouping.

3.3 New Cell Formation Model

The proposed model considers all the above drawbacks for cell formation and accounts for the actual intercellular flow with efficient grouping. When using the two models, i.e. Nair & Narendran (1998), Won & Lee (2001) for calculating the intercellular moves, the first model is sensitive to the initial centroids selected and may not always return the best solution. The second model results not only in erroneous intercellular count but also in poor group formation. In testing various cases with the part flowing to multiple cells we have found that the formulation does not provide the true number of intercellular flows. Hence, a formulation for minimizing intercellular flows is shown below. In this model, the flow from machine 'i' to 'j' for each part is used as the primary input. The notations and formulation for grouping are listed below.

3.3.1 Notations used

n	number of parts
m	number of machines
p_{\min}	minimum number of cells
p_{\max}	maximum number of cells
r	index of part type, $r = 1, \dots, n$
i, j	index of machine type, $1, \dots, m$
k	index of cells (families), $k = 1, \dots, p$
L_f	lower limit on part family size
U_f	upper limit on part family size
L_c	lower limit on machine cell size
U_c	upper limit on machine cell size
A	$= [a_{ri}]$, binary PMIM

$$a_{ri} = \begin{cases} 1 & \text{if part 'r' requires processing on machine i} \\ 0 & \text{otherwise} \end{cases}$$

n_r total number of operations required by part 'r'

d_r production volume of part 'r'

$TOTOP_k$ total number of operations in the k_{th} cell

NOP_k total number of non-operations (voids) in the k_{th} cell

3.3.2 New Grouping Methodology

To begin with, PMIM representing the operation sequences and production volumes for grouping of machines into cells and components into part families are given. The inter-cell flows or the sum of the exceptional elements are minimized using a mathematical model. The formulation of the model is shown below

$$\text{Min } \sum_{k=1}^{p_{\min}} \sum_{r=1}^n \sum_{i=1}^m \sum_{j \neq i}^m (d_r * b_{ijr} * X_{ijrk}) / 2 \quad (3.7)$$

Where,

$$b_{ijr} = \begin{cases} 1 & \text{if volume of material flows from machine 'i' to machine 'j' of part 'r'} \\ 0 & \text{otherwise} \end{cases}$$

$$x_{irk} = \begin{cases} 1 & \text{if machine 'i' of part 'r' belongs to cell k} \\ 0 & \text{otherwise} \end{cases}$$

$$x_{jrk} = \begin{cases} 1 & \text{if machine 'j' of part 'r' belongs to cell k} \\ 0 & \text{otherwise} \end{cases}$$

$$X_{ijrk} = |x_{irk} - x_{jrk}| \quad (3.8)$$

$$\sum_{k=1}^p x_{rk} = 1, \quad r = 1, \dots, n \quad (3.9)$$

$$x_{rk} = \begin{cases} 1 & \text{if part 'r' belongs to cell k} \\ 0 & \text{otherwise} \end{cases}$$

$$L_f \leq \sum_{r=1}^n x_{rk} \leq U_f, \quad k = 1, \dots, p \quad (3.10)$$

$$\sum_{k=1}^p y_{ik} = 1, \quad i=1, \dots, m \quad (3.11)$$

$$y_{ik} = \begin{cases} 1 & \text{if machine 'j' belongs to cell k} \\ 0 & \text{otherwise} \end{cases}$$

$$L_c \leq \sum_{i=1}^m y_{ik} \leq U_c, \quad k = 1, \dots, p \quad (3.12)$$

Equation (3.7) minimizes the intercellular movement for any part machine configuration. Equation (3.8) checks whether there exists any intercellular movement between machines for each product. Constraint sets (3.9) and (3.11) are to ensure that a part and a machine can be assigned to only one cell. Constraint sets (3.10) and (3.12) are to restrict the number of parts and machines that can be allotted to a cell.

The proposed model uses reduced inter-cellular movement as the criterion for grouping resources; single cell configuration could be the optimal configuration for any case. But in pragmatic terms, it cannot be a feasible solution. Hence, the algorithm is run for different part/machine configurations with 2 cluster configuration being the least configuration. The proposed model is used to calculate both the minimum and maximum number of cells to be formed, based on the number of machines and parts given as input. Restrictions are also placed on the number of machines and products that can be allotted to a cell. The minimum number of machines or parts that can be allotted to a cell takes the value of '2' and the maximum value is restricted to '12'. Since from the literature it is found that a cell containing more than '13' machines/parts is considered itself a big size problem. In order to increase the cell efficiency and

also to increase the machine/part utilization, the numbers of machines/parts in a cell are reduced to the value of '12'. The algorithm is as follows,

3.3.3 Algorithm

Step 1: Start the Process

Step 2: Input the number of machines, **m**

Step 3: Input the number of parts, **n**

Step 4: If no. of machines, $m \leq 24$, then $L_{c \min} = 2$, $L_{c \max} = \left(\frac{\text{no.ofmc's}}{L_{c \min}} \right)$

Go to Step 6 Else Go to Step 5

(Here the algorithm makes sure that the maximum number of machines that can be allotted is 12)

Step 5: Calculate $L_{c \min} = \left(\frac{\text{no.ofmc's}}{12} \right)$, $L_{c \max} = \left(\frac{\text{no.ofmc's}}{L_{c \min}} \right)$

Step 6: If no. of parts, $n \leq 24$, then $L_{f \min} = 2$, $L_{f \max} = \left(\frac{\text{no.ofparts}}{L_{f \min}} \right)$

Go to Step 8 Else Go to Step 7

(Here the algorithm makes sure that the maximum number of parts that can be allotted is 12)

Step 7: Calculate $L_{f \min} = \left(\frac{\text{no.of parts}}{12} \right)$, $L_{f \max} = \left(\frac{\text{no.of parts}}{L_{f \min}} \right)$

Step 8: Set Minimum no. of cells, $p_{\min} = \text{Max} (L_{c \min}, L_{f \min})$

Step 9: Set Maximum no. of cells, $p_{\max} = \text{Min} (L_{c \max}, L_{f \max})$

Step 10: Set $L_f = L_{f \min}$ and $U_f = 12$

Step 11: Set $L_c = L_{c \min}$ and $U_c = 12$

Step 12: Group the machines using New GT formulation

Step 13: Calculate Intercellular flow count, Bond Efficiency, MH cost

Step 14: Display the result

Step 15: If $p_{\min} = p_{\max}$, Go to Step 18 Else Go to Step 16

Step 16: Set $p_{\min} = p_{\min} + 1$

Step 17: Go to step 9

Step 18: Stop the process

Note: For $L_{c \min}/L_{f \min}$, the value should be rounded off to the next higher integer value (i.e. if the value is 2.3 its should be rounded off to 3) and

For $L_{c \max}/L_{f \max}$, the value should be rounded off to the lower integer value (i.e. if the value is 2.3 it should be rounded off to 2).

3.3.4 Performance Measure

In order to evaluate the performance of the cells formed using the proposed algorithm, measures like Compactness and Bond efficiency are used. But there exists a trade off between intercellular movement and compactness of cells formed. With an increase in the number of cells, there is a chance of getting high compactness but the number of intercellular movement also increases. So both values are selected in such a way that an optimal solution is obtained without suppressing both of them.

Nair and Narendran (1998) introduced a Bond efficiency measure to address the intercellular efficiency and compactness of the cells formed. But the major drawback of the proposed measure by Nair and Narendran (1998) is that it doesn't consider the production volume in its formulation. Hence, the currently used method of bond efficiency is not effective in determining the best grouping of cells. As a result, the existing formulation has been transformed to accommodate information on production volume.

3.3.4.1 Existing Bond Efficiency Formulation

$$\text{Bond Efficiency } \beta = \underbrace{\frac{I(I-U)}{I}}_{\text{Inter cellular movement}} + \underbrace{\frac{(I-q) \sum_{k=1}^c \text{TOTOP}_k}{\sum_{k=1}^c (\text{TOTOP}_k + \text{NOP}_k)}}_{\text{Compactness}}$$

$$I = \sum_{j=1}^n (r_j - 1), r_j = \text{maximum number of operations for component } j$$

$$U = \sum_{j=1}^n \sum_{k=1}^{r_j-1} x_{l_{jk}}, x_{l_{jk}} = 0 \text{ if operations } k, k+1 \text{ are performed in the same cell}$$

$$= 1 \text{ otherwise}$$

Compactness of each cell is defined as the ratio of the number of operations within it to the maximum number of operations possible in it.

3.3.4.2 Modified Bond Efficiency Formulation

The new method of bond efficiency which minimizes intercellular flow and maximizes the density of 1's is used for determining the cell configuration. Bond Efficiency (β), equation 3.13 is defined as a weighted average of Compactness (3.15) and GT efficiency (3.14)

$$\beta = \left(\frac{\frac{(I-U)}{I} + \frac{\sum_{k=p_{\min}}^{p_{\max}} \text{TOTOP}_k}{\sum_{k=p_{\min}}^{p_{\max}} (\text{TOTOP}_k + \text{NOP}_k)}}{2} \right) \quad (3.13)$$

β is non-dimensional and non-negative

Group Technology Efficiency is defined as the ratio of the difference between the maximum number of inter-cell travels possible and the number of inter-cell travels actually required by the system to the maximum number of inter-cell travels possible.

$$\text{GT efficiency} = \frac{I-U}{I} \quad (3.14)$$

where,

$$I = \sum_{r=1}^n d_r (n_r - 1)$$

$$U = \sum_{r=1}^n \sum_{j=1}^{n_r-1} X_{ijr} d_r$$

Compactness of each cell is defined as the ratio of the number of operations within it to the maximum number of operations possible in it.

$$\text{Compactness} = \frac{\sum_{k=1}^p \text{TOTOP}_k}{\sum_{k=1}^p (\text{TOTOP}_k + \text{NOP}_k)} \quad (3.15)$$

For a perfect diagonal block, Compactness takes the value of ‘1’ and NOP_k takes the value of ‘0’.

3.4 Relative placement of cells

Once the number of cells and the machines within it are determined, they have to be arranged relative to each other based on the intercellular flow between them. The volume of material existing between cells mandates the placement of cells relative to each other. Each cell can be regarded as individual departments and using the flow information between them, they can be arranged with respect to each other. The objective is to minimize material flow distance between machines in cells.

3.4.1 Placement of machines within cells

The objective of reduced material handling cost depends mainly on the location of machines within cells rather than on (but to some extent) relative arrangement of cells within plant layout. As a result, placement of machines within its respective cells needs to be given importance since a machine might be needed by more than one cell to complete its operation or for performing some intermediate operation. Hence, after identifying the relationship of a particular machine that have established strong bonding (in this case, flow volume) with the machines of another cell, the locations of corresponding machines within their subsequent layouts are decided. These cells are then placed within the plant layout.

3.4.2 Proposed Algorithm

The principle objective of this algorithm is that, it tries to achieve reduced flow distance between machines in different cell layouts by placing them in appropriate positions within their respective cells.

The algorithm is carried out in two phases:

- 1). Listing the significant machines
- 2). Allotting these machines to optimal locations.

3.4.2.1 Listing the significant machines

The set of machines that accounts for intercellular flow with the neighboring cells are identified and listed in a prioritized order (in descending order). That is, start with the highest relationship and move on until all flow volumes are accounted for.

3.4.2.2 Machine allocation to optimal locations

After having developed the prioritized list, machines are allocated to optimal locations starting with the highest relationship (that is, just follow the prioritized list). At this point, it

becomes important to define a set of places (“Cardinal & Trivial” locations) within each cell layout to which these prioritized set of machines can be assigned. The probability of any machine occupying those positions will be solely based on the type of relationship they exhibit with machines in another cells and the number of machines involved in intercellular movements. Machines that exhibit strong relationship only with those inside the same cell can be assigned to trivial locations, since these machines have no impact on or not involved in intercellular movements. The positions along the boundary of each cell are called Cardinal locations as these positions are completely dedicated to resources that exhibit strong relationship with machines in other cells. From the significant list of machines, determine the one that exhibit strong relationship with machines (one or two) in another cell. Those machines can be suitably placed along the boundary of their respective cells and they are free to occupy any of the Cardinal locations.

The mathematical explanation is as follows,

X_{inlk} - i_{th} machine type of product ‘n’ assigned to l_{th} cardinal location of cluster ‘k’

$X_{jn lq}$ - j_{th} machine type of product ‘n’ assigned to l_{th} cardinal location of cluster ‘q’

It is taken $j = i + 1$ (that is, the next machine in which product ‘n’ is processed after ‘i’ as per its sequence) and

$q = k + 1$ (that is, cluster which contains j_{th} machine type)

X_{inlk} and $X_{jn lq}$ are binary variables

N_{kn} – Number of machines of cell k involved in intercellular activity for product n

Hence,

If $X_{inlk} = 1$, then $X_{jn lq}, N_{qk} = (1-y) N_{qk} - y$

y is a binary decision variable

$$\sum_{m=1}^g \sum_{k=1}^h \sum_{i=1}^n \sum_{j=1}^o X_{inlk} = 1 \quad \forall l$$

$$\sum_{l=1}^w X_{ijklm} = 1 \quad \forall i, j, k, m$$

$$X_{inlk}, X_{jnlp}, y \in \begin{pmatrix} 0 \\ 1 \end{pmatrix} \forall i, j, k, l, m$$

The corner points of each cell gain supreme importance in the process of allocating significant machines to optimal locations. Of the prioritized machines, there are certain machines that may maintain strong relationship with machines in more than one cell. Those machines that have the highest probability take corner locations. For example, when a machine indicates strong relationship with two other machines in different cells or when 3 machines in 3 different cells are actively involved in any intercellular activity, one can easily conclude that the optimal location for any two of those machines can be the corner points of their respective cells where as the other machine can be properly placed along the boundary of its cell layout (need not be cornered as it depends on the relative location of cells). In case of 4 cells, all the four resources involved in intercellular movement should be assigned to corner points of their respective layouts. But all of the above cases depend primarily on the priority value (highly prioritized or not) assigned to their relationship.

If $X_{inlk} = 1$, then

$$\sum_{q=m+1}^g \sum_{i=1}^n \sum_{p=j+1}^z \sum_{l=1}^w X_{jnlp} \leq \sum_{q=m+1}^g N_{qk}$$

$$\sum_{q=m+1}^g N_{qk} - \sum_{q=m+1}^g \sum_{i=1}^n \sum_{p=j+1}^z \sum_{l=1}^w X_{inlp} \leq \sum_{q=m+1}^g N_{qk} \cdot y \quad \forall k \quad (3.16)$$

$$X_{inlk} \leq \sum_{q=m+1}^g N_{qk} (1-y) \forall i, j, k, l, m \quad (3.17)$$

$$\sum_{m=1}^g \sum_{k=1}^h \sum_{i=1}^n \sum_{j=1}^o X_{inlk} = 1 \quad \forall l \quad (3.18)$$

$$\sum_{l=1}^w X_{inlk} = 1 \quad \forall i, j, k \quad (3.19)$$

$$X_{inlk}, X_{jnlq} \in \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad \forall i, j, k, l, m \quad (3.20)$$

Equation sets (3.16) and (3.17) are conditional constraints and states that the machine pair involved in intercellular movements should be assigned to cardinal locations of their respective layouts. Constraint sets (3.18) and (3.19) ensure that each location can hold only one machine and each machine can be assigned to only one location. Constraint (3.20) places binary restrictions on decision variables.

The argument gets much more complicated when a product has to go through more than four cells to get converted to a finished product. Using the proposed algorithm, the prioritized machines are placed in appropriate locations within their cell layouts. The cells are then placed within the plant layout. Once the layout is generated, the material handling cost is calculated for the flow volume using Euclidean method. The new methodology for cell formation and placement of machines are explained with the case study in the next section.

3.5 Test Case (7 machines X 4 products)

Table 3.1 shows the sequence and production volume details for 7 machines and 4 products case.

Table 3.1 Product Machine matrix with sequence and production volume

		Machines							
		1	2	3	4	5	6	7	P.V
Products	A	1	2	3	4				800
	B		3	2	1		4		200
	C			2	1		3	4	250
	D				1	2	3	4	1000

3.5.1 Number of cells calculation

The step-by-step procedure for the above case study is detailed below,

From the algorithm (3.2.3.),

Number of machines, $m = 7$

Number of parts, $n = 4$

Since number of machines, $m \leq 24$,

then $L_{c \min} = 2$, $L_{c \max} = \left(\frac{\text{no.ofmc's}}{L_{c \min}} \right)$

$$L_{c \max} = \left(\frac{7}{2} \right) = 3.5 = 3 \text{ (rounding off to the lower integer value)}$$

Since number of parts, $n \leq 24$,

then $L_{f \min} = 2$, $L_{f \max} = \left(\frac{\text{no.ofparts}}{L_{f \min}} \right)$

$$L_{f \max} = \left(\frac{4}{2} \right) = 2$$

Minimum cells required, $p_{\min} = \text{Max} (L_{c \min}, L_{f \min})$

$$= \text{Max} (2, 2)$$

$$p_{\min} = 2 \text{ (minimum no. of cells required)}$$

Maximum cells required, $p_{\max} = \text{Min} (L_{c \max}, L_{f \max})$

$$= \text{Min} (3, 2)$$

$$p_{\max} = 2 \text{ (max. no. of cells required)}$$

Setting $L_f = L_{f \min}$ and $U_f = 12$, but in this case $U_f = 4$

$$L_f = 2 \text{ and } U_f = 4$$

Setting $L_c = L_{c \min}$ and $U_c = 12$, but in this case $U_c = 7$

$$L_c = 2 \text{ and } U_c = 7$$

But the sequence information is captured using the below formula,

$$b_{ijr} = \begin{cases} 1 & \text{if volume of material flows from machine 'i' to machine 'j' of part 'r'} \\ 0 & \text{otherwise} \end{cases}$$

By multiplying the production volume with the sequence information, the exact volume of material flowing between machines can be obtained.

d_r = production volume of part 'r'

Therefore, $d_r * b_{ijr}$

3.5.2 Cell formation

The volume of material flowing between different machines for parts A, B, C and D are shown in Table 3.7,

Table 3.7 From-to chart for all products

		Machines (From –to)										
		1 to 2	2 to 3	3 to 4	4 to 3	3 to 2	2 to 6	3 to 6	6 to 7	4 to 5	5 to 6	6 to 7
Products	A	800	800	800								
	B				200	200	200					
	C				250			250	250			
	D									1000	1000	1000

Table 3.7 is taken as input for the formation of cells, by minimizing the intercellular movement as the criterion for cell formation, using equation (3.7). After inputting the values, equation (3.7) becomes,

$$\text{Min} \sum_{k=1}^2 \sum_{r=1}^4 \sum_{i=1}^7 \sum_{j \neq i}^7 (d_r * b_{ijr} * X_{ijrk}) / 2$$

The cell configuration obtained after using the above formula for cell formation is detailed in Table 3.8.

Table 3.8 Product – Machine matrix

		Machines						
		1	2	3	4	5	6	7
Products	A	800	800	800	800			
	B		200	200	200		200	
	C			250	250		250	250
	D				1000	1000	1000	1000

The intercellular movement is calculated by,

$$(d_1b_{121}X_{1211} + d_1b_{121}X_{1212} + d_1b_{231}X_{2311} + d_1b_{231}X_{2312} + d_1b_{341}X_{3411} + d_1b_{341}X_{3412} + d_2b_{432}X_{4321} + d_2b_{432}X_{4322} + d_2b_{322}X_{3221} + d_2b_{322}X_{3222} + d_2b_{262}X_{2621} + d_2b_{262}X_{2622} + d_3b_{433}X_{4331} + d_3b_{433}X_{4332} + d_3b_{363}X_{3631} + d_3b_{363}X_{3632} + d_3b_{673}X_{6731} + d_3b_{673}X_{6732} + d_4b_{454}X_{4541} + d_4b_{454}X_{4542} + d_4b_{564}X_{5641} + d_4b_{564}X_{5642} + d_4b_{674}X_{6741} + d_4b_{674}X_{6742}) / 2$$

$$= ((800*1*0) + (800*1*0) + (800*1*0) + (800*1*0) + (800*1*1) + (800*1*1) + (200*1*1) + (200*1*1) + (200*1*0) + (200*1*0) + (200*1*0) + (200*1*1) + (200*1*1) + (250*1*0) + (250*1*0) + (250*1*0) + (250*1*0) + (250*1*0) + (250*1*0) + (1000*1*0) + (1000*1*0) + (1000*1*0) + (1000*1*0) + (1000*1*0) + (1000*1*0)) / 2$$

Total inter-cellular count= **1200**

From the above intercellular movement value, it's proved that the proposed methodology not only accounts for the exact inter-cellular count but also for the efficient grouping when compared with that accounted by Nair & Narendran (1998) (3.1.1.3) , and Won & Lee (2001) (3.1.2.3)

3.5.3 Performance Measure

In order to evaluate the performance of the cells formed measures like Compactness and Bond efficiency are used from the proposed algorithm.

3.5.3.1 GT Efficiency

Group Technology efficiency is defined as the ratio of the difference between the maximum number of inter-cell travels possible and the number of inter-cell travels actually required by the system to the maximum number of inter-cell travels possible.

$$\text{GT efficiency} = \frac{I-U}{I}$$

Where,

$$\begin{aligned} I &= \sum_{r=1}^n d_r (n_r - 1) \\ &= \sum_{r=1}^4 d_r (n_r - 1) \\ &= ((800*3) + (200*3) + (250*3) + (1000*3)) \end{aligned}$$

$$I = 6750$$

$$\begin{aligned} U &= \sum_{r=1}^n \sum_{j=1}^{n_r-1} X_{ijr} d_r \\ &= \sum_{r=1}^4 \sum_{j=1}^{4-1} X_{ijr} d_r \\ &= (1*800) + (2*200) \end{aligned}$$

$$U = 1200$$

$$\text{GT efficiency} = \frac{6750 - 1200}{6750} = 0.8222$$

3.5.3.2 Compactness

Compactness of each cell is defined as the ratio of the number of operations within it to the maximum number of operations possible in it.

$$\text{Compactness} = \frac{\sum_{k=1}^{P_{\min}} \text{TOTOP}_k}{\sum_{k=1}^{P_{\min}} (\text{TOTOP}_k + \text{NOP}_k)}$$

$$= \frac{(3+8)}{(3+8) + (1+2)}$$

$$= 0.7857$$

Bond Efficiency (β) is defined as a weighted average of compactness and GT efficiency

$$\text{Bond Efficiency, } \beta = \left(\frac{(I - U) + \frac{\sum_{k=p_{\min}}^{p_{\max}} T O T O P_k}{\sum_{k=p_{\min}}^{p_{\max}} (T O T O P_k + N O P_k)}}{I} \right) / 2$$

$$= ((0.8222 + 0.7857)/2)$$

$$\beta = 0.8040$$

Since the maximum number of cells (p_{\max}) possible for the above case is only 2, the algorithm is stopped at this point. Otherwise the algorithm is run until the maximum value of cell configuration is reached and the results are calculated in the same manner for all cell configurations.

3.5.4 Relative Placement of Cells

Since the number of cells and machines within it are determined, the next part of the methodology is to arrange cells and machines inside cell depending on the relationship established between them. The number of intercellular movements mandates the placement of cells relative to each other. Each cell can be treated as individual departments and the flow between them can be identified using from-between charts.

For a 2 - Cell Configuration,

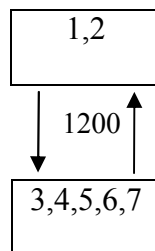


Figure 3.4 Intercellular movement between cells

Total number of intercellular movement between cells: **1200**

From the above relationship, the 2-cells can be placed relative to each other as shown in Figure 3.7,

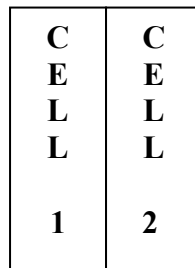


Figure 3.5 Arrangement of cells

Machines within each cell exhibit certain relationship with each other. Using From-to chart for each cell, the relationship is determined and the resources are arranged in such a way that it results in reduced material handling cost.

3.5.5 Relative placement of machines within cells

From-to relationship between machines and their relative arrangement within their respective cells are shown in Table 3.10, 3.11.

Table 3.9 From-to chart for Cell 1

	1	2
1	0	800
2	0	0



Figure 3.6 Suggested layout for Cell 1

Table 3.10 From-to chart for Cell 2

	3	4	5	6	7
3	0	0	0	250	0
4	450	0	1000	0	0
5	0	0	0	1000	0
6	0	0	0	0	1250
7	0	0	0	0	0

3	4	5	6	7
----------	----------	----------	----------	----------

Figure 3.7 Suggested layout for Cell 2

3.5.6 Allocation of machines to optimal locations

Machines involved in intercellular movements are identified and listed in a prioritized order (Table 3.12.). The placement of these machines in appropriate locations within its layout has significant impact on material handling cost of the facility.

Table 3.11 Intercellular movement between machines

From-Between (Machines)	No. of intercellular movement
2 to 3	800
2 to 6	200

From the proposed methodology, machines involved in intercellular movements are assigned to cardinal locations of their respective cell, that is, locations along the boundary of

each cell so as to minimize material handling distance. Other machines inside each cell are assigned to trivial locations of their respective layouts, that is, locations other than cardinal locations, since these machines have no impact on intercellular material handling cost. Individual layouts for the 2 cell configuration have been altered taking into consideration the movement between cells and machines involved in it. As it can be noted from the layouts below, machines involved in intercellular movements take cardinal locations of each cell and others take trivial locations.

Cell 1

1
2

Figure 3.8 Arrangement of Cell 1

Cell 2

4	5	
3	6	7

Figure 3.9 Arrangement of Cell 2

The Final Layout can be represented as shown in Figure 3.10,

1	4	5	
2	3	6	7

Figure 3.10 Final Arrangement of cell

From the layout suggested (Figure 3.11), machine 3 is assigned to cardinal location of its cell. But there are some occasions where it is not possible to allocate machines involved in

intercellular movements to cardinal locations of their respective cells. It's because by doing so the intra-cellular relationship between machines gets affected. Machine 2 of layout 1 **involves in** an intercellular flow of 800 units with machine 3 of layout 2 and 200 units with machine 6 of layout 2. But machine 6 couldn't take cardinal location in its cell, since the intra cellular movement of machine 6 with machine 5 accounts to 1000 units, which is much more than the inter cellular movement with machine 2 of cell 1. So, the algorithm keeps locating resources involved in intercellular movements to cardinal locations as long as it doesn't affect their intra cellular movement to considerable extent.

3.5.7 Material handling cost

Material handling cost for any layout is a function of amount of material movement between machines, cost of moving unit load and distance between machines. All machines are treated as equal sized machines and each of them occupies an area of 5*5. The cost of moving unit load for the above case is taken as \$1 and the centroid to centroid distance between machines is calculated using Euclidean method. The total material handling cost of the suggested layout is estimated to be **\$36000**.

3.6 Conclusion

In this chapter the inefficiencies of Nair & Narendran (1998) and Won & Lee (2001) methods of cell formation techniques are discussed. The mathematical explanation for the new method of cell formation technique along with the arrangement of cells and arrangement of machines inside cell were also detailed with a small case study. In the next chapter feasibility of the proposed approach when applied to medium and large size problems are detailed with two different case studies.

CHAPTER 4

CASE STUDIES AND RESULTS

This chapter discusses the case studies constructed to evaluate the feasibility of proposed approach when applied to a small size, a medium size (more than 25 machines) and a large size problem (more than 50 machines) Section 4.1 discusses a small size problem (8machines and 8 products). Section 4.2 discusses a medium size problem (30 machines and 15 products) case study. Section 4.3 discusses a large size problem (60 machines and 19 products) case study. Section 4.4 discusses the results obtained and concludes with observed remarks.

4.1 Small size problem (8 Machines X 8 Products) Case Study

The process sequence information along with the production volume for 8 products using the 8 machines is shown below in Table 4.1.

Table 4.1 Machine sequence information for all products with production volume

Products	Sequence (Machines)	Production Volume
A	7,8,4,6,2	800
B	5,3,8,1	700
C	4,8,2,5,7,2	1000
D	3,1,5,7,5	600
E	1,4,6,8,2	800
F	5,7,2,3	900
G	3,6,8,1	1000
H	4,7,2,6,4	700

4.1.1 Number of cells calculation

From the algorithm (3.2.3),

Number of machines, **m = 8**

Number of parts, **n = 8**

Since number of machines, **m ≤ 24**,

$$\mathbf{L_{c\ min} = 2}$$

$$\begin{aligned} L_{c\ max} &= \left(\frac{\text{no.ofmc's}}{L_{c\ min}} \right) \\ &= (8/2) \end{aligned}$$

$$\mathbf{i.e. L_{c\ max} = 4}$$

Since number of parts, **n ≤ 24**,

$$\mathbf{L_{f\ min} = 2,}$$

$$\begin{aligned} L_{f\ max} &= \left(\frac{\text{no.ofparts}}{L_{f\ min}} \right) \\ &= \left(\frac{8}{2} \right) \end{aligned}$$

$$\mathbf{i.e. L_{f\ max} = 4}$$

Minimum cells required,

$$\begin{aligned} p_{\min} &= \text{Max} (L_{c\ min}, L_{f\ min}) \\ &= \text{Max} (2, 2) \end{aligned}$$

$$\mathbf{p_{\min} = 2}$$

Maximum cells required,

$$\begin{aligned} p_{\max} &= \text{Min} (L_{c\ max}, L_{f\ max}) \\ &= \text{Min} (4, 4) \end{aligned}$$

$$\mathbf{p_{\max} = 4}$$

Setting $L_f = L_{f \min}$ and $U_f = 8$,

$L_f = 2$ and $U_f = 8$ (lower and upper limits on part family size)

Setting $L_c = L_{c \min}$ and $U_c = 8$,

$L_c = 2$ and $U_c = 8$ (lower and upper limits on machine cell size)

The From -to chart for all the machines are listed in Table 4.2

Table 4.2 From-to chart for 8 machines

	1	2	3	4	5	6	7	8
1				800	600			
2			900		1000	700		800
3	600					1000		700
4						1600	700	1000
5			700				2500	1000
6		800		700	0			1800
7		2600			600			800
8	1700	1000		800				

4.1.2 Cell formation

The From-to chart between different machines (for all the products) is taken as input for the formation of cells, by minimizing the intercellular movement as the criterion for cell formation (equation 3.7). Since the minimum number of cells to be formed is 2 (4.1.1), starting with the minimum cell configuration.

4.1.3 2- Cell Configuration

The possible combination of machines and products for a 2-cell configuration is shown in Table 4.3.

Table 4.3 2-Cell configuration with their corresponding products and machines

	Machines	Parts
Cell 1	1,3	B,D
Cell 2	2,4,5,6,7,8	A,C,E,F,G,H

Total inter-cellular movement for the above configuration is accounted to 6300.

4.1.3.1 Performance Measure

In order to validate the performance of the cells formed, compactness and bond efficiency measures are used (3.3.4.2).

GT efficiency= 0.7595.

Compactness= 0.675.

Bond Efficiency, β = 0.7173.

4.1.3.2 Relative placement of Cells

Figure 4.1 showing arrangement of cells with respect to each other based on intercellular movement established between them,



Figure 4.1 Arrangement of cells

4.1.3.3 Relative placement of machines inside cells

Figure 4.2 shows arrangement of machines within cells and also the best possible machine arrangement for the 2-cell configuration.

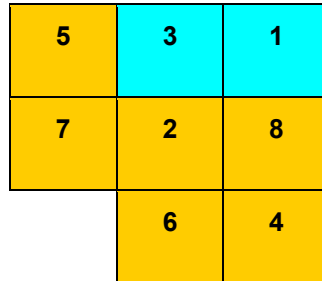


Figure 4.2 Arrangement of machines within cells

For the 2-cell configuration in Figure 4.2, the total material handling cost is \$ **171264**. Similar calculations are performed for the remaining cell configurations.

4.1.4 3-Cell Configuration

The possible combination of machines and products for a 3-cell configuration is shown in Table 4.4.

Table 4.4 3-Cell configuration with their corresponding products and machines

	Machines	Parts
Cell 1	2,4,6,8	A,C,E,H
Cell 2	1,3	D,G
Cell 3	5,7	B,F

Total inter-cellular movement for the above configuration is accounted to 11600.

4.1.4.1 Performance measure

GT efficiency = 0.5575.

Compactness = 0.875.

Bond efficiency $\beta = 0.7163$.

4.1.4.2 Relative placement of cells

Figure 4.3 showing arrangement of cells with respect to each other



Figure 4.3 Arrangement of cells

4.1.4.3 Relative placement of machines inside cells

Figure 4.4 shows arrangement of machines within cells and also the best possible machine arrangement for 3-cell configuration.

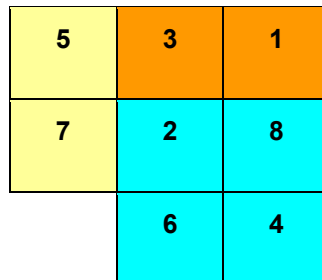


Figure 4.4 Arrangement of machines within cells

For the 3-cell configuration in Figure 4.4 the total material handling cost is **\$ 171264**.

4.1.5 4-Cell Configuration

The possible combination of machines and products for a 4-cell configuration is shown in Table 4.5.

Table 4.5 4-Cell configuration with their corresponding products and machines

	Machines	Parts
Cell 1	1,3	B,G
Cell 2	5,7	D,F
Cell 3	4,6	E,H
Cell 4	2,8	A,C

Total inter-cellular movement for the above configuration is accounted to 16600.

4.1.5.1 Performance measure

GT efficiency = 0.3664.

Compactness = 1.

Bond efficiency $\beta = 0.6832$.

4.1.5.2 Relative placement of cells

Figure 4.5 showing arrangement of cells with respect to each other

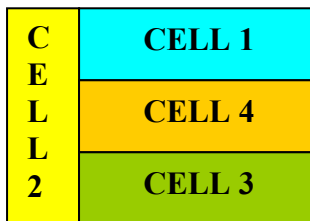


Figure 4.5 Arrangement of cells

4.1.5.3 Relative placement of machines inside cells

Figure 4.6 shows arrangement of machines within cells and also the best possible machine arrangement for 4-cell configuration.

5	3	1
7	2	8
	6	4

Figure 4.6 Arrangement of machines within cells

For the 4-cell configuration in Figure 4.6 total material handling cost is \$ **171264**.

4.1.6 Results discussion

Since the material handling cost for all the three configurations (2, 3, and 4) account for the same value, the performance measure can be used to select the best configuration. The bond efficiency β of cell configuration 2 has the highest value (0.7173) when compared with other configurations, hence we select cell configuration 2 for the given production plan.

4.2 Medium Size problem (30 machines X 15 Products)

The process sequence information along with production volume for 15 products using the 30 machines is shown in Table 4.6.

Table 4.6 Machine sequence information for all products with production volume

Products	Sequence (Machines)	Production Volume
A	4-9-2-5-4-24-10-27-23-18	800
B	6-1-13-3-11-16-5-20-6-23-30-28-26	1200
C	18-14-1-15-4-14-8-17-21-19-8-22-12	1000
D	9-16-17-7-29-2-25-20-7-5-20-24-22-27-28	900
E	20-14-4-17-22-10-24-17-10-26-30-12	450
F	15-14-17-10-18-5-19-1-26-23-29-21	600
G	10-6-2-14-20-8-12-3-25-28-25-22	1000
H	19-12-21-17-1-23-17-4-9-24-27-24-7-30	600
I	3-26-8-22-12-16	900
J	18-21-16-23-14-28-11-26-7-30-2	1500
K	26-22-4-18-28-18-1-13-30-10	500
L	24-5-29-9-27-14-21-19	800
M	12-9-6-3-16-26-20-29-23	700
N	1-4-7-10-14-18-22-26-29-18	1200
O	25-28-17-21-9-13-5-2	750

4.2.1 Number of cells calculation

From the algorithm (3.2.3),

Number of machines, **m = 30**

Number of parts, **n = 15**

Since number of machines, $m > 24$,

$$L_{c \min} = \left(\frac{\text{no.ofmc's}}{12} \right),$$
$$= (30/12)$$

i.e. $L_{c \min} = 2.5 \sqcup 3$

$$L_{c \max} = \left(\frac{\text{no.ofmc's}}{L_{c \min}} \right)$$
$$= (30/3)$$

i.e. $L_{c \max} = 10$

Since number of parts, $n \leq 24$,

$L_{f \min} = 2$,

$$L_{f \max} = \left(\frac{\text{no.ofparts}}{L_{f \min}} \right)$$
$$= \left(\frac{15}{2} \right)$$

i.e. $L_{f \max} = 7.5 \sqcup 7$

Minimum cells to form,

$$p_{\min} = \text{Max} (L_{c \min}, L_{f \min})$$
$$= \text{Max} (3, 2)$$

$p_{\min} = 3$

Maximum cells to form,

$$p_{\max} = \text{Min} (L_{c \max}, L_{f \max})$$
$$= \text{Min} (10, 7)$$

$p_{\max} = 7$

Setting $L_f = L_{f \min}$ and $U_f = 12$,

$L_f = 2$ and $U_f = 12$ (lower and upper limits on part family size)

Setting $L_c = L_{c \min}$ and $U_c = 12$,

$L_c = 3$ and $U_c = 12$ (lower and upper limits on machine cell size)

The From - to chart relationship for all the machines are listed below in Figure 4.7,

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0	0	0	1200	0	0	0	0	0	0	0	0	1700	0	1000	0	0	0	0	0	0	0	600	0	0	600	0	0	0	0
2	0	0	0	0	800	0	0	0	0	0	0	0	0	1000	0	0	0	0	0	0	0	0	0	0	900	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1150	0	0	0	0	0	0	0	0	0	900	0	0	0	0
4	0	0	0	0	0	0	1200	0	1400	0	1200	0	0	1000	0	0	0	0	0	0	0	0	0	800	1000	0	0	0	0	0
5	0	750	0	800	0	0	0	0	0	0	0	0	0	0	0	0	0	0	600	2100	0	0	0	0	0	0	0	0	800	0
6	1200	1000	700	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1200	0	0	0	0	0	0	0
7	0	0	0	0	900	0	0	0	0	1200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	900	2100
8	0	0	0	0	0	0	0	0	0	0	0	1000	0	0	0	0	1000	0	0	0	0	1900	0	0	0	0	0	0	0	0
9	0	800	0	0	0	700	0	0	0	0	0	0	750	0	0	900	0	0	0	0	0	0	450	600	450	0	800	0	0	0
10	0	0	0	0	0	1000	0	0	0	0	0	0	0	1200	0	0	0	600	0	0	0	0	0	0	0	0	800	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1200	0	0	0	0	0	0	0	0	0	1500	0	0	0	0
12	0	0	1000	0	0	0	0	0	700	0	0	0	0	0	0	900	0	0	0	0	600	0	0	0	0	0	0	0	0	0
13	0	0	1650	0	750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	500
14	1000	0	0	0	0	0	0	1000	0	0	0	0	0	0	0	600	1200	0	1000	800	0	0	0	0	0	0	1500	0	0	0
15	0	0	0	1000	0	0	0	0	0	0	0	0	0	600	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	1200	0	0	450	0	0	0	0	0	0	0	900	0	0	0	450	0	1500	0	0	700	0	0	0	0	0
17	600	0	0	600	0	0	900	0	0	600	0	0	0	0	0	0	0	0	0	0	1750	0	0	0	0	0	0	0	0	0
18	500	0	0	0	600	0	0	0	0	0	0	0	0	1000	0	0	0	0	0	0	1500	1200	0	0	0	0	0	500	0	0
19	600	0	0	0	0	0	0	1000	0	0	0	600	450	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	1200	900	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	900	0	0	0	0	700	0
21	0	0	0	0	0	0	0	0	1200	0	0	0	0	0	0	1500	600	0	1800	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	500	0	0	0	0	0	0	0	1900	0	0	0	0	0	0	0	0	0	0	0	0	0	1200	900	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	1500	0	450	600	800	0	0	0	0	0	0	0	0	0	600	1200	0
24	0	0	0	0	800	0	600	0	0	800	0	0	0	0	0	0	0	0	0	0	0	900	0	0	0	0	600	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	900	0	1000	0	0	0	0	0	1750	0	450
26	0	0	0	0	0	0	1500	900	0	0	0	0	0	0	0	0	0	0	0	700	0	500	600	0	0	0	0	0	1200	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	800	0	0	0	0	0	0	0	0	800	600	0	0	0	900	0	0
28	0	0	0	0	0	0	0	0	0	0	1500	0	0	0	0	0	750	500	0	0	0	0	0	0	1000	1200	0	0	0	0
29	0	900	0	0	0	0	0	0	800	0	0	0	0	0	0	0	0	1200	0	0	0	0	700	0	0	0	0	0	0	0
30	0	1500	0	0	0	0	0	0	0	500	450	0	0	0	0	0	0	0	0	0	0	600	0	0	0	0	0	1200	0	0

Figure 4.7 From-to chart for 30 machines

4.2.2 Cell formation

The From-to relationship chart between different machines (for all the products) is taken as input for the formation of cells, by minimizing the intercellular movement as the criterion for cell formation (equation 3.7).

2-cell configuration is not possible in this case, since number of machines in a cell cannot exceed the value of 12. When the numbers of cells are 2, then 15 machines should be placed in a cell, which is not possible for this algorithm. So, the minimum number of cells to be formed will be 3.

4.2.3 3-cell configuration

Table 4.7 shows the possible combination of machines and products for a 3-cell configuration.

Table 4.7 3-cell configuration with their corresponding products and machines

Total intercellular flow = 66650.

4.2.3.1 Performance measure

GT efficiency = 0.4743.

Compactness = 0.52381.

	Machines	Parts
Cell 1	8,12,17,22,24,30	E,I
Cell 2	2,3,6,7,9,11,16,20,23,25,26,28	B,D,G,J,M,O
Cell 3	1,4,5,10,13,14,15,18,19,21,27,29	A,C,F,H,K,L,N

Bond efficiency $\beta = 0.4991$.

4.2.3.2 Relative placement of cells

Figure 4.8 shows the arrangement of cells with respect to each other.

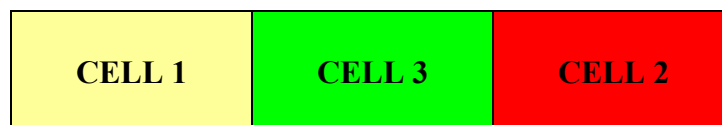


Figure 4.8 Arrangement of cells

4.2.3.3 Relative placement of machines inside cell

Figure 4.9 showing the best possible arrangement of cells and machines within cells for 3-cell configuration.

	29	18	27	13	23	28	26	7	2
24	30	14	10	1	16	25	11	20	
17	19	21	4	15	9	3	6		
12	22	8	5						

Figure 4.9 Arrangement of machines within cells

For the 3-cell configuration Figure 4.9, the total material handling cost is **\$2106084**

4.2.4 4-Cell Configuration

Table 4.8 shows the possible combination of machines and products for a 4-cell configuration.

Table 4.8 4-Cell configuration with their corresponding products and machines

	Machines	Parts
Cell 1	24,27	D,L
Cell 2	2,3,5,6,11,12,13,16,20,23,25,28	A,B,E,G,I,M,O
Cell 3	1,4,7,10,14,15,18,22,26,29,30	F,J,K,N
Cell 4	8,9,17,19,21	C,H

Total intercellular flow = 66850.

4.2.4.1 Performance measure

GT efficiency = 0.4727.

Compactness = 0.5563.

Bond efficiency $\beta = 0.5145$.

4.2.4.2 Relative placement of cells

Figure 4.10 shows arrangement of cells with respect to each other.

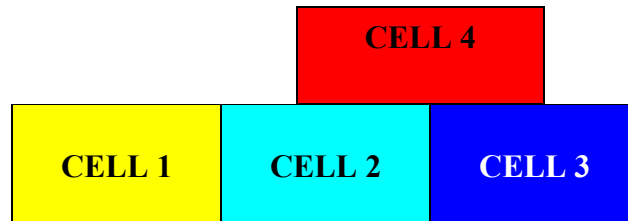


Figure 4.10 Arrangement of cells

4.2.4.3 Relative placement of machines inside cell

Figure 4.11 showing the best possible arrangement of cells and machines within cells for 4-cell configuration.

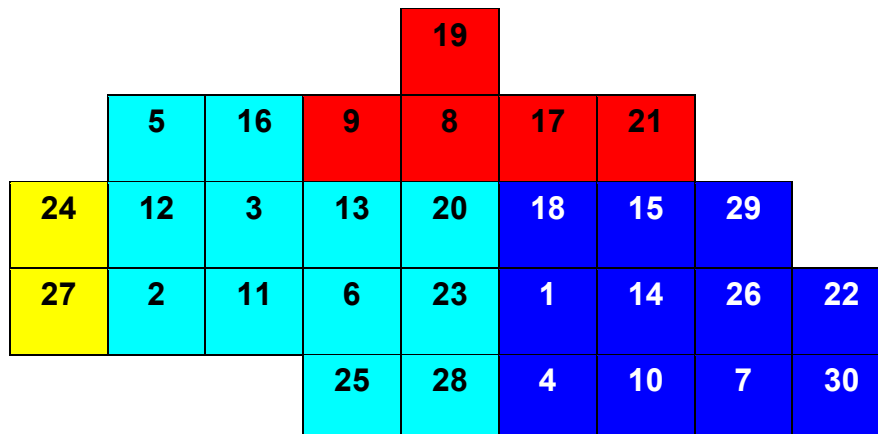


Figure 4.11 Arrangement of machines within cells

For the 4-cell configuration in Figure 4.11, total material handling cost is **\$1870280**.

4.2.5 5-Cell Configuration

Table 4.9 shows the possible combination of machines and products for a 5-cell configuration.

	Machines	Parts
Cell 1	4,9,27	A,L
Cell 2	1,6,13,28	B,K
Cell 3	11,16,21,23,30	E,J
Cell 4	3,8,10,12,14,15,17,18,19,22,26,29	C,F,G,H,I,M,N
Cell 5	2,5,7,20,24,25	D,O

Table 4.9 5-Cell configuration with their corresponding products and machines

Total intercellular flow = 83650.

4.2.5.1 Performance measure

GT efficiency = 0.340.

Compactness = 0.5916.

Bond efficiency $\beta = 0.4658$.

4.2.5.2 Relative placement of cells

Figure 4.12 shows arrangement of cells with respect to each other.

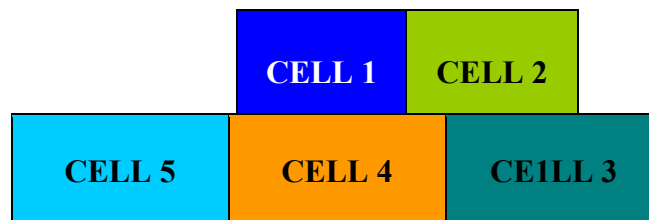


Figure 4.12 Arrangement of cells

4.2.5.3 Relative placement of machines inside cell

Figure 4.13 showing the best possible arrangement of cells and machines within cells for 5-cell configuration.

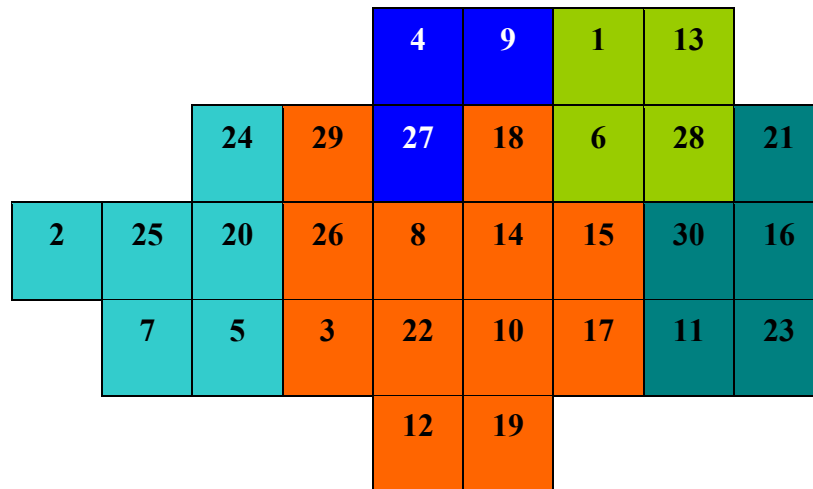


Figure 4.13 Arrangement of machines within cells

For the 5-cell configuration in Figure 4.13 total material handling cost is **\$1868754**.

4.2.6 6-Cell Configuration

Table 4.10 shows the possible combination of machines and products for a 6-cell configuration.

Table 4.10 6-Cell configuration with their corresponding products and machines

	Machines	Parts
Cell 1	8,12,15,17,21,22	C,I
Cell 2	24,25	G,H
Cell 3	1,3,6,13,20	B,M
Cell 4	2,4,5,7,9,10,14,18,26,27,28	A,D,K,N,O
Cell 5	11,16,23,30	E,J
Cell 6	19,29	F,L

Total intercellular flow = 81550.

4.2.6.1 Performance measure

GT efficiency = 0.3568.

Compactness = 0.464.

Bond efficiency $\beta = 0.4104$.

4.2.6.2 Relative placement of cells

Figure 4.14 shows arrangement of cells with respect to each other

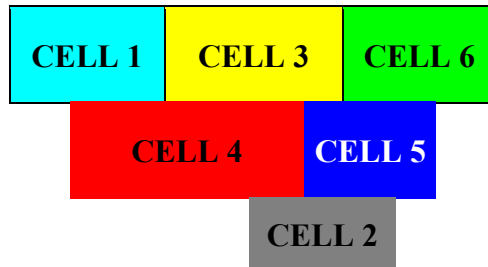


Figure 4.14 Arrangement of cells

4.2.6.3 Relative placement of machines inside cell

Figure 4.15 showing the best possible arrangement of cells and machines within cells for 6-cell configuration.

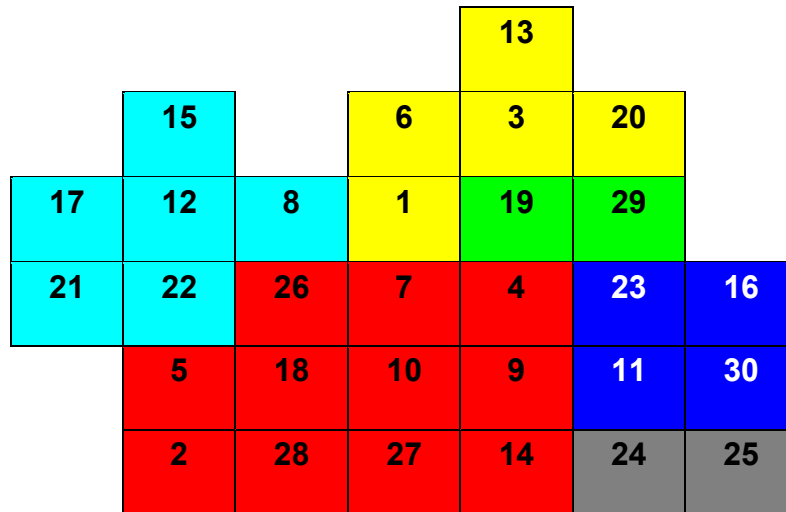


Figure 4.15 Arrangement of machines within cells

For the 6-cell configuration in Figure 4.15 total material handling cost is **\$1847192**.

4.2.7 7-Cell Configuration

Table 4.11 shows the possible combination of machines and products for a 7-cell configuration.

Table 4.11 7-Cell configuration with their corresponding products and machines

	Machines	Parts
Cell 1	1,8,14,15,17,21	C,F
Cell 2	12,22,25	G,I
Cell 3	2,5,13	K,O
Cell 4	4,10,18,29	A,N
Cell 5	19,24,27	H,M
Cell 6	9,7,20	D,E
Cell 7	3,6,11,16,23,26,28,30	B,J,M

Total intercellular flow = 92100.

4.2.7.1 Performance measure

GT efficiency = 0.2736.

Compactness = 0.6764.

Bond efficiency $\beta = 0.475$.

4.2.7.2 Relative placement of cells

Figure 4.16 shows arrangement of cells with respect to each other

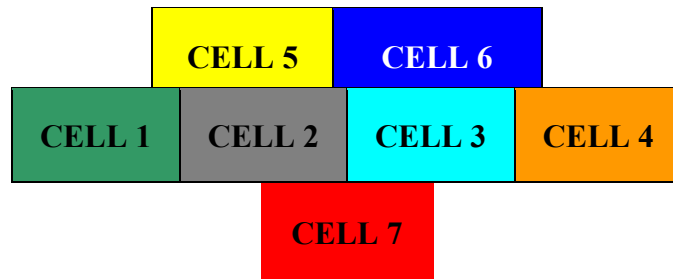


Figure 4.16 Arrangement of cells

4.2.7.3 Relative placement of machines inside cell

Figure 4.17 showing the best possible arrangement of cells and machines within cells for 7-cell configuration.

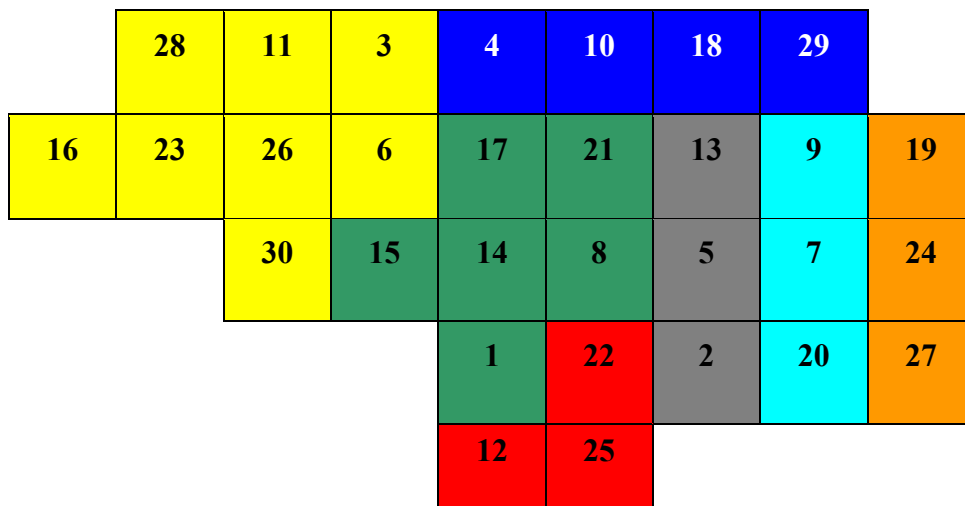


Figure 4.17 Arrangement of machines within cells

For the 7-cell configuration in Figure 4.17 total material handling cost is **\$1897307**.

4.2.8 Results discussion

Since 6-cell configuration results in a reduced MH cost when compared with the other cell configurations, the layout of that configuration is selected for the given production plan.

4.3 Large size problem (60 machines X 19 products)

The proposed method was used to solve a large size problem containing 60 machines and 19 products, whose process sequence and production volume are shown in Table 4.12.

Table 4.12 Machine sequence information for all products with production volume

Products	Sequence (Machines)	Production Volume
1	31,29,56,34,60,37,4,6,44,10,50,42,32,1,26,58,9,11,47,22,16,54,23,14,40, 46,8	90
2	22,51,45,47,49,30,35,33,38,2,17,15,20,12,39,57,9,53,27,7,59,5,41,24,25,36,43,55	60
3	35,48,43,57,3,33,8,21,16,30,26,46,4,6,18,52,45,51, 41, 13,28,56,10,21,23,60,49,37	55
4	39,13,20,8,54,42,31,5,34,10,37,17,29,39,44,15, 47, 56, 20,27,50,2,24	85
5	13,59,33,40,21,49,28,45,3,43,9,18,53,47,25,51, 1,30,11,7,57,55,36,5	70
6	46,22,52,56,58,4,35,48,40,37,6,46,40,28,14,12, 19, 50, 24,10,33,43,59,31,26,54	65
7	8,60,1,50,23,8,39,33,44,25,37,30,19,5,12,48,14,35, 17, 28,45,41,54,57	85
8	32,45,34,16,49,30,26,19,23,12,38,9,40,5,42,28, 21,36,52,52,47,3,58	75
9	16,57,36,9,20,12,34,46,36,40,22,29,52,14,26, 16,48, 50, 1,28,32,44,6,42,54,60,4,24	80
10	2,53,15,49,31,2,45,10,5,8,47,51,35,27,25,18,38,58, 43, 55,23,29,21,33,12,41,14	60
11	13,39,17,13,30,9,26,11,28,52,50,36,23,19,46,54,42, 56, 3,39,33,48,44,6,59	90
12	30,21,26,19,45,24,55,53,47,4,29,27,34,49,39, 32,12, 37, 7,20,18,57,15,11,9,42,60,	55
13	25,26,38,48,31,5,58,22,50,3,13,28,46,8,36,34, 32,10,19,54,41,16,60,42,52,44	75
14	22,23,59,33,17,46,41,35,39,20,27,57,37,51,12,30,43,6,36,49,25,55,21,18,15,53,28,9	65
15	4,38,7,16,32,29,19,11,53,50,42,24,1,35,14,27, 40,45,21,56	85
16	12,50,18,28,52,43,39,41,4,8,46,54,34,37,22,15, 31, 60, 25,19,56,58	70
17	7,44,35,13,10,46,37,29,5,42,40,38,30,15,44,32, 27,2,17,23,51,25,20,48,58	60
18	6,12,3,9,29,45,14,19,47,43,33,36,6,16,39,26,22,52, 49, 57	80
19	15,25,30,1,7,18,13,56,50,37,40,34,32,46,44,20, 42, 27, 11,23,9,4,48,52	75

4.3.1 Number of cells calculation

Calculating number of cells required,

From the algorithm,

Number of machines, **m = 60**

Number of parts, **n = 19**

Since number of machines, **m > 24**,

$$L_{c \min} = \left(\frac{\text{no.ofmc's}}{12} \right),$$
$$= (60/12)$$

i.e. $L_{c \min} = 5$

$$L_{c \max} = \left(\frac{\text{no.ofmc's}}{L_{c \min}} \right)$$
$$= (60/5)$$

i.e. $L_{c \max} = 12$

Since number of parts, **n ≤ 24**,

$L_{f \min} = 2$,

$$L_{f \max} = \left(\frac{\text{no.ofparts}}{L_{f \min}} \right)$$
$$= \left(\frac{19}{2} \right)$$

i.e. $L_{f \max} = 9.5 \square 9$

Minimum cells required,

$$p_{\min} = \text{Max} (L_{c \min}, L_{f \min})$$
$$= \text{Max} (5, 2)$$

$p_{\min} = 5$

Maximum cells required,

$$p_{\max} = \text{Min} (L_{c \max}, L_{f \max})$$

$$= \text{Min} (12, 9)$$

$$p_{\max} = 9$$

Setting $L_f = L_{f \min}$ and $U_f = 12$,

$$L_f = 2 \text{ and } U_f = 12 \text{ (lower and upper limits on part family size)}$$

Setting $L_c = L_{c \min}$ and $U_c = 12$,

$$L_c = 5 \text{ and } U_c = 12 \text{ (lower and upper limits on machine cell size)}$$

4.3.2 Cell formation

2, 3, 4-cell configurations are not possible in this case, since number of machines in a cell cannot exceed the value of 12. When the numbers of cells are 2, 3, 4 then at least 30, 20, 15 machines should be placed in a cell respectively, which is not possible from the algorithm. So, the minimum number of cells to be formed will be 5.

4.3.3 5-Cell Configuration

Table 4.13 shows the possible combination of machines and products for a 5-cell configuration.

Table 4.13 5-Cell configuration with their corresponding products and machines

	Machines	Products
Cell 1	10,13,17,23,31,34,39,42,44,50,54,56	1,4,11,13,19
Cell 2	3,5,22,24,26,30,32,38,45,47,55,59	2,8
Cell 3	1,4,8,19,28,33,35,37,41,46,48,60	3,6,7
Cell 4	6,9,12,14,16,20,36,40,43,49,52,57	5,9,18
Cell 5	2,7,11,15,18,21,25,27,29,51,53,58	10,12,14,15,16,17

Total intercellular flow = 24955.

4.3.3.1 Performance measure

GT efficiency = 0.2402.

Compactness = 0.7061.

Bond efficiency β = 0.4732.

4.3.3.2 Relative placement of cells

Figure 4.18 shows arrangement of cells with respect to each other

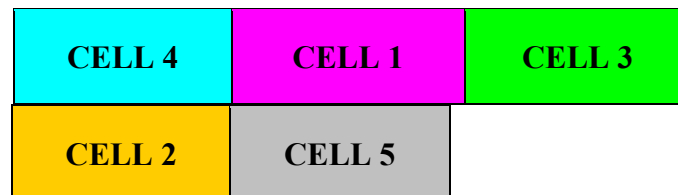


Figure 4.18 Arrangement of cells

4.3.3.3 Relative placement of machines inside cell

Figure 4.19 showing the best possible arrangement of cells and machines within cells for 5-cell configuration.

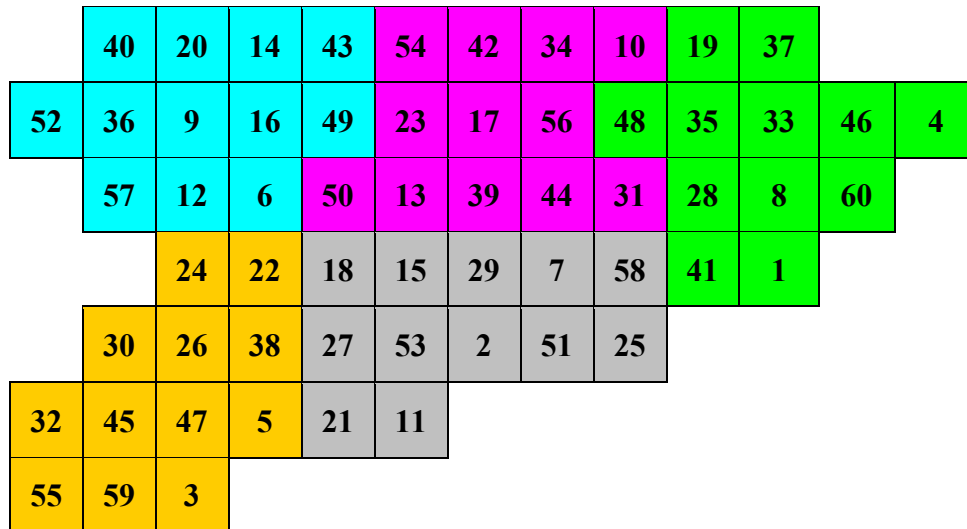


Figure 4.19 Arrangement of machines within cells

For the 5-cell configuration in Figure 4.19 total material handling cost is **\$758587**.

4.3.4 6-Cell Configuration

Table 4.14 shows the possible combination of machines and products for a 6-cell configuration.

Table 4.14 6-Cell configuration with their corresponding products and machines

	Machines	Products
Cell 1	10,17,19,24,29,31,39,42,47,50,54,56	1,4,11,15
Cell 2	2,5,13,32,34,38,44,48,51,53,58	10,13,17
Cell 3	3,16,21,23,26,30,35,49	3,8,14
Cell 4	4,7,11,15,27	12,19
Cell 5	1,8,18,22,25,28,33,37,41,45,57,60	5,7,16
Cell 6	6,9,12,14,20,36,40,43,46,52,55,59	2,6,9,18

Total intercellular flow = 25660.

4.3.4.1 Performance measure

GT efficiency = 0.2187.

Compactness = 0.7136.

Bond efficiency β = 0.4662.

4.3.4.2 Relative placement of cells

Figure 4.20 shows arrangement of cells with respect to each other.

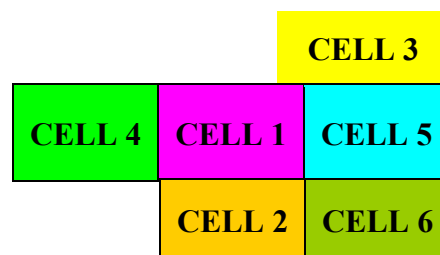


Figure 4.20 Arrangement of cells

4.3.4.3 Relative placement of machines within cell

Figure 4.21 showing the best possible arrangement of cells and machines inside cells for 6-cell configuration.

					30	35	26		
				3	49	21	23		
27	7	54	31	29	16	35	60	57	41
11	15	39	17	19	47	33	8	28	45
4	24	10	56	50	42	25	1	37	18
		44	32	53	2	55	52	22	
		13	34	48	5	40	43	14	
			51	38	58	46	36	12	6
							59	9	20

Figure 4.21 Arrangement of machines within cells

For the 6-cell configuration in Figure 4.21 total material handling cost is **\$691911**.

4.3.5 7-Cell configuration

Table 4.15 shows the possible combination of machines and products for a 7-cell configuration.

Table 4.15 7-Cell configuration with their corresponding products and machines

	Machines	Products
Cell 1	6,10,14,17,19,31,33,40,46,54,56,58	1,6,11
Cell 2	1,21,28,30,38,42,45,47,49,53,59	5,8,14,15
Cell 3	13,15,20,23,27,29,32,34,37,39,44,50	4,17,19
Cell 4	3,9,12,16,22,26,36,48,52,57	9,13,18
Cell 5	2,5,25,35,51	7,10
Cell 6	4,18,41,43,60	3,16
Cell 7	7,8,11,24,55	2,12

Total intercellular flow = 26540.

4.3.5.1 Performance measure

GT efficiency = 0.1919.

Compactness = 0.7898.

Bond efficiency β = 0.4909.

4.3.5.2 Relative placement of cells

Figure 4.22 shows arrangement of cells with respect to each other.

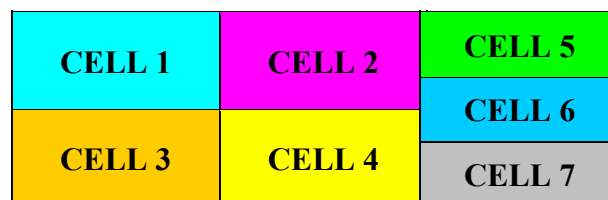


Figure 4.22 Arrangement of cells

4.3.5.3 Relative placement of machines inside cell

Figure 4.23 showing the best possible arrangement of cells and machines within cells for 7-cell configuration.

33	54	46	14	49	30	42	1	2	51
31	56	19	17	21	38	53	45	5	35
10	6	58	40	47	28	59	60	25	8
34	15	44	32	36	9	3	41	4	24
27	20	29	37	26	16	12	43	18	55
23	13	39	50	22	52	48	57	11	7

Figure 4.23 Arrangement of machines within cells

For the 7-cell configuration in Figure 4.23 total material handling cost is **\$678205**.

4.3.6 8-Cell Configuration

Table 4.16 shows the possible combination of machines and products for an 8-cell configuration.

Table 4.16 8-Cell configuration with their corresponding products and machines

	Machines	Products
Cell 1	3,13,26,37,41,59	3,11
Cell 2	42,45,51,53,55	2,10
Cell 3	7,11,18,21,30	5,12
Cell 4	8,10,19,28,31,46,50,54,56,58,60	1,6,13,16
Cell 5	1,4,9,14,23,25,32,34,38,40,52	8,15,19
Cell 6	16,29,35,36,44,48,49	9,17
Cell 7	2,5,15,17,20,24,27,39,47	4,7
Cell 8	6,12,22,33,43,57	14,18

Total intercellular flow = 27685.

4.3.6.1 Performance measure

GT efficiency = 0.1571.

Compactness = 0.7756.

Bond efficiency β = 0.4664.

4.3.6.2 Relative placement of cells

Figure 4.24 shows arrangement of cells with respect to each other.

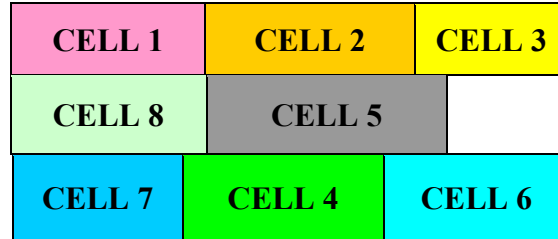


Figure 4.24 Arrangement of cells

4.3.6.3 Relative placement of machines inside cell

Figure 4.25 showing the best possible arrangement of cells and machines within cells for 8-cell configuration.

		26	3	59	51	45	11	21	
		41	37	13	55	53	30	18	7
		43	12	57	40	42	32	34	
		33	6	22	15	1	38	4	52
24	17	20	60	58	10	25	23	9	49
2	39	5	56	50	8	19	36	44	35
27	47	14	31	28	46	54	16	29	48

Figure 4.25 Arrangement of machines within cells

For the 8-cell configuration in Figure 4.25 total material handling cost is **\$687251**.

4.3.7 9-Cell Configuration

Table 4.17 shows the possible combination of machines and products for a 9-cell configuration.

Table 4.17 9-Cell configuration with their corresponding products and machines

	Machines	Products
Cell 1	4,18,41,43,48,60	3,16
Cell 2	6,10,13,14,19,31,33,40,46,58	2,10
Cell 3	16,28,35,36,44	9,17
Cell 4	1,17,21,30,38,42,47,49	5,8,14
Cell 5	6,10,14,19,31,33,40,46	1,6
Cell 6	7,11,15,27,29	12,19
Cell 7	23,34,39,50,54	4,11
Cell 8	2,5,8,24,25,26,37,52,57	7,13
Cell 9	3,9,12,22,32,56	15,18

Total intercellular flow = 28835.

4.3.7.1 Performance measure

GT efficiency = 0.1220.

Compactness = 0.7165.

Bond efficiency β = 0.4193.

4.3.7.2 Relative placement of cells

Figure 4.26 shows arrangement of cells with respect to each other

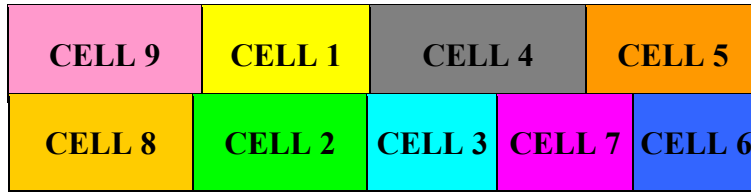


Figure 4.26 Arrangement of cells

4.3.7.3 Relative placement of machines inside cell

Figure 4.27 shows the best possible arrangement of cells and machines within cells for 9-cell configuration.

9	3	12	18	4	43	17	47	1	58	13	33
22	32	56	41	60	48	49	30	38	14	19	31
25	8	52	51	45	20	21	42	46	40	10	6
37	5	57	55	53	28	16	54	39	50	11	15
2	26	24	59	35	44	36	23	34	29	27	7

Figure 4.27 Arrangement of machines within cells

For the 9-cell configuration in Figure 4.27 total material handling cost is **\$819818**.

4.3.8 Results discussion

Since 7-cell configuration results in a reduced MH cost when compared with the other cell configurations, the layout of that configuration is selected for the given production plan.

4.4 Conclusion

In this chapter the feasibility of the new method when applied to small, medium and large size problems was proved using three different case studies. For small size case study considered, where the material handling cost remains the same for a number of cell configurations, performance measure of each configuration was compared to select the best configuration for the given production plan (refer 4.1.6). For medium and large size case studies, material handling cost was used to select the best configuration for a given production plan (refer 4.2.8, 4.3.8).

CHAPTER 5

CONCLUSIONS AND FUTURE RESEARCH

In this work, a systematic methodology to construct cellular layouts using GT technique for large size problems has been developed. Previous researches in this field have addressed heuristics that can be used to solve only medium size problems. A mathematical model that uses reduced intercellular count as a criterion for cell formation is developed. The developed model includes details like machine sequence, production volume and machine revisits for formation of cells. A performance measure that is used to evaluate the cells being formed is proposed after some modifications in the existing method from Nair & Narendran (1998). Once the cells are evaluated, an algorithm to arrange cells and machines inside cell is also proposed. In order to evaluate the entire methodology three different case studies were used, with the size of the problem addressing small, medium and large size.

The methodical approach to construct cellular layouts starts with formation of cells where in grouping of parts and machines are done based on similarity established between them. A new methodology is developed to form part/machine cells of different configuration based on the given production plan. The methodology is run for different part/machine configurations with 2 cell configuration being the least configuration in case of small size problem (machines or parts limited to 24). In case of medium and large size problem (more than 24 machines and parts) the minimum cell configuration is calculated using a small mathematical model and the configuration is set based on the obtained value. The model is also used to calculate the maximum allowable cell configuration for a given production plan. Restrictions are placed on the number of machines and products that can be allotted to a cell configuration. Using

proficient evaluation criteria such as compactness and bond efficiency, all the cell configuration formed are evaluated.

Once the cell configurations are evaluated, separate layouts are developed for each cell depending on the amount of flow between machines within their respective cell. In the next phase of developed methodology, machines that are involved in inter-cellular movements are identified. After accurate estimation of the relationship that machines of a particular layout establishes with the machines of another layout, the locations of corresponding machines within their respective layouts are determined. The layouts are then placed relative to each other based on the amount of flow (inter-cellular movements) between them. Doing so, the material handling distance between machines is reduced. These layouts are then placed within the plant floor. Material handling cost is determined by considering the centroid to centroid distance between machines/departments using Euclidean method. All the above procedures are repeated till the maximum cell configuration for a given production plan is reached. The best configuration is selected based on the least material handling cost that a configuration accounts for. This process defines entire steps of the proposed approach.

The validity of the proposed approach was verified using small, medium and large size case studies. For the small size case, since all the cell configurations accounted for the same material handling cost, the configuration with the highest bond efficiency was chosen as the best configuration. For medium and large size case studies, the configuration that accounted for least material handling cost was selected as the best configuration for given production plan.

5.1 Conclusions

From the case study results, it is concluded that the proposed methodology can be used to solve large facility layout problems using GT. The developed model proved to be efficient irrespective of the size of the problem considered, even after inclusion of details such as machine sequence, production volume and machine revisits along with the performance measure for the cells formed. By restricting the number of cell configurations between an upper and lower limit, the model eliminated the possibility of unwanted configurations that increases the complexity of the problem. So for a large size facility layout problem, the proposed method can be used to get the actual number of intercellular movement between cells and also can be used to select the best configuration for a given production plan using reduced material handling cost as the criteria.

5.2 Future Research

The prime focus of this work was to develop a systematic approach to solve large facility layout problems using GT technique. Capacity requirement have not be considered for the present model. So the future research could address issues on capacity calculation for machines while grouping them. Computational time for the developed methodology when applied to different size problems can be considered in order to prove its efficiency over the other methods. In the present scenario, performance measures such as compactness and bond efficiency is calculated for the entire layout which might not be a good measure, because even if one of the cells has a lower efficiency the global efficiency of the system gets affected. So some few bad cell configurations can lower the total system efficiency. New measures have to be developed to find out the machines which are not necessarily being a part of the system. There are two perspectives to look at this problem. One is that the inclusion of that machine may not have any

effect on the efficiency of the system and other view is that the inclusion of that machine will definitely deteriorate the global efficiency of the system. In other words the measure should identify the machines to be eliminated from the grouping. This can be done by considering the utilization of the machine. Hence all the above discussed criteria should be addressed and studied.

REFERENCES

LIST OF REFERENCES

- G. Aiello, M. Enea, (2001). Fuzzy approach to the robust facility layout in uncertain production environments. *International Journal of Production Research*, Volume 39, Number 18, 4089 – 4101.
- Anita Lee-Post, (2000). Part family identification using a simple genetic algorithm. *International Journal of Production Research*, Volume 38, Number 4, 793 – 810.
- Askin R.G., Zhou M., (1997). A parallel station heuristic for the mixed-model production line balancing problem. *International Journal of Production Research*, Volume 35, Number 11 / November 1, 3095 – 3106.
- Askin R.G., Zhou M. (1998). Formation of independent flow-line cells based on operation requirements and machine capabilities. *Institute for Industrial Engineers Transaction*, 30, 319-329.
- Azadivar F, Tompkins G, (1999). Simulation optimization with qualitative variables and structural model changes: A genetic algorithm approach. *European Journal of Operational Research*, Volume 113, Number 1, 16, pp. 169-182(14).
- Azadivar, F and Wang J., (2000). Facility Layout Optimization Using Simulation and Genetic Algorithms. *International Journal of Production Research*, 38, 17, 4369-4383.
- Bhaba R. Sarker, Kun Li, (1997). Simultaneous route selection and cell formation: a mixed-integer programming time-cost model. *Integrated Manufacturing Systems*, Volume: 8 Issue: 6 Page: 374 – 377.
- Benjaffar, S. and Sheikhzadeh, M., (2000). Design of flexible plant layouts. *IIE Transactions*, 32, 309-322.
- Boe, W.J., Cheng, C.H., (1991). Close neighbour algorithm for designing cellular manufacturing systems. *International Journal of Production Research*, 29 (10), 2097–2116.
- R.E. Burkard, and F. Rendl, (1984). A Thermodynamically Motivated Simulation Procedure for Combinatorial Optimization Problems. *European Journal of Operational Research*, 17, pp. 169–174.
- Burbridge, J. L., (1969). An introduction to group technology. *Proceedings of an international seminar on group technology* (pp. 1-29), Turin.
- Burbidge, J. L., (1975). *The Introduction of Group Technology*, Heimemann, London.

- Chandrasekharan, M. P.; Rajagopalan, R., (1986). Ideal seed non-hierarchical clustering algorithm for cellular manufacturing. *International Journal of Production Research*. Vol. 24, pp. 451-64.
- Chandrasekharan, M. P., & Rajagopalan, R., (1989). Groupability: an analysis of the properties of binary data matrices for group technology. *International Journal of Production Research*, 27, 1035-1105.
- Chang Ouk Kim, Jun-Geol Baek and Jin Jun, (2005). A machine cell formation algorithm for simultaneously minimising machine workload imbalances and inter-cell part movements. *The International Journal of Advanced Manufacturing Technology*, Volume 26, Number 3, 268-275
- Chiang, W. C., (2001). Visual facility layout design system. *International Journal of Production Research*, 39, 1811–36.
- C. H. Cheng Y. P. Gupta W. H. Lee K. F. Wong, (1998). A TSP-based heuristic for forming machine groups and part families. *International Journal of Production Research*, Volume 36, Number 5 / May 1, 1325 – 1337.
- Choobineh, F., (1988). A framework for the design of cellular manufacturing systems. *International Journal of Production Research*, 26, 1161- 1172.
- C. Dimopoulos and N. Mort, (2004). Evolving knowledge for the solution of clustering problems in cellular manufacturing, *International Journal of Production Research*, Volume 42, Number 19, 4119 – 4133.
- Drolet, J.R. (1989). Scheduling virtual cellular manufacturing systems. Ph.D. dissertation, School of Industrial Engineering, Purdue University, West Lafayette, IN.
- Evans, G. W., Wilhelm, M. R. and Karwowski, W, (1987). A layout design heuristic employing the theory of fuzzy sets. *International Journal of Production Research*, 25(10), 1431-1450.
- Elin M. Wicks and Roderick J. Reasor, (1999). Designing cellular manufacturing systems with dynamic part populations. *IIE Transactions*, Volume 31, Number 1, 11- 20.
- Foulds, L. R., and Partotiv, F. V. (1998). Integrating the analytical hierarchy process and graph theory to model facilities layout. *Annals of Operations Research*, 82, 435-451.
- Francis, R., McGinnis, L., and White, J., (1992). *Facility Layout and Location: An Analytical Approach*, 2nd ed. (Englewood Cl. s, NJ: Prentice Hall).
- K.-Y. Gau, R. D. Meller, (1999). An iterative facility layout algorithm. *International Journal of Production Research*, Volume 37, Number 16 / November 15.

- Gen, M. and Cheng, R. (2000). *Genetic Algorithms and Engineering Optimization* (New York: John Wiley).
- Grobenlyn, J, (1998). Linguistic patter method for a workstation layout analysis. *International Journal of Production Research*, 26, 1779-1798.
- T. Gupta and H. Seifoddini., (1990). Production data based similarity coefficient for machine-component grouping decisions in the design of a cellular manufacturing system. *IJPR*, 28(7):1247-1269.
- G. Harhalakis, J. M. Proth and X. L. Xie, (1990). Manufacturing cell design using simulated annealing: An industrial application. *Journal of Intelligent Manufacturing*, Volume 1, Number 3 / September, 185-191.
- Heragu, S.S. Alfa. A.S., (1992). A distance assignment approach to the facility layout problem. *European Journal of Operational Research*, 1992, 57. 190-202.
- S.S. Heragu, (1992). A heuristic algorithm for identifying machine cells. *Information and Decision Technologies*, Forthcoming.
- Hugues Delmaire, André Langevin and Diane Riopel, (1997). Skeleton-based facility layout design using genetic algorithms. *Annals of Operations Research*, Volume 69, Number 0, 85-104.
- Islam K.M.S.; Sarker B. R., (2000). A similarity coefficient measure and machine-parts grouping in cellular manufacturing systems. *International Journal of Production Research*, Volume 38, Number 3, 15, pp. 699-720(22).
- A.A. Isler, (1998). A genetic algorithm approach for multiple criteria facility layout design. *International Journal of Production Research*, Volume 36, Number 6 / June 1, 1549 – 1569.
- JR Immer, (1953). *Materials handling*.
- Jaccard, P, (1908). *Novelles recgerches sur la distribution florale*. *Bulletin de la Société Vaudoise des Sciences Naturelles*, 44, 223-270.
- Jajodia, S., Minis. I. Harhalakia. G. Proth. J.-M., (1992). CLASS: Computerized layout solutions using simulated annealing. *International Journal of Production Research* 30 (I). 95 - 108.
- Jeon G.; Leep H.R.; Parsaei H.R., (1998). A cellular manufacturing system based on new similarity coefficient which considers alternative routes during machine failure. *Computers and Industrial Engineering*, Volume 34, Number 1, pp. 21-36(16).
- S. Kirkpatrick, C.D. Gelatt, and M.P. Vecchi, (1983). *Optimization by Simulated Annealing*. *Science*, 220, pp. 671–680.

- Kochhar, J.S. and Heragu, S.S., (1999). Facility layout design in a changing environment. *International Journal of Production Research*, 37, 2429-2446.
- Kouvelis, P. Chiang, W.C., (1992). A simulated annealing procedure for single row layout problems in flexible manufacturing systems. *International Journal of Production Research*, 30 (4), 717-732.
- K.R. Kumar and M.P. Chandrasekharan, (1990). Grouping efficacy: a quantitative criterion for goodness of block diagonal forms of binary matrices in group technology. *IJPR*, 28(2):233-243.
- A. Kusiak and M. Cho, (1992). Similarity coefficient algorithms for solving the group technology problem. *IJPR*, 30(11):2633-2646.
- Lacksonen, T. A. (1994). Static and dynamic facility layout problems with varying areas. *Journal of Operational Research Society*, 45, 59-69.
- Langevin, A., Montreuil, B. and Riopel, D., (1994). Spine layout design. *International Journal of Production Research*, 32, 429-442.
- P.S. Laursen, (1993). Simulated Annealing for the QAP-Optimal Tradeoff Between Simulation Time and Solution Quality. *European Journal of Operational Research*, 69, pp. 238–243.
- Lee, H., and Garcia-Diaz, A., (1993). A network flow approach to solve clustering problems in group technology, *International Journal of Production Research*, 31 (3), 603-612.
- Li, M.-L., Parkin, R.E., (1997). Group technology revisited: A simple and robust algorithm with enhanced capability. *International Journal of Production Research* 35 (7), 1969–1992.
- Mahesh, O.; Srinivasan, G., (2002). Incremental cell formation considering alternative machines, *International Journal of Production Research*. Vol. 40, no. 14, pp. 3291-3310. 20.
- Malakooti, B & Malakooti, NR & Yang, Z. (2004). Integrated group technology, cell formation, process planning, and production planning with application to the emergency room. *International Journal of Production Research*, 42(9), 1769 - 1786.
- J McAuley, Machine grouping for efficient production, *Production Engineer*.
- R.D. Meller, and Y.A. Bozer, (1991). A new Simulated Annealing Algorithm for the Facility Layout Problem. Technical Report 91-29, Department of Industrial and Operations Engineering, The University of Michigan.
- Meller R. D.; Gau K.-Y., (1996). Facility layout objective functions and robust layouts. *International journal of production research*, vol.34, n 10, pp. 2727-2742.

- Meller R.D.; Narayanan V.; Vance P.H., (1998). Optimal facility layout design. *Operations Research Letters*, Volume 23, Number 3, pp. 117-127(11).
- Meller R. D. and Gau, K.Y., (1999). An iterative facility layout algorithm. *International Journal of Production Research*, 37, 16, 3739- 3758.
- Montreuil, B. (1990). A modeling framework for integrating layout design and flow network design. *Proceedings of the Material Handling Research Colloquium*, Hebron, KY, 43-58
- Montreuil, R, Venkatadri, U. and Ratliff, H D., (1993). Generating a layout from a design skeleton, *IIE Transactions*, 25, 3-15.
- Mu-Chen Chen, (2003). Configuration of cellular manufacturing systems using association rule induction. *International Journal of Production Research*, Volume 41, 381 - 395
- Mukhopadhyay S. K.; Babu K.R; Sai K.V.V., (2000). Modified Hamiltonian chain: a graph theoretic approach to group technology. *International Journal of Production Research*, Volume 38, Number 11, 20 pp. 2459-2470(12).
- Nair, G. J. and Narendran, T.T., (1998). CASE: A clustering algorithm for cell formation with sequence data. *International Journal of Production Research*, 36, 1, 157-180.
- Ng S., (1993). Worst-case analysis of an algorithm for cellular manufacturing. *EJOR*, 69(3):384-398.
- O.F. Offodile, (1991). Application of similarity coefficient method to parts coding and classification analysis in group technology. *JMS*, 10(6):442-448.
- Offodile, O. F. Mehrez, A. Grznar, J., (1994). Cellular Manufacturing: A Taxonomic Review Framework. *Journal of Manufacturing Systems*, vol 13; number 3, pages 196.
- Rajasekharan, M., Peters, B. and Yang, T. (1998). A genetic algorithm for facility layout design in flexible manufacturing systems. *International Journal of Production Research*, 36, 1, 95-110.
- Ranson, G.M., 1972, *Group Technology* (London: McGraw Hill).
- Richard E.Billo, Bopaya Bidanda & David Tate (1996). A genetic cluster algorithm for the machine-component grouping problem. *Journal of Intelligent Manufacturing*, 7(3), 229-241.
- Ronald G. Askin & Ming Zhou (1998). Formation of independent flow-line cells based on operation requirements and machine capabilities. *Institute for Industrial Engineers Transactions*, 30(4), 319-329.

- Rosenblatt, M.J. and Lee, H.L., (1987). A robustness approach to facilities design. *International Journal of Production Research*, 25, 479-486.
- Saif Benjaafar, Sunderesh S. Heragu, Shahrukh A. Irani (2002). Next Generation Factory Layouts: Research Challenges and Recent Progress. *Interfaces-Providence- Institute of Management Sciences*, 32(6), 58 – 76.
- H. Seifoddini and M.Djassemi, (1991). The production data-based similarity coefficient versus jaccard's similarity coefficient. *Computers Industrial Engineering*, 21(1-4):263-266.
- Selim, H. M, R.G. Askin, and A. Vakharia., (1998). Cell formation in group technology: review, evaluation and directions for future research. *Computers and Industrial Engineering* 34(1):3-20.
- N. Singh, (1993). 'Design of Cellular Manufacturing Systems: An Invited Review. *European Journal of Operational Research*, 69, 284-291.
- S. Sofianopoulou, (1997). Application of simulated annealing to a linear model for the formulation of machine cells in group technology. *International Journal of Production Research*, Volume 35, Number 2 / February 1, 501 – 511.
- Sofianopoulou S (1999). Manufacturing cells design with alternative process plans and/or replicate machines. *International Journal of Production Research*, 37, 707-720.
- Tam, K. Y.; Li, S. G., (1991). Hierarchical approach to the facility layout problem. *International Journal of Production Research*, Vol. 29, pp. 165-84.
- K. Y. Tam, (1998). Solving facility layout problems with geometric constraints using parallel genetic algorithms: experimentation and findings. *International Journal of Production Research*, Volume 36, Number 12, 3253 – 3272.
- D. M. Tate and A. E. Smith,(1995). Unequal Area Facility Layout Using Genetic Search. *IIE Transactions*, 27, 465-472.
- Tompkins, J.A. and White, J.A., (1984). *Facilities Planning* (John Wiley & Sons)
- Tompkins, J.A. and White, J.A., (1996). *Facilities Planning* (New York: Wiley).
- A.J. Vakharia and U. Wemmerlov., (1990). Designing a cellular manufacturing system: A material flow approach based on operation sequences. *IIE Transactions*, 22(1):84-97.
- A. J. Vakharia and Y.-L. Chang, (1997).Cell formation in group technology: a combinatorial search approach. *International Journal of Production Research*. Volume 35, Number 7 2025 – 2044.

- Vishwanath Ramabhatta & Rakesh Nagi (1998). An integrated formulation of manufacturing cell formation with capacity planning and multiple routings, *Annals of Operations Research*, 77(0), 79-95.
- Welgama P. S.; Gibson P. R.; (1993). A construction algorithm for the machine layout problem with fixed pick-up and drop-off points. *International journal of production research*, vol. 31, no11, pp. 2575-2589.
- M.R. Wilhelm, and T.L. Ward, (1987). Solving Quadratic Assignment Problems by Simulated Annealing, *IIE Transactions*, 19, pp. 107–119.
- Won Y., (2000). Two-phase approach to GT cell formation using efficient p-median formulations. *International Journal of Production Research*, Volume 38, Number 7, 10 pp. 1601-1613(13).
- Won, Y. and Lee K.C., (2001). Group technology cell formation considering operation sequences and production volumes. *International Journal of Production Research*, 39, 13, 2755-2768.
- Wu, N., (1998). A concurrent approach to cell formation and assignment of identical machines in group technology. *International Journal of Production Research*, 36, 2099-2114.
- Yang, T. and Peters, B.A., (1998). Flexible machine layout design for dynamic and uncertain production environments. *European Journal of Operations Research*, 108, 49-64.