INTEGRATED APPROACH FOR DESIGN OF CELLULAR MANUFACTURING SYSTEMS

THESIS

Submitted in partial fulfilment
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DOCTOR OF PHILOSOPHY

by

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Under the Supervision of
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Dedicated

To my Father - Captain Partap Singh; epitome of courage

To my Mother - Smt. Bhateri Devi, epitome of sacrifice

To my Wife - Devika; epitome of sincerity

To my Daughter - Yashodhara; epitome of affection

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Kuldip Singh Sangwan

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CERTIFICATE

This is to certify that the thesis entitled "**Integrated Approach for Design of Cellular Manufacturing Systems**" and submitted by **Kuldip Singh Sangwan,** ID. No. 1998PHXF007 for award of Ph.D. Degree of the Institute, embodies original work done by him under my supervision.

Signature of the Supervisor RB Kodali

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ABSTRACT

Manufacturing industries are under intense pressure from the increasingly competitive global market place to improve the efficiency and productivity of their production activities. In addition, the manufacturing system should be able to adjust or respond quickly to changes in the product design and demand without major investment. Traditional manufacturing systems such as job shops and flow lines are not capable of satisfying such requirements. As a result, cellular manufacturing system (CMS), an application of group technology (GT), has emerged as a promising alternative manufacturing system. The design of CMS involves three inter-related phases, namely cell formation which is to identify the machine grouping and part families, intra-cell layout (machine layout) which determines the arrangement of machines within cells, and inter-cell layout (cell layout) which is concerned with the arrangement of cells on the shop floor. A common strategy adopted by many researchers, to address these sub-problems, has been to handle each phase separately and sequentially without evaluating the effect of each phase on the previous phase(s). This limitation, results in generating solutions, which may be efficient to one particular phase, but it does not necessarily offer a good solution to the overall CMS. Therefore, there is need for integrated approach for design of CMS.

In this research, an integrated approach, which tackles these three phases simultaneously, for design of cellular manufacturing systems is developed and validated. Models using simulated annealing, genetic algorithms, fuzzy mathematics, neural networks, and traditional heuristics are developed for design and validation of integrated approach. The integrated approach is also evaluated by using simulation model. Use of multi-criteria decision models shows that the CMS is the best alternative for implementation and to maintain competitive advantage compared to the traditional manufacturing systems.

Chapter 1

Introduction

1.1 Overview

Group Technology (GT) is defined as 'bringing together and organizing (grouping) common concepts, principles, problems, and tasks (technology) to improve productivity'. Cellular manufacturing (CM) is the most common application of group technology. It is the physical division and conversion of all or part of a firm's manufacturing system into manufacturing cells. In the past two decades or so cellular manufacturing has been emerging as an important manufacturing concept. It has probably had a greater impact on increasing manufacturing productivity than any other manufacturing concept. This can be attributed partly to contributions made by cellular manufacturing concepts to other manufacturing technologies such as robotics and flexible manufacturing systems. The advantages of cellular manufacturing over traditional functional manufacturing are many folds. Reduction in setup time, throughput time, work-in-process inventories, simplified flow of parts and tools, centralization of responsibility, and improved human relations are just a few. The basic idea in cellular manufacturing is to group parts that have similar processing needs into part families, and machines that meet these needs into machine cells.

While the idea for GT/CM has existed for quite some time, research on the topic didn't take off until the 1970's. Considerable research has been undertaken in the past to investigate the part family-machine cell formation problem. Most of the empirical research centred on methods of cell formation (King 1980, Vakharia 1986, Burbidge 1992), including the determination of which cell formation technique to use (Burbidge 1989, Balakrishnan 1996). Other papers gave an overview of the different procedures for cell formation (Singh 1993, Heragu 1994). Another area of research is scheduling (Mahmoodi *et al.* 1990a, 1990b, Mahmoodi and Dooley 1991). Also, a number of computer simulation studies have been completed comparing job shop and cellular layouts (Flynn and Jacobs 1987, Morris and Tersine 1990, Garza and Smunt 1991, Suresh 1992, Shafer and Charnes 1995, Suresh and Meredith 1994), but most of the other research on GT/CM has been anecdotal in nature. Numerous authors have cited different potential advantages from GT/CM (Burbidge 1980, 1992, Greene and Sadowski 1984, Schonberger 1986, Flynn and Jacobs 1987, Wemmerlov and Hyer 1989). The advantages can be grouped into three parts: operating environment, human resources, and quality advantages.

1.2 Need of Integrated Approach for Design of Cellular Manufacturing Systems

The design of cellular manufacturing systems (CMS) involves three inter-related phases, namely cell formation which is to identify the machine grouping and part families, intra-cell layout (machine layout) which determines the arrangement of machines within cells, and inter-cell layout (cell layout) which is concerned with the arrangement of cells on the shop floor (Hassan 1995). The literature review on design of CMS reveals that design of CMS contains only the cell formation. Bilberg and Alting (1994) considered that a major cause to low productivity is failure to utilize the resources due to poor management, organization, planning, and layouts. Accordingly an efficient cell partitioning strategy and layout design are key elements in achieving the benefits expected from CMS. A common strategy adopted by many researchers, to address these research centred on methods of cell formation (King 1980, Vakharia 1986, Burbidge 1992), including the determination of which cell formation technique to use (Burbidge 1989, Balakrishnan 1996). Other papers gave an overview of the different procedures for cell formation (Singh 1993, Heragu 1994). Another area of research is scheduling (Mahmoodi *et al.* 1990a, 1990b, Mahmoodi and Dooley 1991). Also, a number of computer simulation studies have been completed comparing job shop and cellular layouts (Flynn and Jacobs 1987, Morris and Tersine 1990, Garza and Smunt 1991, Suresh 1992, Shafer and Charnes 1995, Suresh and Meredith 1994), but most of the other research on GT/CM has been anecdotal in nature. Numerous authors have cited different potential advantages from GT/CM (Burbidge 1980, 1992, Greene and Sadowski 1984, Schonberger 1986, Flynn and Jacobs 1987, Wemmerlov and Hyer 1989). The advantages can be grouped into three parts: operating environment, human resources, and quality advantages.

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1.3 Objectives of the Research

The objective of the research is to develop and validate an integrated approach for design of cellular manufacturing systems. The objective of the research is achieved by the following objectives:

- The multi-attribute decision models, i.e., analytical hierarchy process (AHP) and performance value analysis are developed for the justification of CMS.
- The fuzzy logic approach, i.e., fuzzy logic and AHP, and fuzzy equivalence relations and AHP are developed for the part family formation.
- The neural networks and simulated annealing approaches are developed for the design of cell formation by considering the practical factors like production volume (demand), processing time of parts on machines, number of cells, minimum acceptable utilization of individual machines, machine downtime, desirable machine utilization, maximum permissible workload on machines and other management constraints like number of shifts, working days, maximum and effective time available on machines, operation sequence and transfer batch size of parts.
- The multicriteria mathematical formulation is developed for design of layout (intracell as well as intercell) for CMS. MUCH (based on multi-criteria heuristic)

models are developed for the design of layout for CMS by considering the practical inputs like operation sequence, multiple non-consecutive visits to the same machine, production volume and the transfer batch size of parts.

- The multicriteria mathematical formulation is developed for integrated approach and two models: SAMUCH (based on simulated annealing and a traditional heuristic) and SAFUGA (based on simulated annealing, genetic algorithm with embedded fuzzy logic and AHP) are developed for integrated approach for design of CMS.
- The simulation model is developed for validation of integrated approach for design of CMS. The effects of various scheduling philosophies are studied using simulation model.
- The production planning and control models are developed for operation of CMS.

The present research is an attempt to outline the significant features of the integrated approach for design of CMS.

1.4 Arrangement of Thesis

Chapter two discusses the literature review. The justification of CMS is discussed in chapter three. Chapter four describes the part family formation. Cell formation is discussed in chapter five. Chapter six describes the design of layout for CMS. The integrated approach for design of CMS is discussed in chapter seven. The chapter eight describes the production planning and control of CMS. Chapter nine summarizes the research contributions with conclusions.

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Chapter 2

Literature Review

2.1 Introduction

Manufacturing industries are under intense pressure from the increasingly competitive global market place. Shorter product life-cycles, time-to-market, and diverse customer needs have challenged manufacturers to improve the efficiency and productivity of their production activities. Manufacturing systems must be able to manufacture the high quality products with low production costs as quickly as possible in order to deliver the products to customers on time. In addition, the system should be able to adjust or respond quickly to changes in the product design and product demand without major investment. Traditional manufacturing systems such as job shops and flow lines are not capable of satisfying such requirements.

Job shops are the most common manufacturing systems. In general, job shops are designed to achieve maximum flexibility such that a wide variety of products with small lot sizes can be manufactured. Products manufactured in job shops usually require different operations and have different operation sequences. Operating time for each operation could vary significantly. Products are released to the shops in batches (jobs). The requirements of the job shop - a variety of products and small lot sizes - dictate what types of machines are needed and how they are grouped and arranged. General-purpose machines are utilized in job shops because they are capable of performing many different types of operations. Machines are functionally grouped according to the general type of manufacturing process- lathes in one department, drill presses in another, and so forth. Figure 2.1 illustrates a job shop. A job shop layout can also be called a functional layout.

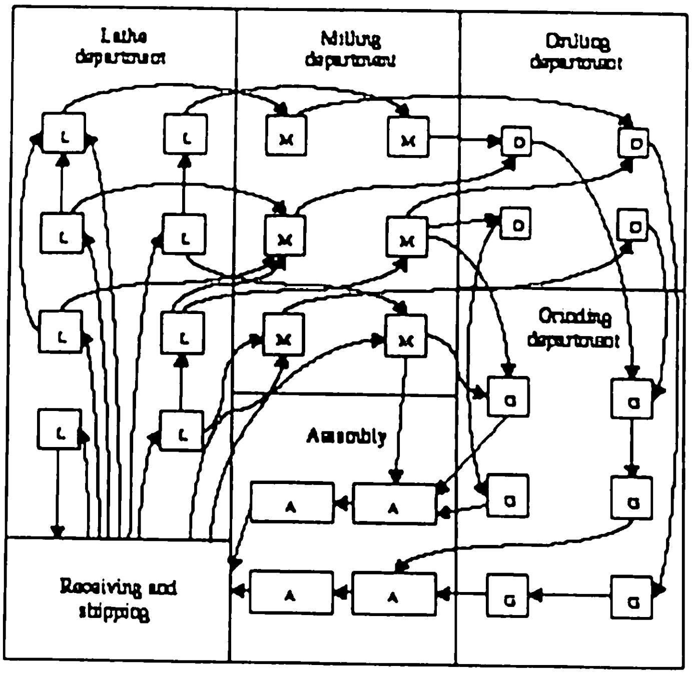

Figure 2.1: Job shop manufacturing system (Black 1991)

In job shops, jobs spend 95% of their time in non-productive activity; much of the time is spent in waiting in queue and remaining 5% is split between lot setup and processing (Askin and Standridge 1993). When the processing of a part in the job shop has been completed, it usually must be moved a relatively large distance to reach the next stage. It may have to travel entire facility to complete all of the required processes as shown in figure 2.1. Therefore, to make processing more economical, parts are moved in batches. Each part in a batch must wait for the remaining parts in its batch to complete processing before it is moved to the next stage. This leads to longer production times, high levels of in-process inventory, high production costs and low production rates.

In contrast to job shops, flow lines are designed to manufacture high volumes of products with high production rates and low costs. A flow line is organized according to the sequence of operations required for a product. Specialized machines, dedicated to the manufacture of the product, are utilized to achieve high production rates. These machines are usually expensive; to justify the investment cost of such machines, a large volume of the products must be produced. A major limitation of flow lines is the lack of flexibility to produce products for which they are not designed. This is because the specialized machines are setup to perform limited operations and are not allowed to be reconfigured. Figure 2.2 shows an example of a flow line.

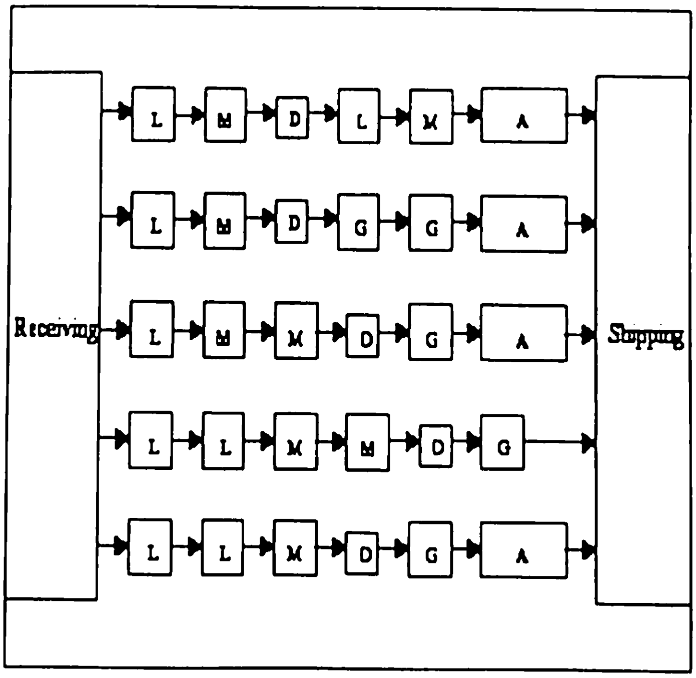

Figure 2.2: Transfer line manufacturing system

As indicated above, job shops and flow lines cannot meet today's production requirements, where manufacturing systems are often required to be reconfigured to respond to changes in product design and demand. As a result, cellular manufacturing (CM), an application of group technology (GT), has emerged as a promising alternative manufacturing system. Within the manufacturing context, GT is defined as a manufacturing philosophy identifying similar parts and grouping them together into families to take advantage of their similarities in design and manufacturing (Selim *et al.* 1998). CM involves the formation of part families based upon their similar processing requirements and the grouping of machines into manufacturing cells to produce the formed part families. A part family is a collection of parts which are similar either because of the geometric shape and size or similar processing steps required in their manufacture (Groover 1987). A manufacturing cell consists of several functionally dissimilar machines which are placed in close proximity to one another and dedicated to the manufacture of a part family.

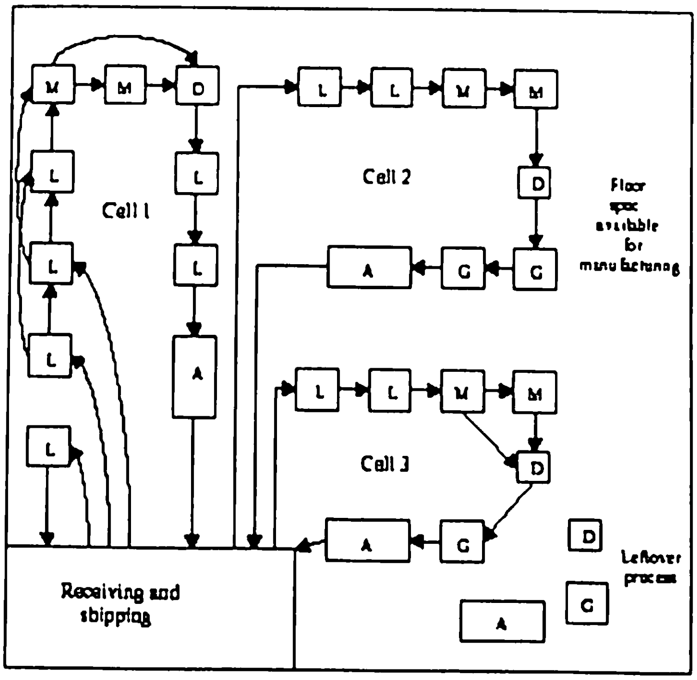

Figure 2.3: Cellular manufacturing system (Black 1991)

The tenet of CM is to break up a complex manufacturing facility into several groups of machines (cells), each being dedicated to the processing of a part family. Therefore, each part type is ideally produced in a single cell. Thus, material flow is simplified and the scheduling task is made much easier. As reported in the survey by Wemmerlov and Johnson (1997), production planning and control procedures have been simplified with the use of CM. The job shop in the figure 2.1 is converted into a cellular manufacturing system as shown in figure 2.3. Obvious benefits gained from the conversion of the shop are less travel distance for parts, less space required, and fewer machines needed. Since similar part types are grouped, this could lead to a reduction in setup time and allow a quicker response to changing conditions. Some of the reported benefits of CMS are given in tables 2.1, 2.2, and 2.3. On the other hand, in the job shop, each part type may have to travel through the entire shop; hence scheduling and materials control are difficult. In addition, job priorities are complex to set and hence large inventories are needed so as to ensure that ample work is available.

Table 2.1: Benefits of CM after the first two months of operation (Levasseur *et al.* 1995)

Criteria	Job Shop	CMS	Resulting improvement
Work in process	$590,000	$116,336	$473,664 (80%)
Finished goods	$880,000	$353,167	$526,833 (60%)
Suppliers	$8,333/months	0	$8,333 (100%)
Lead time	14 days	2 days	12 days (86%)
Late orders	100	4	96%
Scraps	22%	14%	8%
Direct labour	198	145	53 employees (27%)
Mfg. Space (sq. ft)	45,000	20,000	25,000 sq. ft. (56%)

Table 2.2: Reported benefits from CMS (Wemmerlov and Hyer 1989)

Types of benefits	Number of Responses	Average % Improvement	Minimum % Improvement	Maximum % Improvement
1. Reduction in throughput time	25	45.6	5.0	90.0
2. Reduction in WIP inventory	23	41.4	8.0	90.0
3. Reduction in material handling	26	39.3	10.0	83.0
4. Improvement of operator job satisfaction	16	34.4	15.0	50.0
5. Reduction in number of fixtures for cell parts	9	33.1	10.0	85.0
6. Reduction in setup time	23	32.0	2.0	95.0
7. Reduction in space needed	9	31.0	1.0	85.0
8. Improvement of part quality	26	29.6	5.0	90.0
9. Reduction in finished goods inventory	14	29.2	10.0	75.0
10. Reduction in labour cost	15	26.2	5.0	75.0
11. Increase in utilization of equipment in the cells	6	23.3	10.0	40.0
12. Reduction in the pieces of equipment required to manufacture the cell parts	10	19.5	1.0	50.0

Table 2.3: Effects on performance measures (Wemmerlov and Johnson 1997)

Performance measure	Number of Responses	Average % Improvement	Minimum % Improvement	Maximum % Improvement
1. Reduction of move distance/time	37	61.3	15.0	99.0
2. Reduction in throughput time	40	61.2	12.5	99.5
3. Reduction in response time to orders	37	50.1	0.0	93.2
4. Reduction in WIP inventory	40	48.2	10.0	99.7
5. Reduction in setup times	33	44.2	0.0	96.6
6. Reduction in finished goods inventory	38	39.3	0.0	100.0
7. Improvement in parts/product quality	39	28.4	0.0	62.5
8. Reduction in unit cost	38	16.0	0.0	60.0

There are many research papers available on cellular manufacturing systems but the number of research papers available on the design of cellular manufacturing systems are limited. In the pre 90's, researchers used to call cell formation problem itself as the design of CMS. In this chapter, review of literature on design of CMS is done.

2.2 Design of Cellular Manufacturing Systems

Kaebernick and Bazargan-Lari (1996) proposed that design of cellular manufacturing systems involves three interrelated phases: cell formation which is to identify the machine groupings and part families, intra-cell layout (machine layout) which determines the arrangement of machines within cells, and finally inter-cell layout (cell layout) which is concerned with the arrangement of cells on the shop floor. Wemmerlov and Hyer (1987) divided the design phase of cellular manufacturing systems in five stages: (i) selection of parts and part families generation; (ii) selection of machines and processes and grouping these into cells; (iii) selection of tools, fixtures, and pallets; (iv) selection of material handling equipment; and (v) plant layout. Rajamani *et al.* (1990) developed three integer programming models to successively study the effect of alternative process plans and simultaneous formation of part families and machine groups. The first model gives the part/machine incidence matrix, which is used for cell formation using the total investment as objective and selects the suitable process plans. The second model is used to form machine groups assuming that the part families are known. The third model identifies part families and machine groups simultaneously. The objective was to model and analyse how alternate process plans influence the resource utilization when the part families and machine groups are formed simultaneously. Rajamani *et al.* (1996) developed a mixed integer model for the design of cellular manufacturing systems. The model identifies the part families and machine groups concurrently with the objective to minimize the sum of investment, processing, and material handling costs. Alternate process plans, processing time, capacities of machines and cell size restrictions were considered in the process. Kusiak *et al.* (1993) presented an efficient branch-and-bound heuristic algorithm for design of cellular manufacturing systems. The heuristic developed is for identification of machine cells and formation of part families. An A* algorithm was also developed to obtain optimal machine cells. Rajagopalan and Batra (1975) used graph-theoretic approach for the design of cellular production systems. Information derived from the route cards of the components is analysed and the situation is represented in the form of graph whose vertices corresponds to the machines and whose edges represent the relationships created between the machines by the components using them. The cells were formed using a graph portioning approach. Wu *et al.* (1986) used a syntactic pattern recognition approach for formation of machining cells by classification of machining sequences based on production flow analysis. Choobineh (1988) proposed a two-stage procedure for the design of cellular manufacturing systems. The first stage forms the part families and the second stage forms the machine cells. A proximity measure using the manufacturing operations and the operation sequence is suggested for first stage and an integer programming model is formulated for the second stage. Venugopal and Narenderan (1993) proposed an algorithm based on the asymptotic forms of Boolean matrix to identify machine cells and part families in case mutually independent cells exists. They also proposed an algorithm to identify bottleneck machines and parts when mutually independent cells do not exist. Finally, they proposed a methodology that can be used by designers of CMS to form mutually independent cells. Irani *et al.* (1995) described a method for layout design of cellular manufacturing systems that would allow simultaneously, the grouping of machines unique to a part family into cells and those shared by several cells to be located together in functional sections. A graph-theoretic structure for simultaneous machine grouping and layout design was developed and validated. Rao and Gu (1994) formed machine and component grouping based on practical constrains like duplicate machine availability and machine capacity. They also considered the material handling cost for the evaluation of the process plans. The distance between the machines required for the calculation of the material handling cost is randomly generated without actual layout of the machines. Rao and Gu (1995) developed a multi-layered neural network that can configure alternate cell designs by considering multiple constraints and objectives. These constraints and objectives are embedded within the network as transfer functions, which help impose the practical constraints and guide the cell design process. Dahel (1995) developed a cell formation approach for cellular manufacturing systems in which intercell moves are restricted to flow in one direction from one cell to the other immediately downstream, without backtracking. The model subdivides the underlying manufacturing system into cells based on an intercell traffic minimization criterion and subject to machine capacity and operation sequence constraints. Cheng *et al.* (1996) also formed the part families and machine cells in the design of cellular manufacturing systems using truncated tree search. They formulated the problem as a 0-1 quadratic programming model with a view to minimize intercellular moves using a distance measure. Cantamessa and Turroni (1997) developed a decision support tool for the designer of cellular manufacturing systems during the machine cell and part family formation phase taking a wide set of factors into account (safety, technological, organizational ...). Baker and Maropoulos (1997) presented an automatic clustering algorithm for cell formation and also noted that for successful design of cellular manufacturing systems three steps are required: clustering of workstations into cells, layout of the cells for the efficient flow of parts through the factory, and the continuous improvement of the cells. Lee and Chen (1997) developed a multicriteria weighted approach to form machine cells and part families for configuring cellular manufacturing systems considering parameters like demand, batch size, pallet size, routing sequence, processing times, machine capacities, and workload status of machines. Heragu and Chen (1998) developed a mathematical model for CMS design which incorporates three aspects - resource utilization, alternative routings, and practical constraints (safety constraints, technological constraints, and upper/lower limits on cell size). Benders' decomposition approach (Benders 1962) was used to form the cells. Shanker and Vrat (1999) used fuzzy programming models for the design of cellular manufacturing systems at the post-clustering stage for the design of cellular manufacturing systems. The models are designed to handle exceptional elements, bottleneck machines, and vagueness in the estimation of system parameters. Venkataramanaiah *et al.* (2000) modelled the cell formation problem in cellular manufacturing as a multiple objective with an objective of minimization of inter and intra cell transfer and load imbalance among machines and cells. A simulated annealing algorithm was developed to solve the problem. Wu and Salvendy (1999) developed a merging-and-breaking heuristic to solve concurrently both the traditional cell formation problem and the assignments of the identical machines to different cells in the design of cellular manufacturing systems. Akturk and Turkcan (2000) proposed a local search heuristic to solve the part-family and machine-cell formation problem by simultaneously considering the within-cell layout problem but for layout they considered that a material handling cost is not incurred when the two consecutive machines in the operation sequence are next to each other otherwise a material handling cost is incurred. Actual distances are not considered. Massay *et al.* (1995) described a systematic approach to the design of cellular manufacturing systems. They divided the design into four phases: analysis, conceptual design, embodiment design, and detailed design. Singh (1993), Heragu (1994), Offodile *et al.* (1994), and Mukherjee *et al.* (1999) provide thorough survey of papers on group technology and cellular manufacturing system design. Wemmerlov and Johnson (2000) adds to the sparse literature on empirical cell design by reporting about the methods, goals, considerations, and constraints that industrial users apply to cell formation and cell layout.

2.3 Drawbacks of the Current CMS Design Methods

As the review of papers on CMS design reveals in the above section that the CMS should contain the cell formation, layout of machines inside the cells and the layout of cells with respect to each other. Most of the techniques for the design of CMS consider only cell formation, the common objective being the minimization of exceptional elements or a weighted sum of exceptional elements and voids. The exceptional elements and voids have been used as surrogate measures for inter-cell and intra-cell moves cost. However, these measures do not reflect the actual moves cost. The moves cost is proportional to the distance travelled and the number of moves. The number of moves depends on the operation sequence, multiple non-consecutive visits to the same machine, production volume and the transfer batch size; the distance travelled depends on the layout of machines within the cells and the layout of cells on the shop floor.

Logendran (1990) proposed a heuristic that considers minimization of a weighted sum of intracell and intercell moves. He ignores the sequence of operations and assumes that a part makes $(n-1)$ intercell moves if it visits n different cells. Similarly, the part makes $(m-1)$ intracell moves in a cell where m of its operations are performed. Later, Logendran (1991) incorporated the effects of sequence of operations on intercell moves for an assumed layout of machines and modified his total move equation to compute the exact number of inter and intracell moves. Based on the Logendran's work, Gupta *et al.* (1996) developed two models - one for a linear single row layout and other for a linear double row layout. In this model the distances computed are approximation only. Moreover, from this model it is not clear how the intracell moves are computed and the intracell layout is not considered.

Adil and Rajamani (2000) proposed a model that considers the number of intercell and intracell moves exactly but the distances travelled are approximated for three types of layouts where expected distance (d_l) between machines in a cell of N machines is computed as follows:

$d_l(N) = 0.333\ (1+N)$ for a straight line layout

$d_l(N) = 0.333\ (R+N)$ for a rectangular layout with R rows

$d_l(N) = 0.666\ N$ for a square layout

The intercell travel distance per move between cells is assumed as the centroid distance between these cells.

Kaebernick and Bazargan-Lari (1996) used the integrated approach for design of CMS. They formed the cells with the objective of reducing the inter-cellular moves and putting the maximum and minimum number of cells as constraints. Next, they designed the intra-cell layout and finally generated the inter-cell layout based on criteria of shape and cost by considering all possible combinations for efficient intra-cell layout designs. In true sense, this is not an integrated approach as they have solved the cell formation and layout problems sequentially (once the machines are grouped to different cells based on the above algorithm for different cell numbers, the intra-cell and inter-cell layout designs can be carried out... Kaebernick and Bazargan-Lari (1996): 423) in a forward pass with no feedback. This approach is called sequential approach. Bazargan-Lari *et al.* (2000) solved a practical problem using this sequential approach.

This sequential approach may be efficient to one particular phase but need not to be efficient for the overall design of CMS. For a true integrated approach the cell formation and layout problem should be tackled simultaneously. The cell formation and layout design are to be carried out iteratively (by repeating each stage with input obtained from the other stage) till the solution converges, i.e., each solution to the cell formation problem should be evaluated only after designing the intra and inter cell layouts and continued till the solution converges.

2.4 Conclusions

A number of publications related to the design of CMS have been published over the last three decades. However, all except few papers discuss only cell formation/design (part family formation and machine cell formation) as the design of CMS. The design of cellular manufacturing systems involves three inter-related phases, namely cell formation which is to identify the machine grouping and part families, intra-cell layout (machine layout) which determines the arrangement of machines within cells, and finally inter-cell layout (cell layout) which is concerned with the arrangement of cells on the shop floor. A common strategy adopted by many researchers, to address these sub-problems, has been to handle each phase separately and sequentially without evaluating the effect of each phase on the previous phase(s). This limitation, results in generating solutions, which may be efficient to one particular phase, but it does not necessarily offer a good solution to the overall CMS. Therefore, there is need for integrated approach for design of CMS, which will tackle the phases simultaneously for design of CMS.

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Chapter 3

Justification of Cellular Manufacturing Systems

3.1 Introduction

One school of thought concerning justification of advanced manufacturing systems states that if manufacturing is to be a competitive tool, justification has to become more of a policy decision rather than an accounting or financial procedure. Another school of thought concerning justification of advanced manufacturing systems states that advanced manufacturing systems can be 'sold' to top-level management only if all relevant costs and benefits are quantified and presented in an easy-to-understand format. Managers, who are considering the introduction of CMS in their organizations not only have to identify the application and plan its implementation but also have to ensure that the use of CMS will be a viable alternative. Few attempts were made to address the benefits to be achieved from the CMS implementation. Dale (1980, 1999) introduced a method for measuring the applicability of CMS. His approach is to collect data from a number of companies before and after the implementation of CMS. He concluded that the average reductions in setup time and throughput time were 17% and 55% respectively. In another cellular manufacturing implementation studied by Nagarkar (1979), the throughput time declined by 75%. Wemmerlov and Hyer (1989) surveyed the benefits achieved from cellular manufacturing in 32 US firms. The results were very impressive. Wemmerlov and Johnson (1997) employed a mail survey methodology, and made a contribution to the knowledge gap by providing insights into implementation experiences and performance achievements at 46 US firms. They collected data mirror several aspects of cellular manufacturing previously explored by Wemmerlov and Hyer (1989), where appropriate, the results from both studies were contrasted. Olorunniwo (1997) analysed a part of the data collected in a survey of US firms that operated manufacturing cells. The survey identified two underlying dimensions or constraints that explain the relationship amongst the performance measures commonly used to assess the relative magnitude of success of cellular manufacturing implementation. He proposed methodology to categorize relative success of cellular manufacturing implementation. The above literature supports the former school of thought for justification of CMS.

The economic justification process has long been identified as the biggest hurdle to the adoption of advanced automated manufacturing systems (Kaplan 1986). In recent years, the literature has been inundated with a large number of methodologies and evaluation techniques that look promising for the economic justification process for advanced manufacturing systems (Bennett and Hendricks 1987, Canada 1986, Curtin 1984a, 1984b, Meredith and Suresh 1986, Michael and Millen 1985, Moerman 1988, Parsaei *et al.* 1988, Parsaei and Wilhelm 1989, Zahran *et al.* 1992, Primrose 1999). Several traditional financial techniques have been proposed that are complex and exhaustive in nature, and require hard-core quantitative data that may be difficult to retrieve or formulate. Today, most major organizations are struggling with their traditional investment justification procedures because they are either misapplied or the information included in the calculations is inadequate for the multifaceted problems being tackled. The use of multi-attribute decision models for justification of CMS justifies the latter school of thinking. Some type of multi-attribute decision analysis techniques are called upon to aid in breaking down, analysing, communicating, and synthesizing the nature of the problem, and hopefully to lead one to the best decision under the circumstances. The complex, multi-attribute nature of alternative advanced manufacturing systems may tend to be overwhelming to analysis and decision makers. Multi-attribute decision models, i.e., analytical hierarchy process and performance value analysis, have been developed for justification of cellular manufacturing systems.

3.2 Development of Analytic Hierarchy Process (AHP) for Justification of CMS

The AHP has been well received by all concerned as reported in the literature (Roger 1987). Application of this methodology has been found in numerous fields. The general approach of AHP model is to decompose the problem and make pairwise comparison of all the elements on a given level with the related elements in the level just above to which it belongs. The schematic of the model is shown in figure 3.1. A thorough analysis of the problem is required along with the identification of the important attributes involved. The selection of the attributes has been determined through literature survey and discussions held with experts in the field (Heragu 1994, Wemmerlov and Hyer 1987, Zahran *et al.* 1992, Huq 1992, Afzulpurkar *et al.* 1993, Choi 1996, Singh and Rajamani 1996, Singh 1996, Wemmerlov and Johnson 1997, 2000, Olorunniwo 1997, Masnata and Settineri 1997, Talluri *et al.* 1997, Shang and Tadikamalla 1998, Eckstein and Rohleder 1998, Dale 1999, Primrose 1999, Choobineh and Nare 1999, Marsh *et al.* 1999). The selection of attributes and sub-attributes used in the AHP for justification of CMS are:

1. Cost [CST]
    - Setup cost [SUC]
    - Labour cost [LRC]
    - Equipment cost [EQC]
    - Tooling cost [TLC]
    - Material handling cost [MHC]

• Unit cost	[UTC]
• Inspection cost	[INC]
• Design cost	[DGC]
• Supervision cost	[SNC]
• Relocation cost	[RLC]
2. Process	**[PRS]**
• Production modes/Layout styles	[PML]
• Choice of equipment and material handling system	[EMH]
• Capacity balancing and product flow	[CBF]
• Setup time/tooling	[SUT]
• Quality tools/management	[QTM]
• Disciplined production control	[DPC]
3. Quality	**[QTY]**
• Defect rate	[DFR]
• Scrap rate	[SCR]
• Rework	[REW]
• Consistent quality	[COQ]
4. Inventory	**[INV]**
• Raw material inventory	[RMI]
• Work-in-process	[WIP]
• Finished goods inventory	[FGI]
5. Implementation	**[IMP]**
• Planning for conversion	[PLC]
• Implementation time	[IMT]
• Education and training	[EAT]
• Empowerment	[EMP]

6. Workforce	**[WFC]**
• Turnover rate	[TOR]
• Commitment	[COM]
• Number of workers	[NOW]
• Assessment and rewards	[AAR]
• Job rotation/enrichment	[JRE]
• Morale	[MOR]
• Operator/cell leader selection	[OCS]
• Learning rate	[LER]
7. Benefits	**[PMB]**
• Productivity	[PRO]
• Resource utilization	[UOR]
• Transfer/transport time	[TTT]
• Throughput time	[TPT]
• Response time to customer	[RTC]
• Flexibility	[FLX]
• Quality	[QTY]
• Inventory	[INV]
• Lead time	[LTM]
• Lot size	[LOT]

Alternatives: The alternative manufacturing systems evaluated and compared in the light of above determined set of attributes and sub-attributes are:

• Transfer line	[TL]
• Job shop	[JS]
• Cellular manufacturing systems	[CMS]

Analytical Hierarchy Process Methodology

AHP (Satty 1980) was developed as a practical approach in solving relatively complex problems. AHP enables the decision maker to represent the simultaneous interaction of many factors in complex, unstructured situation. For the justification of cellular manufacturing systems, the judgments based on observations are fed into AHP for each attribute and sub-attribute of all levels of hierarchy. Pairwise comparisons of attribute at each level are done on a scale of relative importance, 1 reflecting equal weightage and 9 reflecting absolute importance as shown in table 3.1.

Table 3.1: Scale of relative importance

Intensity	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Weak importance of one over the other	Experience and judgment slightly favour one another
5	Essential or strong	Experience and judgment slightly favour one another
7	Very strong	An activity is strongly importance favoured and its dominance is demonstrated in practice
9	Absolute importance	The evidence favouring one activity over another is of the highest degree
2,4,6,8	Intermediate values	When compromise is needed

The steps to follow in using the AHP (Roger 1987) are:

Step 1. Define the problem and determine the objective.

Step 2. Structure the hierarchy from the top through the intermediate levels to the lowest level. See figure 3.1.

Step 3. Construct a set of pairwise comparison matrices for each of the lower levels. An element in the higher level is said to be a governing element for those in the lower level, since it contributes to it or affects it. The elements in the lower level are then compared to each other based on their effect on the governing element above. This yields a square matrix of judgments. The pairwise comparisons are done in terms of which an element dominates another. These judgments are then expressed as integers. If element A dominates over element B, then the whole number integer is entered in row A, column B and reciprocal is entered in row B, column A. If the elements being compared are equal, a one is assigned to both positions. Table 3.2 shows the pairwise comparison matrix for level 2.

Step 4. There are n (n-1)/2 judgments required to develop the set of matrices in step 3 (reciprocals are automatically assigned in each pairwise comparisons).

Step 5. Having done all the pairwise comparisons and entered the data, the consistency is determined using the eigenvalue. To do so, normalize the column of numbers by dividing each entry by the sum of all entries. Then sum each row of the normalized values and take the average. This provides Principal Vector (PV). The check of the consistency of judgments is as follows:

Let the pairwise comparison matrix be denoted M1 and principal vector be denoted M2.

Then define M3 = M1*M2; and M4 = M3/M2.

λ_{max} = average of the elements of M4.

Consistency Index (CI) = $(\lambda_{max} - N) / N - 1$

Consistency Ratio (CR) = CI/RI corresponding to N

where RI : Random Consistency Index and

N : Number of elements

Random index table

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

If CR is less than 10%, judgments are considered consistent. And if CR is greater than 10%, the quality of judgments should be improved to have CR less than or equal to 10%.

Step 6. Steps 3-5 are performed to have relative importance of each attribute for all levels and clusters in the hierarchy. Table 3.3 illustrates the sub-attribute analysis of attribute, 'cost'.

Step 7. The alternative analysis for the lowest level of sub-attribute to be carried out in the similar manner as above. Table 3.4 illustrates the alternative analysis of 'turnover rate'.

Step 8. The desirability index for each alternative is calculated by multiplying each value in 'weight of sub-attribute' column by the respective value of 'attribute weight' column, then multiplying by the value for each respective alternative and summing the results.

For use in this problem, the focus is developed. In this case, it is to determine the justification of CMS. The attributes are compared with each other in a pairwise comparison with respect to case situation discussed in table 3.5. From the analysis, it is clear that the CMS option is the best under the circumstances of the developed case situation (see tables 3.6, 3.7, 3.8, 3.9, 3.10, and 3.11).

Highly user-friendly software, the multi-attribute decision model (AHP) is developed in VC^{++} to aid the user for pairwise comparison of the attributes as well as for the alternatives and for analysing the user inputs. The judgements supplied by the user can be estimated from the graphs (figures 3.2, 3.3, and 3.4) that are generated for each alternative and its corresponding deciding criteria.

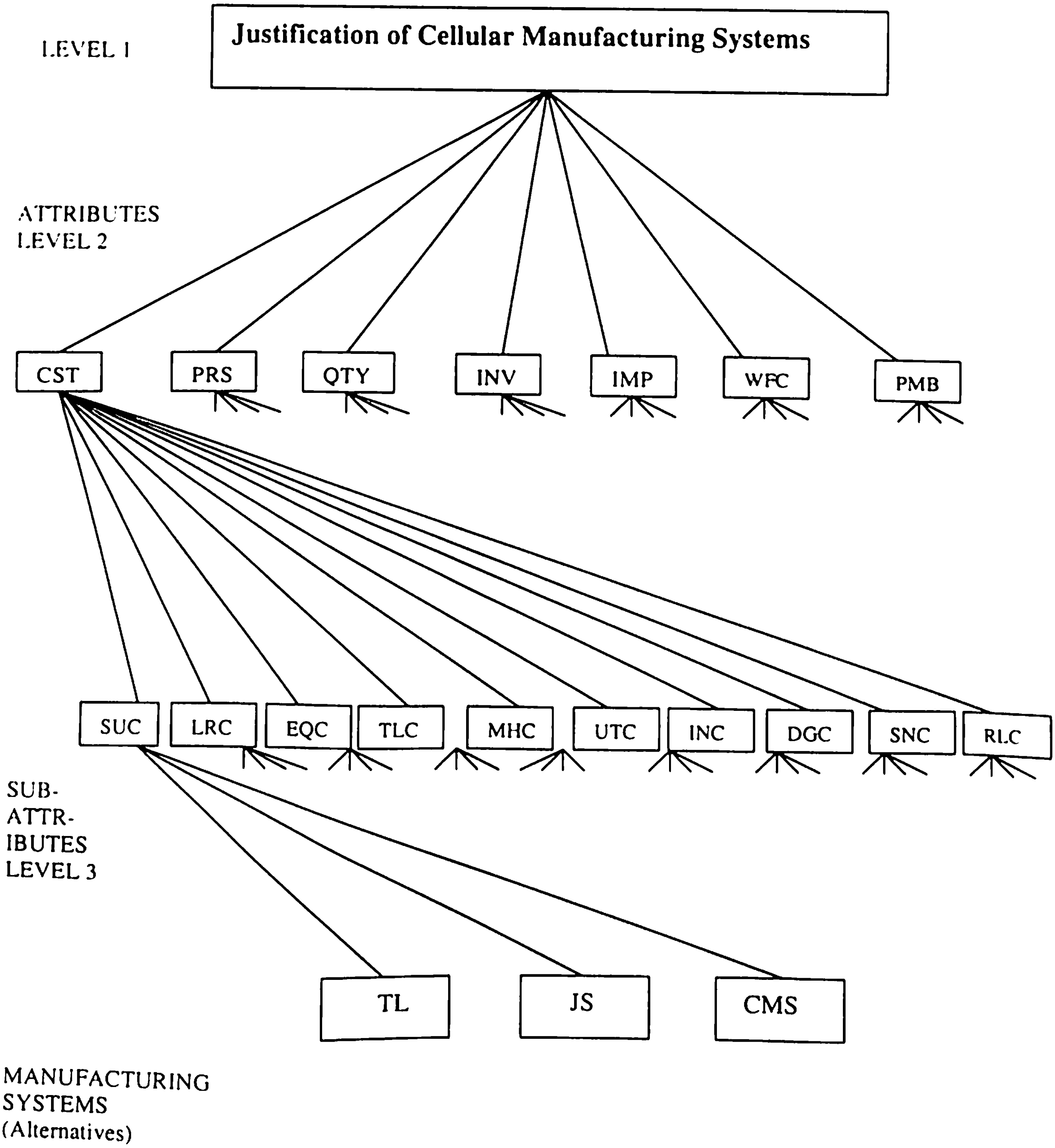

Figure 3.1. Schematic of AHP model

Table 3.2: Pairwise comparison matrix - level 2

	CST	PRS	QTY	INV	IMP	WFC	PMB
CST	1.000	2.000	3.000	6.000	8.000	4.000	3.000
PRS	0.500	1.000	2.000	3.000	4.000	2.000	2.000
QTY	0.333	0.500	1.000	2.000	3.000	2.000	1.000
INV	0.167	0.333	0.500	1.000	0.500	0.333	0.500
IMP	0.125	0.250	0.333	2.000	1.000	2.000	0.200
WFC	0.250	0.500	0.500	3.000	0.500	1.000	0.167
PMB	0.333	0.500	1.000	2.000	5.000	6.000	1.000
Sum	2.708	5.083	8.333	19.000	22.000	17.333	7.867
Principal Vector	0.34	0.19	0.12	0.05	0.06	0.07	0.16

Table 3.3: Cost sub-attribute analysis - level 3

	SUC	LRC	EQC	TLC	MHC	UTC	INC	DGC	SNC	RLC
SUC	1.000	2.000	3.000	6.000	8.000	4.000	3.000	5.000	0.250	2.000
LRC	0.500	1.000	2.000	3.000	4.000	2.000	2.000	3.000	0.111	1.000
EQC	0.333	0.500	1.000	2.000	3.000	2.000	1.000	2.000	0.111	0.500
TLC	0.167	0.333	0.500	1.000	2.000	0.500	0.500	0.500	0.111	0.333
MHC	0.125	0.250	0.333	0.500	1.000	0.500	0.333	0.500	0.111	0.200
UTC	0.250	0.500	0.500	2.000	2.000	1.000	0.500	2.000	0.143	0.500
INC	0.333	0.500	1.000	2.000	3.000	2.000	1.000	2.000	0.111	0.200
DGC	0.200	0.333	0.500	2.000	2.000	0.500	0.500	1.000	0.111	0.333
SNC	4.000	9.000	9.000	9.000	9.000	7.000	9.000	9.000	1.000	7.000
RLC	0.500	1.000	2.000	3.000	5.000	2.000	5.000	3.000	0.143	1.000
Sum	7.408	15.417	19.833	30.500	39.000	21.500	22.833	28.000	2.202	13.067
Principal Vector	0.158	0.085	0.057	0.029	0.021	0.045	0.054	0.035	0.413	0.102

Table 3.4: Alternative analysis for turnover rate

	TL	JS	CMS
TL	1.000	3.000	5.000
JS	0.333	1.000	2.000
CMS	0.200	0.500	1.000
Sum	1.533	4.500	8.000
Principal Vector	0.648	0.230	0.122

Table 3.5: Case situation

Industry type	Discrete type manufacturing
Production volume	Mid volume
Company vision	Star performer and market leader
Mission	Continuous improvement of processes, products, and people

Table 3.6: Weightages for main attributes

Main Attributes	Level 2 weightages
CST	0.34
PRS	0.19
QTY	0.12
INV	0.05
IMP	0.06
WFC	0.07
PMB	0.16

Table 3.7: Weightages for sub-attributes

Sub-attributes	Level 3 weightages
SUC	0.16
LRC	0.08
EQC	0.06
TLC	0.03
MHC	0.02
UTC	0.05
INC	0.05
DGC	0.03
SNC	0.41
RLC	0.10
PML	0.29
EMH	0.11
CBF	0.07
SUT	0.05
QTM	0.25
DPC	0.23
DFR	0.45
SCR	0.15
REW	0.27
COQ	0.14
RMI	0.24
WIP	0.55
FGI	0.21
PLC	0.45
IMT	0.13
EAT	0.22
EMP	0.19
TOR	0.32
COM	0.18
NOW	0.12
AAR	0.05
JRE	0.04
MOR	0.09
OCS	0.11
LER	0.10
PRO	0.16
UOR	0.09
TTT	0.06
TPT	0.03
RTC	0.02
FLX -	0.05
QTY	0.05
INV	0.03
LTM	0.41
LOT	0.10

Table 3.8: Weightages for alternatives

Sub-attributes	TL	JS	CMS
SUC	0.1111	0.2222	0.6667
LRC	0.1578	0.1867	0.6555
EQC	0.4000	0.4000	0.2000
TLC	0.2106	0.2409	0.5485
MHC	0.1279	0.5119	0.3601
UTC	0.2000	0.6000	0.2000
INC	0.1976	0.4905	0.3119
DGC	0.1698	0.3873	0.4429
SNC	0.3873	0.4429	0.1698
RLC	0.3873	0.1698	0.4429
PML	0.5390	0.1638	0.2973
EMH	0.1007	0.4330	0.4663
CBF	0.2308	0.0769	0.6923
SUT	0.0909	0.7273	0.1818
QTM	0.1513	0.3767	0.4720
DPC	0.1638	0.2973	0.5390
DFR	0.1638	0.2973	0.5390
SCR	0.1638	0.2973	0.5390
REW	0.1593	0.2519	0.5889
COQ	0.1638	0.2973	0.5390
RMI	0.2409	0.2106	0.5485
WIP	0.5571	0.1226	0.3202
FGI	0.1976	0.4905	0.3119
PLC	0.2973	0.1638	0.5390
IMT	0.1429	0.4286	0.4286
EAT	0.1698	0.3873	0.4429
EMP	0.0637	0.2674	0.6689
TOR	0.6479	0.2299	0.1222
COM	0.5485	0.2409	0.2106
NOW	0.2500	0.5000	0.2500
AAR	0.2409	0.2106	0.5485
JRE	0.0526	0.4737	0.4737
MOR	0.0526	0.4737	0.4737
OCS	0.3278	0.2611	0.4111
LER	0.3873	0.1698	0.4429
PRO	0.4330	0.1007	0.4663
UOR	0.4905	0.1976	0.3119
TTT	0.4737	0.0526	0.4737
TPT	0.4706	0.0588	0.4706
RTC	0.1000	0.1000	0.8000
FLX	0.0640	0.4367	0.4992
QTY	0.1924	0.1749	0.6327
INV	0.5455	0.0845	0.3700
LTM	0.4667	0.0667	0.4667
LOT	0.4615	0.0769	0.4615

Table 3.9: Weightages of attributes for alternatives

Sub-attributes	L3 - Wt	L2 - Wt	TL	JS	CMS
SUC	0.16	0.34	0.1111	0.2222	0.6667
LRC	0.08	0.34	0.1578	0.1867	0.6555
EQC	0.06	0.34	0.4000	0.4000	0.2000
TLC	0.03	0.34	0.2106	0.2409	0.5485
MHC	0.02	0.34	0.1279	0.5119	0.3601
UTC	0.05	0.34	0.2000	0.6000	0.2000
INC	0.05	0.34	0.1976	0.4905	0.3119
DGC	0.03	0.34	0.1698	0.3873	0.4429
SNC	0.41	0.34	0.3873	0.4429	0.1698
RLC	0.10	0.34	0.3873	0.1698	0.4429
PML	0.29	0.19	0.5390	0.1638	0.2973
EMH	0.11	0.19	0.1007	0.4330	0.4663
CBF	0.07	0.19	0.2308	0.0769	0.6923
SUT	0.05	0.19	0.0909	0.7273	0.1818
QTM	0.25	0.19	0.1513	0.3767	0.4720
DPC	0.23	0.19	0.1638	0.2973	0.5390
DFR	0.45	0.12	0.1638	0.2973	0.5390
SCR	0.15	0.12	0.1638	0.2973	0.5390
REW	0.27	0.12	0.1593	0.2519	0.5889
COQ	0.14	0.12	0.1638	0.2973	0.5390
RMI	0.24	0.05	0.2409	0.2106	0.5485
WIP	0.55	0.05	0.5571	0.1226	0.3202
FGI	0.21	0.05	0.1976	0.4905	0.3119
PLC	0.45	0.06	0.2973	0.1638	0.5390
IMT	0.13	0.06	0.1429	0.4286	0.4286
EAT	0.22	0.06	0.1698	0.3873	0.4429
EMP	0.19	0.06	0.0637	0.2674	0.6689
TOR	0.32	0.07	0.6479	0.2299	0.1222
COM	0.18	0.07	0.5485	0.2409	0.2106
NOW	0.12	0.07	0.2500	0.5000	0.2500
AAR	0.05	0.07	0.2409	0.2106	0.5485
JRE	0.04	0.07	0.0526	0.4737	0.4737
MOR	0.09	0.07	0.0526	0.4737	0.4737
OCS	0.11	0.07	0.3278	0.2611	0.4111
LER	0.10	0.07	0.3873	0.1698	0.4429
PRO	0.16	0.16	0.4330	0.1007	0.4663
UOR	0.09	0.16	0.4905	0.1976	0.3119
TTT	0.06	0.16	0.4737	0.0526	0.4737
TPT	0.03	0.16	0.4706	0.0588	0.4706
RTC	0.02	0.16	0.1000	0.1000	0.8000
FLX	0.05	0.16	0.0640	0.4367	0.4992
QTY	0.05	0.16	0.1924	0.1749	0.6327
INV	0.03	0.16	0.5455	0.0845	0.3700
LTM	0.41	0.16	0.4667	0.0667	0.4667
LOT	0.10	0.16	0.4615	0.0769	0.4615

Table 3.10: Data summary

Sub-attributes	TL	JS	CMS
SUC	0.0061	0.0121	0.0363
LRC	0.0036	0.0067	0.0190
EQC	0.0065	0.0065	0.0065
TLC	0.0034	0.0034	0.0034
MHC	0.0009	0.0038	0.0027
UTC	0.0023	0.0105	0.0028
INC	0.0031	0.0101	0.0056
DGC	0.0015	0.0055	0.0050
SNC	0.0552	0.0631	0.0242
RLC	0.0235	0.0031	0.0086
PML	0.0301	0.0091	0.0166
EMH	0.0021	0.0090	0.0096
CBF	0.0029	0.0010	0.0087
SUT	0.0009	0.0074	0.0019
QTM	0.0071	0.0176	0.0221
DPC	0.0072	0.0131	0.0237
DFR	0.0087	0.0157	0.0285
SCR	0.0028	0.0051	0.0093
REW	0.0050	0.0080	0.0187
COQ	0.0026	0.0048	0.0086
RMI	0.0029	0.0025	0.0065
WIP	0.0151	0.0033	0.0087
FGI	0.0021	0.0051	0.0032
PLC	0.0082	0.0045	0.0149
IMT	0.0011	0.0033	0.0033
EAT	0.0023	0.0053	0.0061
EMP	0.0008	0.0032	0.0079
TOR	0.0153	0.0054	0.0029
COM	0.0072	0.0032	0.0028
NOW	0.0021	0.0042	0.0021
AAR	0.0009	0.0008	0.0020
JRE	0.0001	0.0013	0.0013
MOR	0.0003	0.0031	0.0031
OCS	0.0025	0.0020	0.0031
LER	0.0028	0.0012	0.0032
PRO	0.0112	0.0026	0.0121
UOR	0.0068	0.0028	0.0044
TTT	0.0044	0.0005	0.0044
TPT	0.0024	0.0003	0.0024
RTC	0.0004	0.0004	0.0028
FLX	0.0005	0.0032	0.0037
QTY	0.0017	0.0016	0.0057
INV	0.0031	0.0005	0.0021
LTM	0.0316	0.0045	0.0316
LOT	0.0075	0.0012	0.0075

Table 3.11: Desirability indices for alternatives

TL	:	0.2589
JS	:	0.2816
CMS	:	0.4595

The Most Desirable Alternative is: CMS

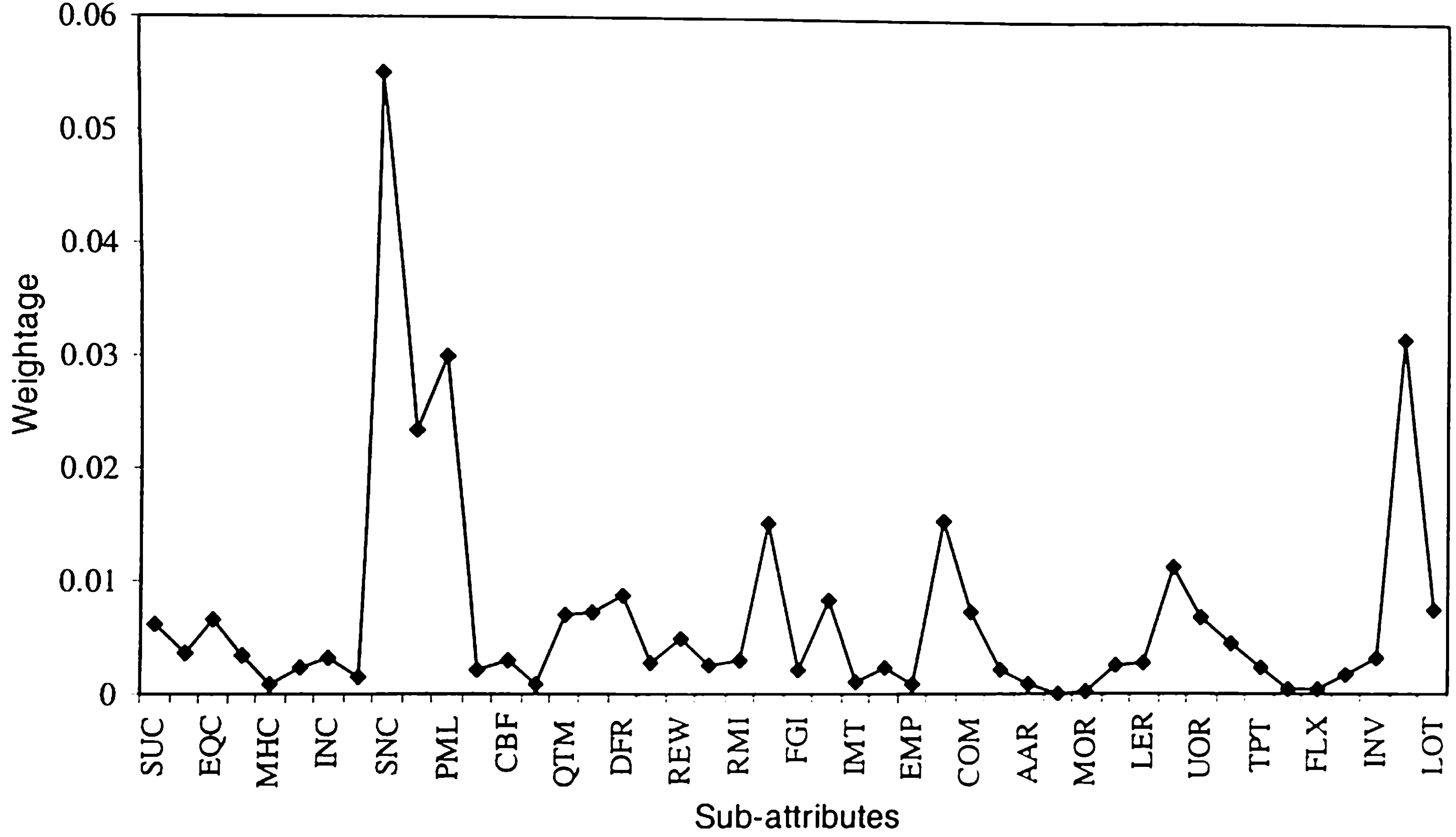

Figure 3.2: Data summary for alternative: Transfer Line (TL)

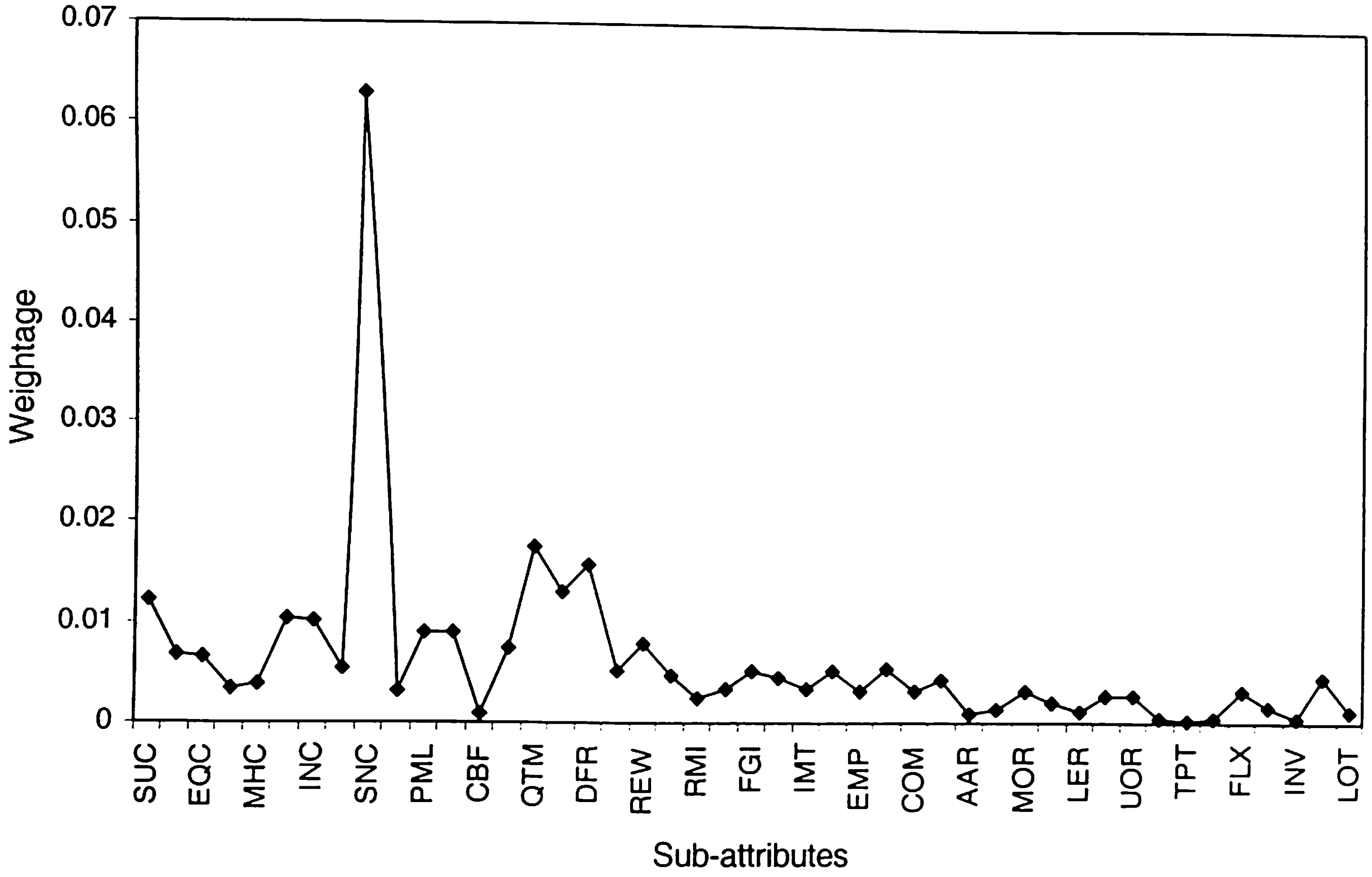

Figure 3.3: Data summary for alternative : Job Shop (JS)

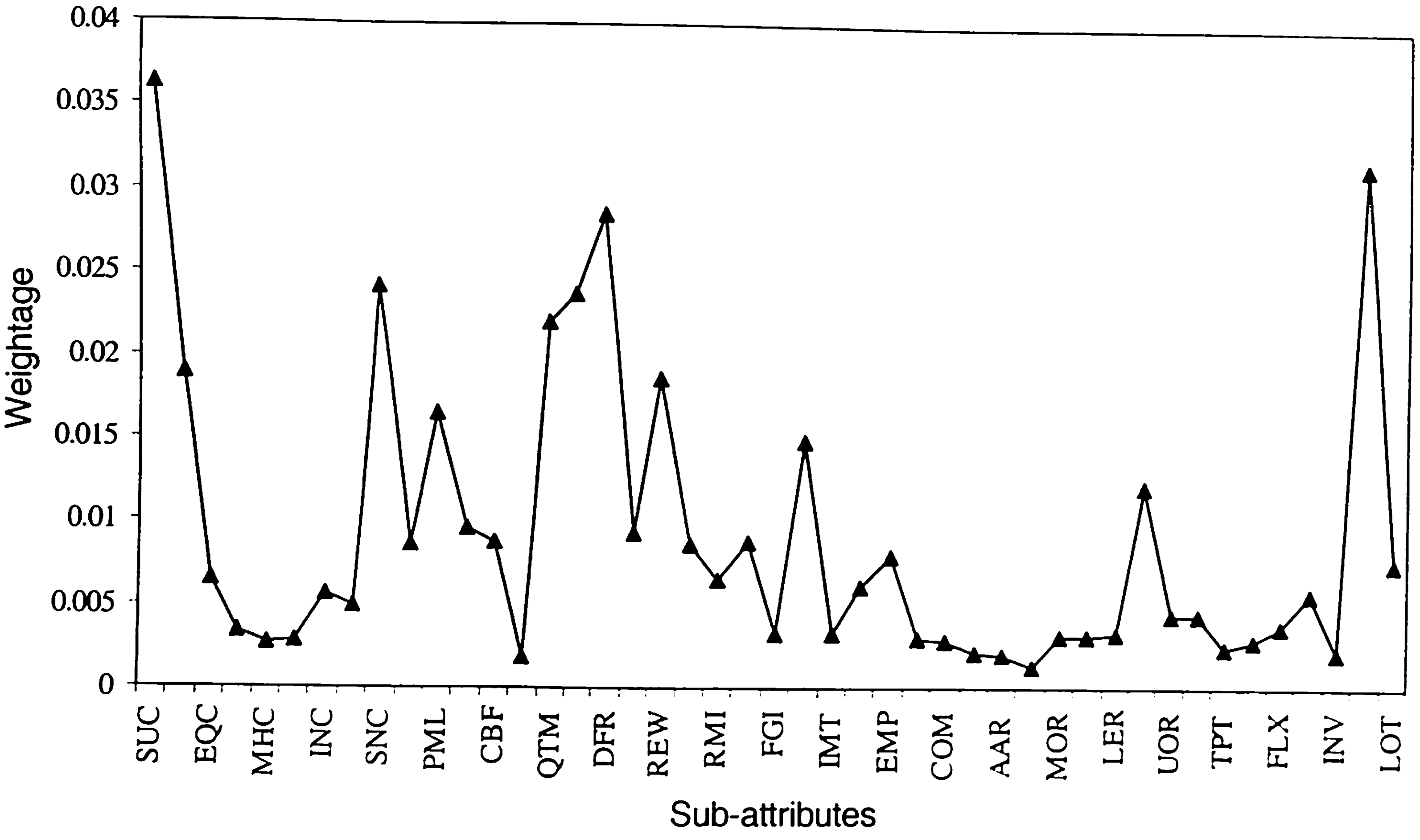

Figure 3.4: Data summary for alternative: Cellular Manufacturing Systems (CMS)

3.3 Development of Performance Value Analysis (PVA) Model for Justification of CMS

In recent years the CMS has been widely considered for implementation to maintain competitive advantage. However, the implementation of such systems is expensive and relative investments tend to be irreversible, thus necessarily requiring careful consideration before a decision can be made. Decision making is not only strategic but also involves issues at the tactical and operational levels. The decision making process depends upon both the quantitative and qualitative criteria involving a lot of factors. The performance value analysis model is well received in literature (D'Angelo *et al.* 1996). This model is revised version of utility value analysis. PVA model is introduced with respect to different objectives, considering appropriate performance indicators related to Cost (CST), Process (PRS), Quality (QTY), Inventory (INV), Implementation (IMP), Workforce (WFC), and Benefits (PMB). The performance value analysis, a multi-criteria technique that aggregates the multiple criteria, is here applied on data obtained from literature and experts (Heragu 1994, Wemmerlov and Hyer 1987, Zahran *et al.* 1992, Huq 1992, Afzulpurkar *et al.* 1993, Choi 1996, Singh and Rajamani 1996, Singh 1996, Wemmerlov and Johnson 1997, 2000, Olorunniwo 1997, Masnata and Settineri 1997, Talluri *et al.* 1997, Shang and Tadikamalla 1998, Eckstein and Rohleder 1998, Dale 1999, Primrose 1999, Choobineh and Nare 1999, Marsh *et al.* 1999).

The steps to follow in using the performance value analysis are:

Step 1. Define the problem and determine the objective.

Step 2. Identify the alternatives (a_i) available. (The alternatives are: transfer line [TL], job shop [JS], and cellular manufacturing system [CMS]).

Step 3. Determine the attributes/criteria/performance indicators (c_j) that govern the problem.

Step 4. Classify the attributes/criteria/performance indicators into significant categories.

Step 5. Classify the attributes/criteria/performance indicators into direct (performance grows while measure increases) and indirect categories (performance grows while measure decreases). (Steps 3, 4, and 5 are shown in table 3.12)

Step 6. Form the performance matrix, i.e., co-efficient e_{ij} related to the attribute/criterion/performance indicator c_j ($j = 1, 2, \ldots J$) and the alternative a_i ($i=1, 2, \ldots I$) (see table 3.13)

Step 7. Quantify the qualitative attributes using the scale of 1 to 10, where 1 means very low, 3 means low, 5 means medium, 7 means high, and 9 means very high.

Step 8. Absolute weightage w_j on a suitable scale (say 1 to 10) is assigned for each attribute/criterion/performance indicator reflecting the normative judgment of the decision maker.

Step 9. Form the normalized performance matrix. It is transforming the initial performance measure in a score/weight for easier interpret based on the value function f_j for each attribute/criterion/performance indicator (c_j) as follows:

i) Direct category (when performance increases while measure increases)

$$p_{ij} = \frac{e_{ij}}{\max(e_j)}$$

for each alternative a_i related to attribute c_j

ii) Indirect category (when performance grows while measure decreases)

$$p_{ij} = \frac{\min(e_j)}{e_{ij}}$$

for each alternative a_i related to attribute c_j

The normalized performance matrix is given in table 3.14.

Step 10. Obtain the relative weightage for each attribute/criterion/performance indicator (c_j) from absolute weightage w_j:

$$\overline{W_j} = \frac{w_j}{\sum w_j} \quad \text{such that} \sum \overline{W_j} = 1$$

Step 11. Obtain partial performance measure Z_{ij} by multiplying relative weightage $\overline{W_j}$ of attribute/criterion/performance indicator to each of its row members (alternatives), i.e., p_{ij} as:

Partial performance of j^th^ attribute: $Z_{ij} = p_{ij} \times \overline{W_j}$ (i = 1, 2, . . . I)

Step 12. Aggregate the partial performance measures for each alternative as: overall measure (N_i) of alternative a_i is the sum of Z_{ij}

$$N_i = \sum_{j=1}^{J} Z_{ij}$$

(Steps 10, 11, and 12 are shown in table 3.15)

Step 13. Rank the alternatives (a_i) in accordance with decreasing value of N_i

Step 14. Perform the significant category analysis. The results of this analysis are obtained by setting to zero the weights of each attribute/criterion/performance indicator different from the significant category being considered. Run step 8 to step 13. Repeat the step 14 for all significant categories.

Step 15. Take the decision based on above aggregated partial performance measures and the aggregated performance measures of significant categories (see table 3.16).

Highly user-friendly software, the PVA model is developed in VC^{++} to aid the user to compute the partial performance measures for all performance indicators/attributes/ criteria and to compute the significant category analysis. The decision can be taken based on the figures (figures 3.5 - 3.14) and table 3.16 generated by the developed software.

Table 3.12: Criteria/attributes/performance indicators

Criteria/attributes/performance indicators	Direct/ Indirect	Significant category
Setup cost [SUC]	▼	CST
Labour cost [LRC]	▼	CST
Equipment cost [EQC]	▼	CST
Tooling cost [TLC]	▼	CST
Material handling cost [MHC]	▼	CST
Unit cost [UTC]	▼	CST
Inspection cost [INC]	▼	CST
Design cost [DGC]	▼	CST
Supervision cost [SNC]	▼	CST
Relocation cost [RLC]	▼	CST
Production modes/Layout styles [PML]	▲	PRS
Choice of equipment and MHS [EMH]	▲	PRS
Capacity balancing and product flow [CBF]	▼	PRS
Setup time/tooling [SUT]	▼	PRS
Quality tools/management [QTM]	▲	PRS
Disciplined production control [DPC]	▲	PRS
Defect rate [DFR]	▼	QTY
Scrap rate [SCR]	▼	QTY
Rework [REW]	▼	QTY
Consistent quality [COQ]	▲	QTY
Raw material inventory [RMI]	▼	INV
Work in process [WIP]	▼	INV
Finished goods inventory [FGI]	▼	INV
Planning for conversion [PLC]	▼	IMP
Implementation time [IMT]	▼	IMP
Education and training [EAT]	▼	IMP
Empowerment [EMP]	▲	IMP
Turnover rate [TOR]	▼	WFC
Commitment [COM]	▲	WFC
Number of workers [NOW]	▼	WFC
Assessment and rewards [AAR]	▲	WFC
Job rotation/enrichment [JRE]	▲	WFC
Morale [MOR]	▲	WFC
Operator/cell leader selection [OCS]	▼	WFC
Learning rate [LER]	▲	WFC
Productivity [PRO]	▲	PMB
Resource utilization [UOR]	▲	PMB
Transfer/transport time [TTT]	▼	PMB
Throughput time [TPT]	▼	PMB
Response time to customer [RTC]	▼	PMB
Flexibility [FLX]	▲	PMB
Quality [QTY]	▲	PMB
Inventory [INV]	▼	PMB
Lead time [LTM]	▼	PMB
Lot size [LOT]	▼	PMB

The best value is the lowest one (Indirect) ▼
The best value is the highest one (Direct) ▲

Table 3.13: Performance matrix

Criteria	Weights	TL	JS	CMS
SUC	4	2.75	2.5	1.5
LRC	4	5.5	5	4.1
EQC	3	5.5	5	4.1
TLC	7	11	10	8
MHC	5	5.5	8	4
UTC	8	Medium	High	Low
INC	6	1.65	1.5	1.2
DGC	3	2.75	2.5	2.4
SNC	2	2.75	2.5	2
RLC	4	Very High	Low	High
PML	9	Low	Very High	Very High
EMH	4	Low	High	Very High
CBF	8	Very High	Low	Low
SUT	9	3	20	1
QTM	6	Low	Medium	Very High
DPC	6	Medium	Low	Very High
DFR	7	5	10	1
SCR	8	2.5	5	0.5
REW	4	2.5	5	0.5
COQ	5	High	High	Very High
RMI	6	19	34	8
WIP	9	12	20	10
FGI	6	11	17	4
PLC	7	High	Low	Very High
IMT	5	5	1	1.5
EAT	2	1.5	1.25	2.5
EMP	8	Low	High	Very High
TOR	7	25.6	12.3	2.2
COM	6	Low	Medium	Very High
NOW	7	132	175	40
AAR	3	Low	Low	Very High
JRE	5	Low	High	Very High
MOR	6	Medium	High	Very High
OCS	1	Low	High	Medium
LER	3	Low	High	Very High
PRO	7	40	30	60
UOR	8	86	40.25	94.5
TTT	9	6.27	12	3.3
TPT	7	Low	High	Very Low
RTC	8	Very High	Low	Low
FLX	4	Low	High	High
QTY	7	High	High	Very High
INV	5	Low	Very High	Low
LTM	6	15.1	20.4	9
LOT	2	Very Low	High	Low

Table 3.14: Normalized performance matrix

Criteria	Relative Wts	TL	JS	CMS
SUC	0.0156	0.5454	0.6	1
LRC	0.0156	0.7454	0.82	1
EQC	0.0117	0.7454	0.82	1
TLC	0.0273	0.7272	0.8	1
MHC	0.0195	0.7272	0.5	1
UTC	0.0313	0.6	0.4285	1
INC	0.0234	0.7272	0.8	1
DGC	0.0117	0.8727	0.96	1
SNC	0.0078	0.7272	0.8	1
RLC	0.0156	0.3333	1	0.43
PML	0.0352	0.3333	1	1
EMH	0.0156	0.3333	0.7777	1
CBF	0.0313	0.3333	1	1
SUT	0.0352	0.3333	0.05	1
QTM	0.0234	0.3333	0.5555	1
DPC	0.0234	0.5555	0.3333	1
DFR	0.0273	0.2	0.1	1
SCR	0.0313	0.2	0.1	1
REW	0.0156	0.2	0.1	1
COQ	0.0195	0.7777	0.7777	1
RMI	0.0234	0.4210	0.4	1
WIP	0.0352	0.8333	0.5	1
FGI	0.0234	0.3636	0.2	1
PLC	0.0273	0.4285	1	0.3333
IMT	0.0195	0.3	1.5	1
EAT	0.0078	0.8333	1	0.5
EMP	0.0313	0.3333	0.7777	1
TOR	0.0273	0.0859	0.1788	1
COM	0.0234	0.3333	0.5555	1
NOW	0.0273	0.3030	0.2285	1
AAR	0.0117	0.3333	0.3333	1
JRE	0.0195	0.3333	0.7777	1
MOR	0.0234	0.5555	0.7777	1
OCS	0.0039	1	0.4285	0.6
LER	0.0117	0.3333	0.7777	1
PRO	0.0273	0.6666	0.5	1
UOR	0.0313	0.9100	0.4259	1
TTT	0.0352	0.5263	0.275	1
TPT	0.0273	0.3333	0.1428	1
RTC	0.0313	0.3333	1	1
FLX	0.0156	0.4285	1	1
QTY	0.0273	0.7777	0.7777	1
INV	0.0195	1	0.3333	1
LTM	0.0234	0.5960	0.4411	1
LOT	0.0078	1	0.1428	0.3333

Table 3.15: Partial performance measures

Criteria	TL	JS	CMS
SUC	0.0085	0.0094	0.0156
LRC	0.0116	0.0128	0.0156
EQC	0.0087	0.0096	0.0117
TLC	0.0199	0.0219	0.0273
MHC	0.0142	0.0098	0.0195
UTC	0.0187	0.0134	0.0313
INC	0.017	0.0187	0.0234
DGC	0.0102	0.0113	0.0117
SNC	0.0057	0.0063	0.0078
RLC	0.0052	0.0156	0.0067
PML	0.0117	0.0352	0.0352
EMH	0.0052	0.0122	0.0156
CBF	0.0187	0.0313	0.0313
SUT	0.0117	0.0018	0.0352
QTM	0.013	0.0078	0.0234
DPC	0.013	0.0078	0.0234
DFR	0.0055	0.0027	0.0273
SCR	0.0063	0.0031	0.0313
REW	0.0031	0.0016	0.0156
COQ	0.0152	0.0152	0.0195
RMI	0.0099	0.0055	0.0234
WIP	0.0293	0.0176	0.0352
FGI	0.0085	0.0055	0.0234
PLC	0.0117	0.0273	0.0091
IMT	0.0039	0.0195	0.013
EAT	0.0065	0.0078	0.0039
EMP	0.0104	0.0243	0.0313
TOR	0.0023	0.0049	0.0273
COM	0.0078	0.013	0.0234
NOW	0.0083	0.0062	0.0273
AAR	0.0039	0.0039	0.0117
JRE	0.0065	0.0152	0.0195
MOR	0.013	0.0182	0.0234
OCS	0.0039	0.0028	0.0028
LER	0.0065	0.0091	0.0117
PRO	0.0182	0.0137	0.0273
UOR	0.0284	0.0133	0.0313
TTT	0.0185	0.0097	0.0352
TPT	0.0091	0.0055	0.0273
RTC	0.0104	0.0313	0.0313
FLX	0.0067	0.0156	0.0156
QTY	0.0091	0.0213	0.0273
INV	0.0195	0.0065	0.0195
LTM	0.014	0.0103	0.0234
LOT	0.0078	0.0011	0.0026
Total	**0.4978**	**0.5565**	**0.9561**

The Most Desirable Alternative is: CMS

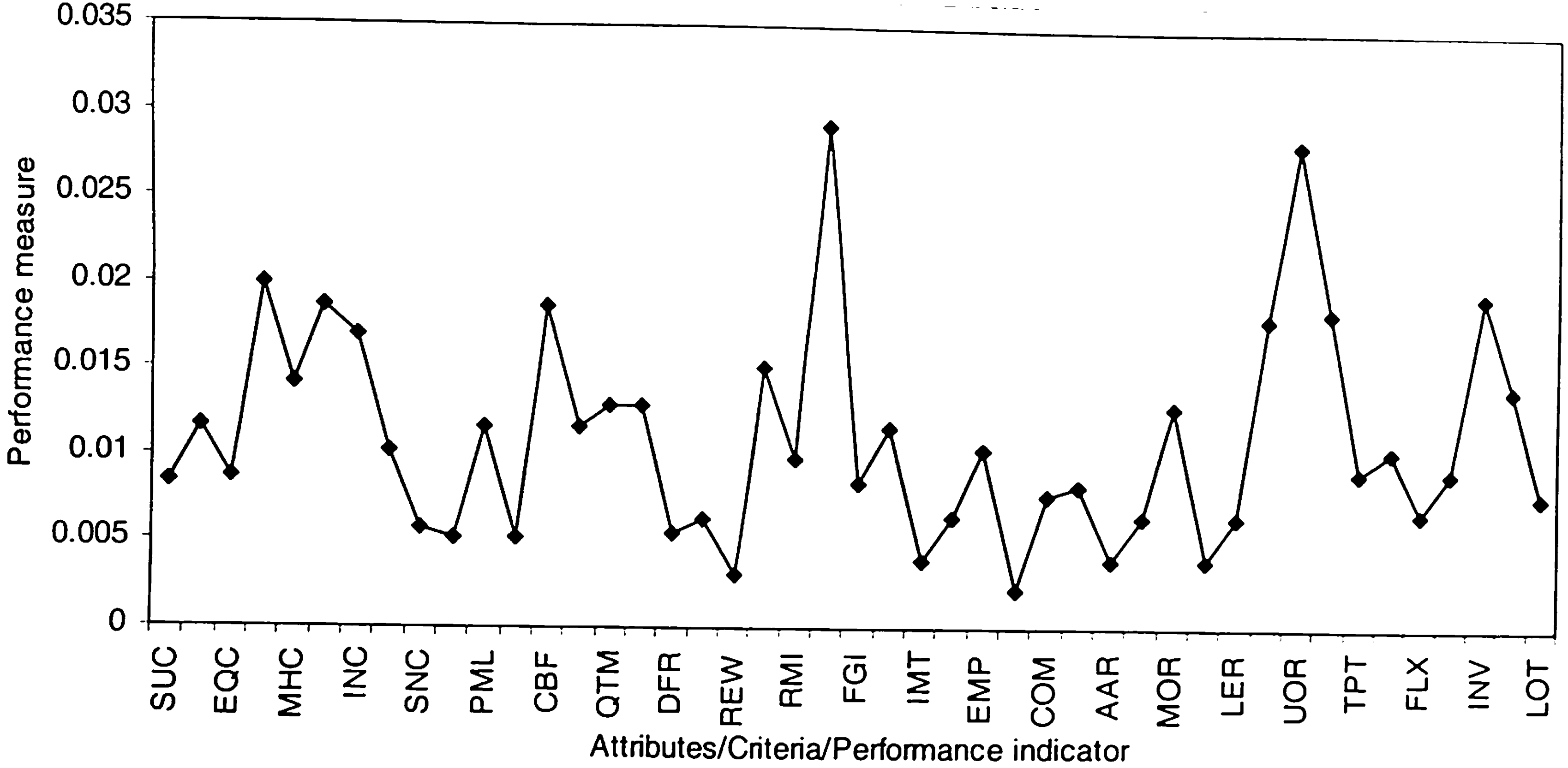

Figure 3.5: Partial performance measure for alternative: Transfer Line (TL)

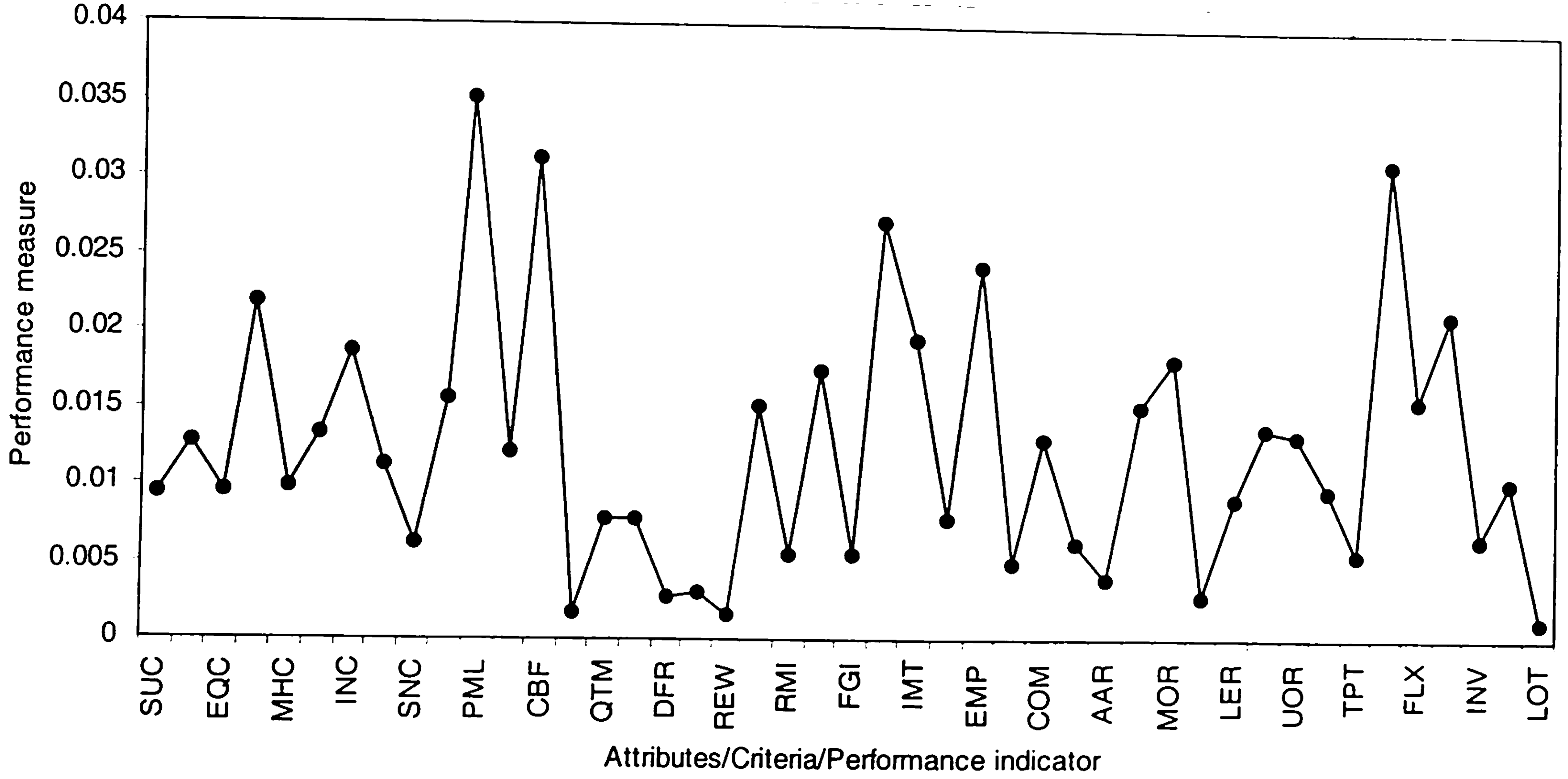

Figure 3.6: Partial performance measure for alternative: Job Shop (JS)

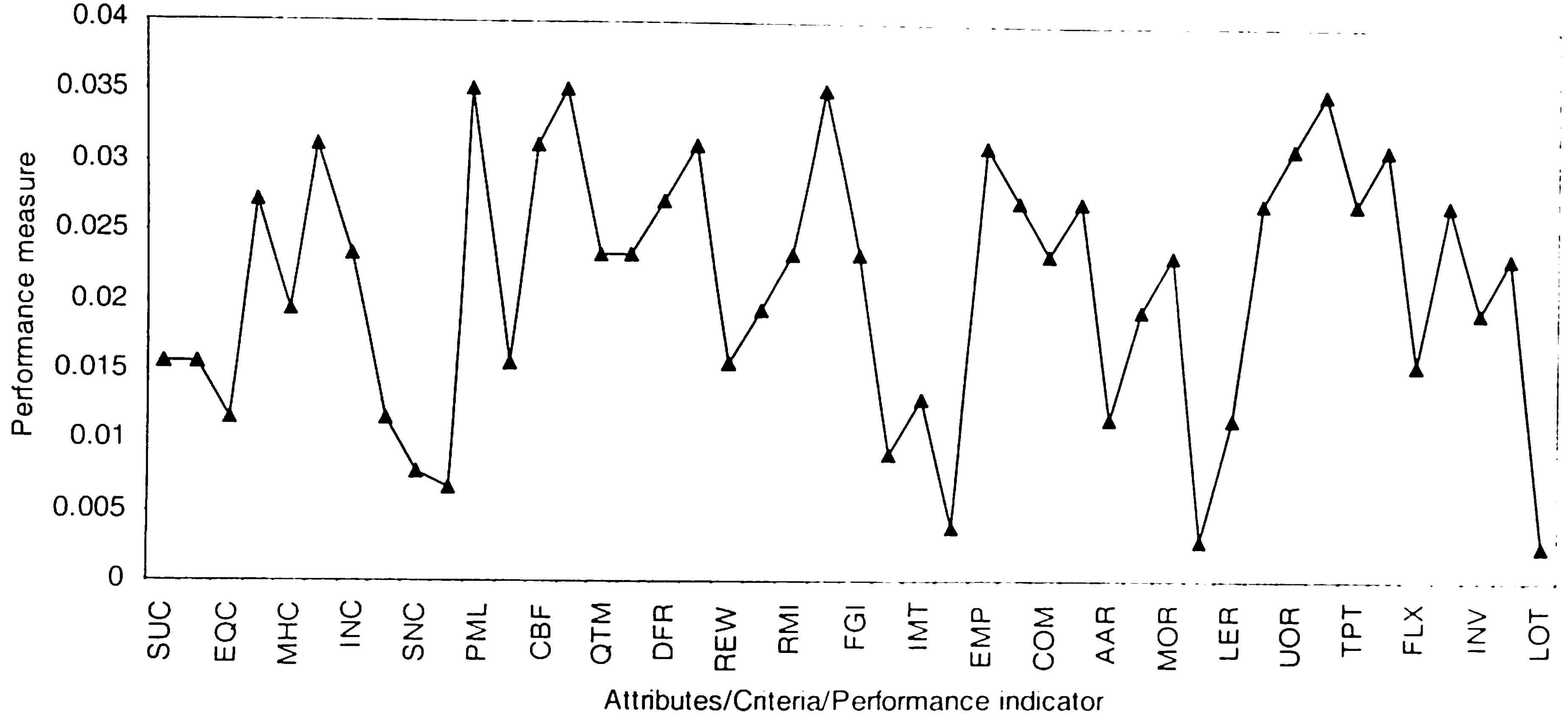

Figure 3.7: Partial performance measure for alternative: Cellular Manufacturing Systems (CMS)

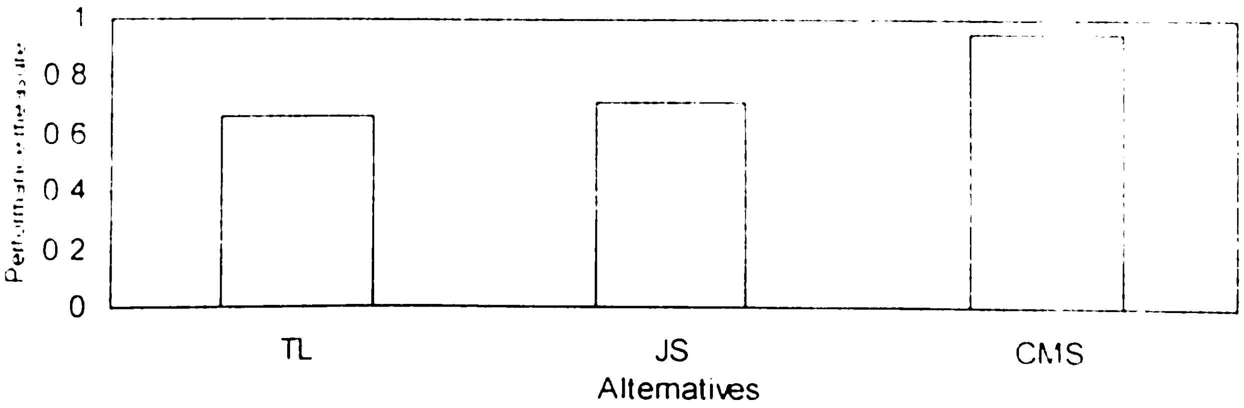

Figure 3.8: Significant category analysis based on cost (CST)

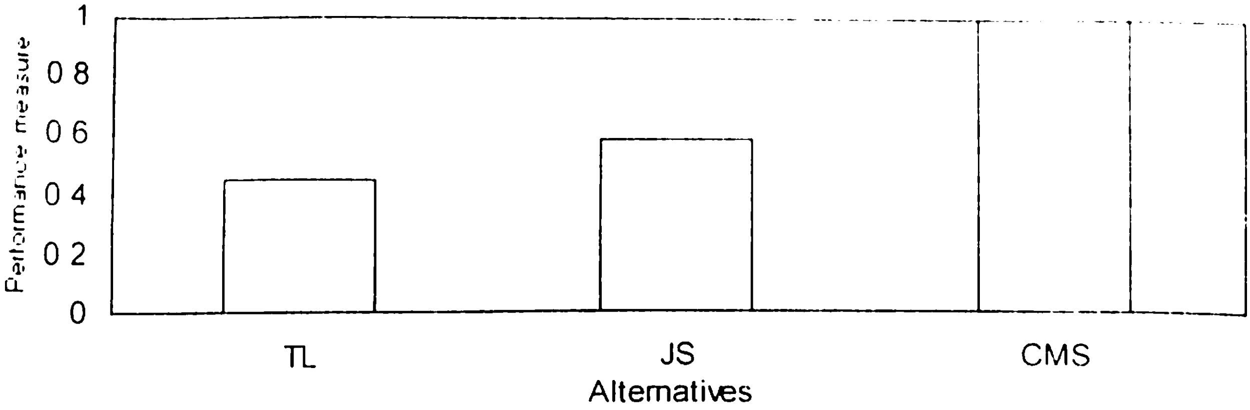

Figure 3.9: Significant category analysis based on process (PRS)

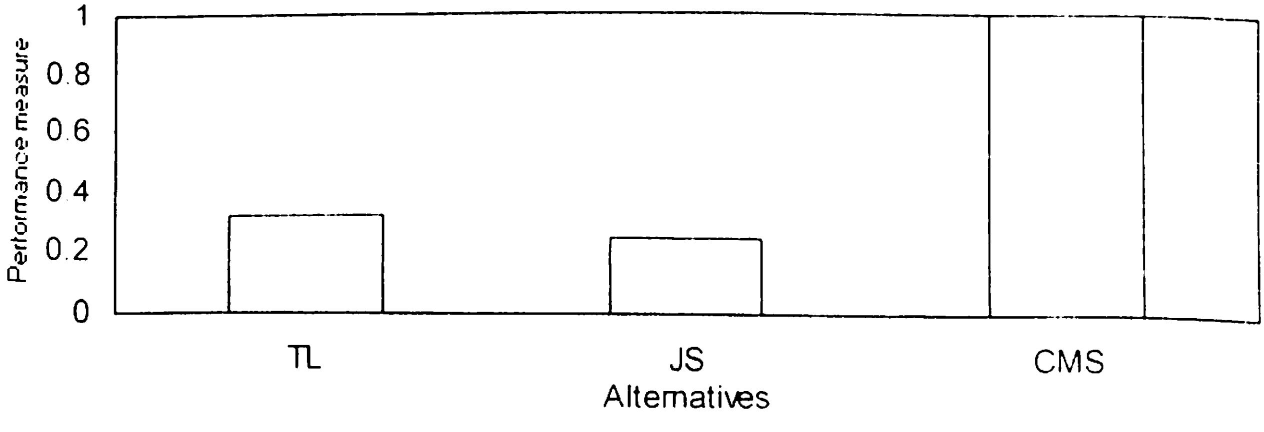

Figure 3.10: Significant category analysis based on quality (QTY)

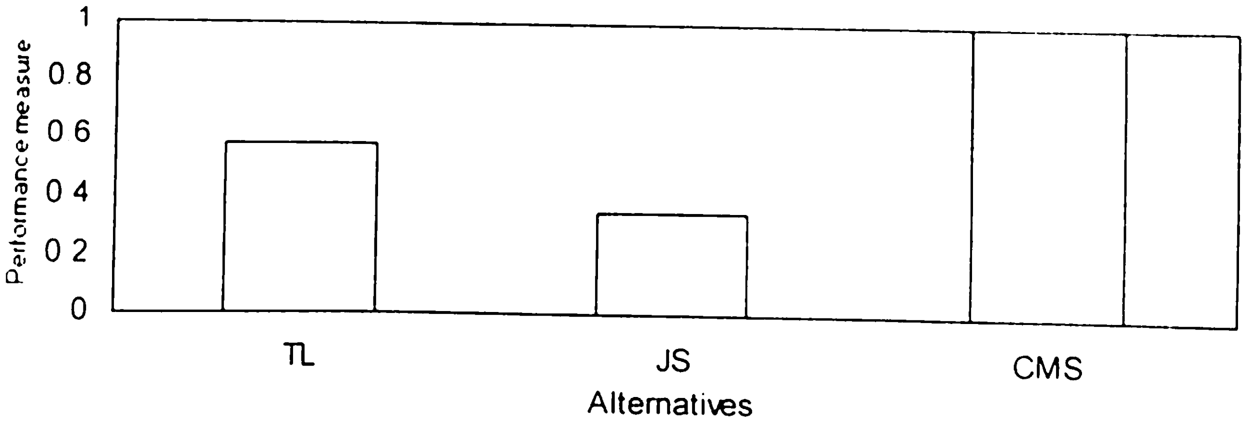

Figure 3.11: Significant category analysis based on inventory (INV)

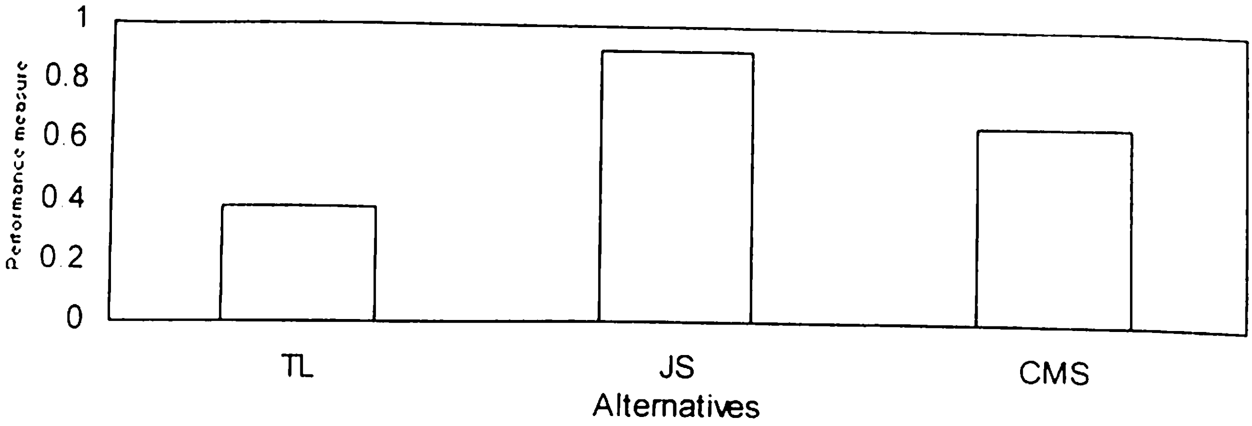

Figure 3.12: Significant category analysis based on implementation (IMP)

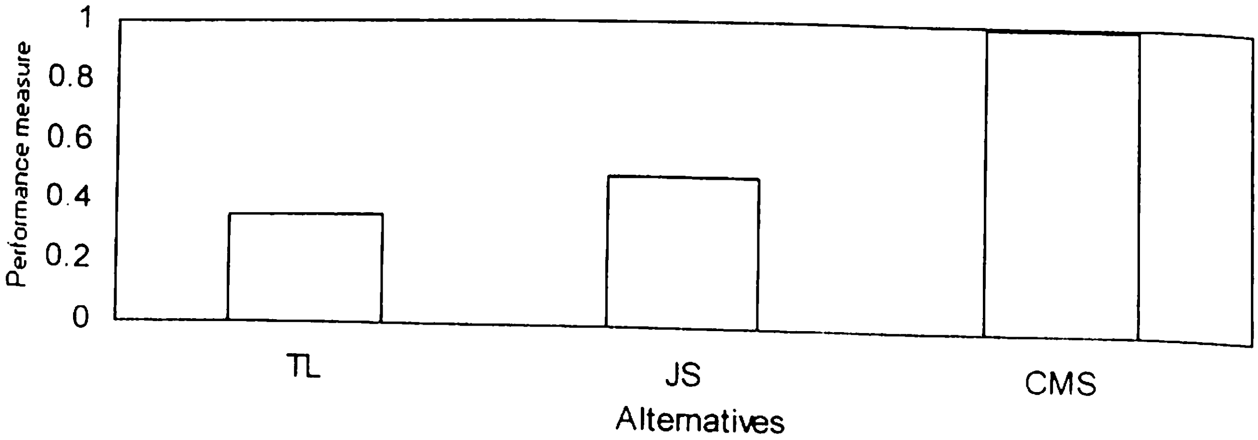

Figure 3.13: Significant category analysis based on workforce (WFC)

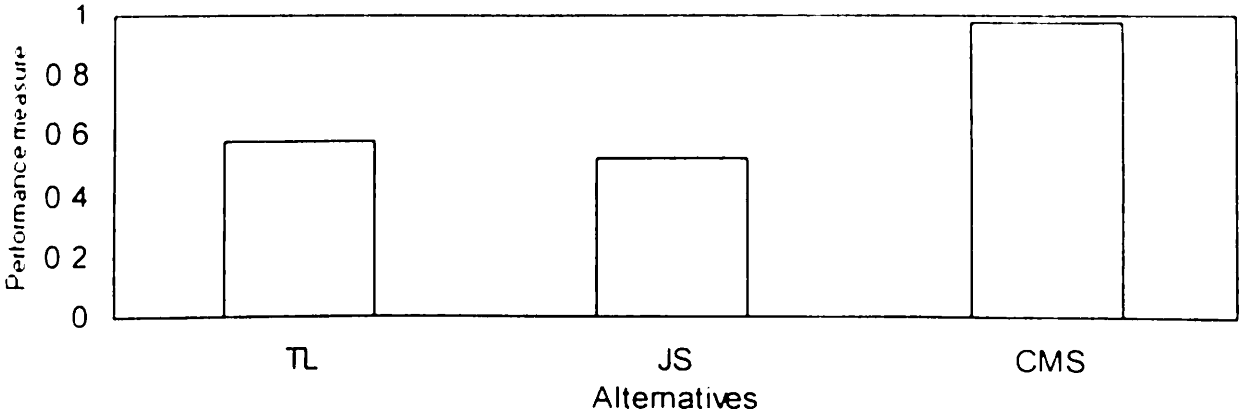

Figure 3.14: Significant category analysis based on benefits (PMB)

Table 3.16: Aggregated indices for alternatives

	Significant category analysis							Total performance analysis
	CST	PRS	QTY	INV	IMP	WFC	PMB	
TL	0.6673	0.4476	0.3204	0.5813	0.3788	0.3524	0.5763	0.4978
JS	0.7163	0.8848	0.2412	0.3487	0.9192	0.4944	0.5211	0.5565
CMS	0.9503	1.0	1.0	1.0	0.6667	0.9925	0.9788	0.9561

3.1 Conclusions

In this chapter, two multi-criteria decision models for the justification of CMS have been developed. One is analytical hierarchy process and the other is performance value analysis. From the results of both the models, it is evident that the CMS is the best alternative for implementation and to maintain competitive advantage. In this chapter, one such attempt is made to demonstrate the usefulness of the multi-attribute decision models for justification of CMS.

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Chapter 4

Part Family Formation

4.1 Introduction

The biggest single design problem in changing over to a cellular system from an existing system is the problem of grouping parts into families (Irani *et al.* 1999). A part family is a collection of parts that share some common attributes. Part family formation deals with the recognition and classification of parts into part families based on certain attributes of the parts. This serves as a prelude to the overall process of cellular manufacturing implementation and can have far reaching effects on the performance of the manufacturing system. The decomposition; based on similarities of design attributes, manufacturing features, and functions; leads to improved productivity in various functional areas of organization. For example, in product design, parts are classified and coded on the basis of their geometric similarities. The emphasis is on families of parts having similarities of function, shape, and size. When designing a new part, a design engineer can find a part in the database that has geometric and functionality features similar to those of the new part. In some cases, only minimal modifications may be necessary. This results in the reduced time and cost of product development. In manufacturing, productivity and cost saving are realized by exploiting similarities in machining operations, tooling, setup procedure, and material handling. Parts having similar manufacturing requirements can be processed together in dedicated work cells, leading to reduced setups, tooling, and material handling.

In this chapter, a literature review on part family formation approaches is presented followed by two models developed for the part family formation. First model uses fuzzy logic and AHP and the second model uses fuzzy equivalence relations and AHP.

4.2 Literature Review

The most popular and most researched area in cellular manufacturing is to base part's similarity on their processing requirements with an objective of processing a part family in a self-sufficient machine cell with minimum intercellular movements. Three most commonly used methods for part family formation are:

- Eyeballing or visual inspection method
- Product flow analysis
- Classification and coding systems

Eyeballing

The eyeballing method also called visual inspection method is the simplest and least expensive method. It involves the classification of parts into families by looking either at the parts themselves or their drawings and arranging them into groups based on general criteria. This method is very limited in scope when dealing with a large number of parts.

Production Flow Analysis (PFA)

Production flow analysis was first introduced by Burbidge (1963, 1971, 1975, 1991) and is a method for forming part families and machine groups by analysing the production process data listed in the route sheets of parts produced in a factory. It groups together the parts that have similar operation sequences. This method requires reliable and well-documented route sheets. Therefore, a drawback of PFA is that it assumes the accuracy of existing route sheets, with no consideration given to whether those process plans are up-to-date or optimal with respect to the existing mix of machines.

Parts Classification and Coding

Classification and coding systems have emerged during early development period of group technology. This method attempts to group parts with identical or similar design and manufacturing attributes into families. Parts that are similar in shape or function could be made in the same group (Gombinski 1964). Attributes of a part such as dimensions, shape features, auxiliary holes, or gear teeth are captured in a code number. The code number for each part provides a compact and consistent description of the attributes of each part. Such numerically processable information serves as a basis for sorting and grouping the parts into families. A part's code can consists of a numerical, alphabetical, or alpha-numerical string. Dunlap and Hirlinger (1983) contended that well planned coding and classification system offers company wide synergic benefits.

A large number of classification and coding systems have been developed, and a number of commercial codes are available. Opitz (1970) explained his coding scheme for parts, which is based on the geometric and technical features. Opitz and Weindahl (1971) extended the classification scheme for a form code and supplementary code of five digits and four digits respectively. A brief summary of 44 systems is given in Ham *et al.* (1985). A comparative evaluation of four systems - BRISCH BIRN, CODE, MICLASS/MULTICLASS, and Opitz - based on usage, structure and length, computer strength, and other special features, is given in Hyer and Wemmerlov (1984). Eckert (1975), Gallagher and Knight (1973), and Bedworth *et al.* (1991) have also presented the details of some coding schemes. Kamrani and Parsaei (1994) developed a methodology for part family formation using dissimilarity between parts and formulated a 18-digit code (KAMCODE).

Parts classification and coding is a highly time-consuming and complicated activity. Three types of coding structures are: Monocode (hierarchical), Polycode (attribute or chain code), and Mixed (hybrid code).

Monocode

In this system each digit code is dependent on the meaning of the previous digit code. The advantages of this code are that it stores more information in a short code and provides deep analysis. However, the coding system is complicated and very difficult to implement. Monocode is preferred by the design departments to store part attributes.

Polycode

In this system the meaning of each attribute is independent of any other digit within the code. Each attribute of a part is tagged with a specific position in the code. This system is easy to implement but a large number of digits may be required. Polycode is preferred by the manufacturing department.

Mixed code

A mixed code is a combination of both the monocode and polycode systems. These codes consist of few digits connected as monocode followed by the rest of the digits as polycode. Most of the coding systems available are implemented as mixed systems.

Mathematical Approaches

A number of mathematical approaches have also been developed to form part families using classification and coding systems. Kusiak (1983) proposed a hierarchical clustering algorithm to form part families using 'nearest neighboring approach'. In this procedure, the parts are first grouped into a few broad families, each of which is then partitioned into smaller part families and so on. Kusiak (1985, 1987) proposed p-median model to identify f part families optimally, such that the distance between parts in each family is minimized with respect to the median of the family. Unlike the hierarchical clustering algorithm, this model allows parts to be transferred from one family to another to achieve the optimal solution. Gongaware and Ham (1981), and Han and Ham (1986) used part codes in a multi-objective clustering algorithm to form part families. Srinivasan *et al.* (1990) proposed an assignment model for the part families and machine grouping problem based on similarity coefficient. Kumar *et al.* (1986) proposed the quadratic programming model with the objective of maximising the production flow between machines using k-weighted networks. Srinivasan and Moon (1997) proposed a goal driven approach using conceptual clustering techniques to induce part families. A symbolic representation scheme was employed instead of traditional coding systems. Tam (1990) used k-Nearest-Neighbor (kNN) clustering method developed by Wong (1982) for part grouping. They formulated the problem using similarity coefficient that takes into account both the commonality of operations and similarity in operation sequence.

Genetic Algorithms

Hon and Chi (1994) presented an approach for part family formation by using genetic algorithm. They formulated the problem as a 0-1 quadratic integer programming. Lee-Post (2000) presented a novel approach to form part families using a simple genetic algorithm. The technique explored the nature of similarities captured in an existing classification and coding scheme.

Neural Networks

Kao and Moon (1991) have suggested the application of supervised learning rule (back-propagation) for the part family formation. In this model, a few distinctive parts are chosen as seed parts to represent part families and then the network is trained to group the rest of parts into these families. This model has several problems - network was to be trained for the every new part entering the system, the number of part families were predefined, and the learning results depended on the frequency of presenting a part. Chung and Kusiak (1994) presented an application of back-propagation neural networks for generating part families. The network was trained using binary images describing geometric part shapes. To decrease the chances of reaching a local optimum and to speed up the computation process, three parameters - bias, momentum, and learning rate - were taken into consideration. Moon and Chi (1992) adopted a constraint satisfaction model of neural networks for generalized part family formation. In generalized part family formation, several practical factors such as sequence of operations, lot size, and multiple process plans were considered. Liao and Chen (1993) used ART1 model integrated with a feature based design system for automatic Group Technology (GT) coding and part family formation. Henderson and Musti (1988), Bond and Jain (1988), and Kaparthi and Suresh (1991) had developed automatic classification and coding systems for forming part families.

Fuzzy Set Theory

Xu and Wang (1989) presented a technique of forming part families using the concept of fuzzy classification and fuzzy equivalence. In addition, a dynamic part family assignment procedure is presented using the methodology of fuzzy pattern recognition to assign new parts to existing part families. Zhang and Wang (1992) applied fuzzy set methodology by identifying a degree of match or appropriateness between a machine and a part feature on the basis of the dimensional tolerance desired. Ben-Arieh and Triantaphyllou (1992) proposed a methodology for quantifying part features for grouping that deals with crisp and fuzzy data in a unified manner. Narayanaswamy *et al.* (1996) employed a fuzzy logic methodology to handle the dependency or interaction between part features during the determination of the overall suitability of a machine to process a part. The concept of linguistic hedges or modifiers is used to indicate the relative importance of a feature. Uncertainties in the dimensional machine tolerance and processing time were considered and the machine suitabilities were depicted in the form of a non-binary machine-component matrix. Ben-Arieh *et al.* (1996) presented a methodology for coding parts using fuzzy codes. The methodology is general and applies to attributes that have crisp value, an interval value or a fuzzy value. The methodology considered the range of attribute's values relevant for the grouping. Gill and Bector (1997) suggested an approach based on fuzzy linguistics to quantify part feature information for part family formation. Chu and Hayya (1991) have developed a fuzzy c-means clustering algorithm for identifying the degree of membership of a part to a part family in addition to determining the specific part family the part belongs to. Masnata and Settineri (1997) tailored the fuzzy c-means algorithm for developing a non-binary approach to cellular manufacturing. Gindy *et al.* (1995) also proposed an extended version of the fuzzy c-means clustering algorithm for component grouping with cluster validation procedure for selection of optimum number of component groups. Component partitioning is based upon assessing the compactness of components within a group and overlapping between the component groups.

4.3 Fuzzy Mathematics Approach to Part Family Formation

A drawback of non-fuzzy techniques is that they demand precise input data regarding the part's attributes and hence dichotomously force the part to fall into the classification scheme. For example, a part code C depends on the attribute L in the following manner:

$$C = \begin{cases} 0 & \text{for } L<=3 \\ 1 & \text{for } 3<L<=5 \\ 2 & \text{for } L>5 \end{cases}$$

According to this approach, two parts with values of 4.99 and 5.01 will carry two different codes, which may lead to inaccurate grouping. Thus, there is always some uncertainty or fuzziness deeply rooted in the description of the part's feature itself. The application of fuzzy set theory allows a part to belong to different families with different membership.

Suppose that n parts are to be grouped into C families. In the traditional methods, a binary classification matrix is used as follow:

$$A = \begin{array}{c|cccc|} & X_1 & X_2 & \cdots & X_N \\ \hline G_1 & 1 & 0 & \cdots & 0 \\ G_2 & 0 & 1 & \cdots & 0 \\ \cdot & \cdot & \cdot & \cdots & \cdot \\ G_C & 0 & 0 & \cdots & 1 \end{array}$$

$$\text{where } u_{ij} = \begin{cases} 1, \text{if the } j^{th} \text{part belongs to the } i^{th} \text{family} \\ 0, \text{if the } j^{th} \text{part does not belongs to the } i^{th} \text{family} \end{cases}$$

and (1) $u_{ij} = 0 \text{ or } 1 \qquad \forall i, j$

(2) $\sum_{i=1}^{C} u_{ij} = 1 \qquad \forall j$

(3) $\sum_{j=1}^{n} u_{ij} > 0 \qquad \forall i$

As a result component X_j belongs to a group G_i ($u_{ij} = 1$) and does not belong to any other group. Fuzzy clustering has been advocated as an appropriate methodology for part family formation in cases where no clear division between groups can be achieved and hence crisp logic of family formation does not seem appropriate (Wang and Li 1991). According to the fuzzy logic (Kaufmann 1975), components may belong to different groups with various probabilities (fuzzy membership) reflecting the similarity between the component and the component groups. Component membership, therefore, not restricted to a binary value of 0 or 1. Instead it is defined in the whole interval [0, 1] and can be represented by a matrix of the form:

$$A = \begin{array}{c} \\ G_1 \\ G_2 \\ . \\ . \\ G_C \end{array} \begin{array}{c} \begin{array}{cccc} X_1 & X_2 & \cdots & X_N \end{array} \\ \begin{bmatrix} u_{11} & u_{12} & \cdots & u_{1n} \\ u_{21} & u_{22} & \cdots & u_{2n} \\ . & . & \cdots & . \\ . & . & \cdots & . \\ u_{c1} & u_{c2} & \cdots & u_{cn} \end{bmatrix} \end{array}$$

where component membership is defined as:

(1) $0 \le u_{ij} \le 1 \quad \forall i, j$

(2) $\sum_{i=1}^{c} u_{ij} = 1 \quad \forall j$

(3) $\sum_{j=1}^{n} u_{ij} > 0 \quad \forall i$

4.3.1 Introduction to fuzzy set theory

Fuzzy set theory was introduced by Zadeh (1965) to deal with vague, imprecise and uncertain problems. The lack of data is the reason for uncertainty in many daily problems. Fuzzy set theory has been used as a modeling tool for complex systems that are hard to define precisely, but can be controlled and operated by humans. Humans can make decisions in the absence of clearly defined boundaries based on expertise and general knowledge of the task of the system. The human actions are based on the IF-THEN rules, which are developed over the years of knowledge and experience. Basic concepts of fuzzy theory are presented here. More detailed discussion on fuzzy set theory can be found in Zimmerman (1987), Mamdani and Gains (1981), Schmucker (1984), Lee (1990), Zadeh (1965, 1973, 1975, 1978), and Klir *et al.* (1997).

Definition

A collection of objects U has a fuzzy set A described by a membership function μ_A that takes values in the interval [0,1], μ_A: $U \rightarrow [0,1]$. Thus A can be represented as: $A = \{(\mu_A (u)/u) \mid u \varepsilon U\}$. The degree that u belongs to U is the membership function $\mu_A(u)$.

Fuzzy linguistic variables

Linguistic variables take on values that are words in natural language, while numerical variables use numbers as values. Since words are usually less precise than numbers, linguistic variables provide a method to characterize complex systems that are ill-defined to be described in traditional quantitative terms (Zadeh 1975). A linguistic variable is defined by the name of the variable x and the set term $P(x)$ of the linguistic values of x with each value a fuzzy number defined on U. For example, if part attribute similarity is a linguistic variable, then its term set P(part attribute similarity)={Very high, High, Medium, Low, Very low},where each term is characterized by a fuzzy set in a universe of discourse U=[0,1] as shown in figure 4.1. It shows that a part attribute similarity of 0.52 belongs to the linguistic variable *medium* and *high* with membership values of 0.8 and 0.2 respectively

Fuzzy control

Fuzzy set theory is very useful in modeling complex and vague systems. It depicts the control actions of the operators when they can only describe their actions using natural language. Fuzzy set theory is a tool that transforms this linguistic control strategy into mathematical control method. Fuzzy control was first introduced by Mamdani (1974). It has been successfully applied to many areas.

4.3.2 Development of model (Model 1) using fuzzy logic and AHP for part family formation

A model for part family formation using fuzzy logic and AHP is developed. The similarity between various parts based on the part attributes is developed using normalization technique. Next, these similarity coefficients are fuzzified (linguistic variable with membership value) using a fuzzy membership function. In this model a trapezoidal membership function (figure 4.1) is used for fuzzification of part similarity coefficients. Similarly, weight factors computed using AHP model from the expert/designer/user importance for different attributes are fuzzified (linguistic variable with membership value). A triangular membership function (figure 4.2) is used for fuzzification of weight factors. Now, using these linguistic variables and their membership values, final similarity matrix is generated. The clustering is done using single linkage clustering method as adopted by McAuley (1972). The detailed algorithm of the model is given next and the flow chart is shown in figure 4.3.

4.3.2.1 Algorithm

Step 1: Input the number of parts, number of attributes, and their values.

Step 2: Compute the membership value of the individual attributes between the parts as:

$$\mu_{1-2}^{a} = 1 - \frac{(x_1 - y_2)}{(x - y)_{\max}^{a}} \qquad (1)$$

Where x and y are values of the attribute a for parts 1 and 2 respectively.

Step 3: Define the membership function for the attributes and accordingly define the linguistic variables (in case of a tie, choose the variable on the lower side).

Step 4: Determine weight factors for each attribute by using AHP.

Step 5: Define the membership function for the weight factors and accordingly define the linguistic variables (in case of a tie, choose the variable on the lower side).

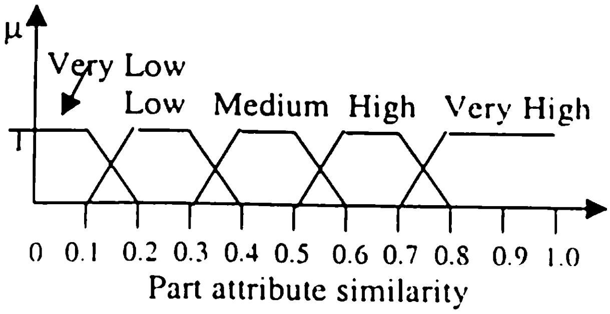

Figure 4.1: Membership function for part attributes

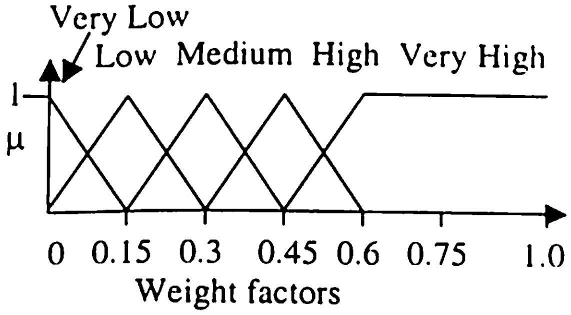

Figure 4.2: Membership function for weight factors

Step 6: Establish the decision making logic or decision rules. These rules usually take the form of IF-THEN rules. These rules imitate the designer/user's decision and are conveniently tabulated in look-up tables.

Step 7: Find the membership using the minimum operator (Mamdani and Assilian 1975, Mamdani 1976), i. e., the membership function of the similarity for each decision is the minimum value of the input variable's membership, as shown below:

$$\mu^{label}_{similarity\ rating} = Minimum\left\{\mu^{label}_{input_1 value} \cdots\cdots \mu^{label}_{input_2 value}\right\}$$

Step 8: Find the similarity coefficients between all parts (similarity matrix) using centre of area method as given below:

$$R_0 = \frac{\sum_i \mu^g_R \times R}{\sum_i \mu^g_R}$$

Where: R_o = the similarity for the pair of parts

i = the rules used

R = the numerical rating

μ_R^g = the minimum membership value for the rule

Step 9: Find the maximum value in the similarity matrix.

Step 10: Join the two part groups (two parts, a part and a part group or two part groups) having maximum similarity. At each stage, part group *p*` and *q*` are merged into a new group; say *v*. This new group consists of all the parts of both the groups. Add the new group *v* and update the similarity matrix by computing the similarity between the new group *v* and some other group *g* as:

$$S_{vg} = \text{Max}\ \{S_{pq}\}\ p \varepsilon v,\ q \varepsilon g$$

Step 11: Repeat step 9 to 10 until all parts are grouped.

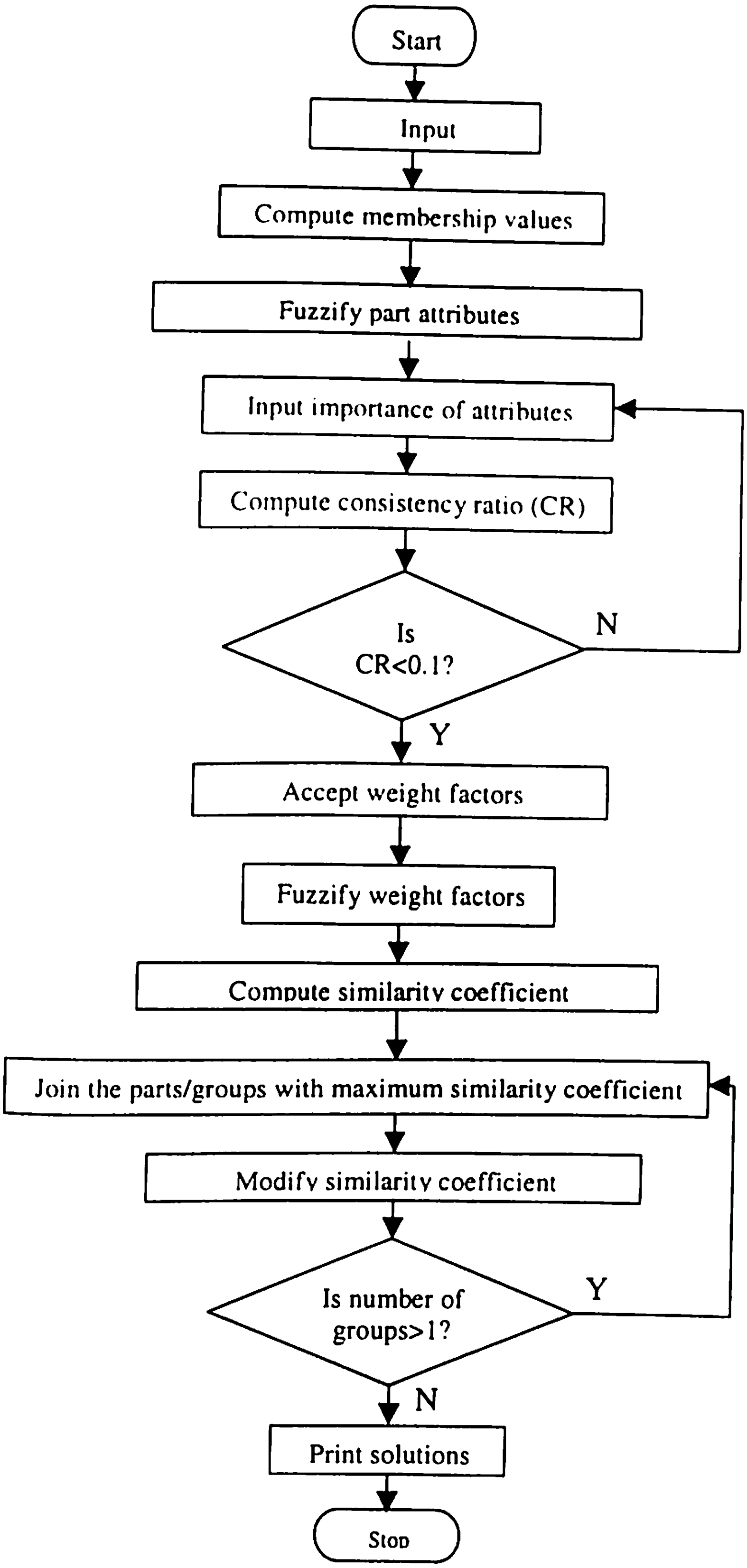

Figure 4.3: Flowchart of the model (model 1) using fuzzy logic and AHP for part family formation

4.3.2.2 Validation

The model is validated by solving two examples - one from literature and other generated with hypothetical values.

Example 1: Consider an example of clustering six parts in families considering three attributes; length (L), tolerance on the part (T), and the length/Diameter ratio (L/D). The problem is further divided in three sub-problems taking different weightage for different attributes (case I, case II, and case III). A step-by-step solution procedure is given below.

Step1: Input the number of parts, number of attributes, and values of attributes as shown in table 4.1.

Table 4.1: Parts and the values of different attributes

Parts	Length (L)	Tolerance (T)	Length/Dia (L/D)
1	70	0.1	2.0
2	10	0.3	2.5
3	30	0.2	3.0
4	60	0.5	4.0
5	70	0.1	2.0
6	20	0.25	3.0

Step2: Compute the membership value of the individual attributes between the parts using equation (1). These computed values are shown in tables 4.2, 4.3, and 4.4 for L, T, and L/D respectively.

Table 4.2: Membership values for attribute L (length)

Parts	1	2	3	4	5	6
1	1.0	0	0.166	0.833	1.0	0.166
2		1.0	0.833	0.166	0	0.833
3			1.0	0.333	0.166	1.0
4				1.0	0.833	0.333
5					1.0	0.166
6						1.0

Table 4.3: Membership values for attribute T (tolerance)

Parts	1	2	3	4	5	6
1	1.0	0.5	0.75	0	1.0	0.375
2		1.0	0.75	0.5	0.5	0.875
3			1.0	0.25	0.75	0.875
4				1.0	0	0.375
5					1.0	0.625
6						1.0

Table 4.4: Membership values for attribute L/D (length/diameter)

Parts	1	2	3	4	5	6
1	1.0	0.75	0.5	0	1.0	0.5
2		1.0	0.75	0.25	0.75	0.25
3			1.0	0.5	0.5	1.0
4				1.0	0	0.5
5					1.0	0.5
6						1.0

Step 3: Fuzzification of part attributes: The values for part pair 1-3 for L, T and L/D are 0.166, 0.75, and 0.5 respectively (see tables 4.2, 4.3, and 4.4). The linguistic variables and membership values for these values are *low* with 0.666, *high* with 0.5 and *medium* with 1.0 respectively (see figure 4.1).

Step 4: Determination of weight factors of attributes using AHP: the given intensity importance for attribute 1 (L) over 2 (T), 1 (L) over 3 (L/D), and 2 (T) over 3 (L/D) are 2, 5, and 1 respectively. Table 4.5 illustrates a sample calculation of weight factors for part pair 1-3 (details of AHP are given in chapter 3). The weight factors for L, T, and L/D are 0.6, 0.23, and 0.17 respectively.

Table 4.5: Sample weight factors using AHP

	L	T	L/D	PV
L	1	2	5	0.60
T	½	1	1	0.23
L/D	1/5	1	1	0.17

Step 5: Fuzzification of weight factors: The weight factor 0.6 belongs to fuzzy subset *very high* with a membership value of 1.0 (see figure 4.2). Similarly, 0.23 and 0.17 belong to fuzzy subsets *medium* and *low* with membership values of 0.533 and 0.866 respectively.

Step 6: When this process is completed for all pairs of facilities, IF-THEN decision rules are developed. The IF-THEN rules for the part pair 1-3 framed using table 4.6 are:

Rule 1: IF μ^L is *Low* and its weight factor is *Very High* THEN similarity coefficient is 0.4

Rule 2: IF μ^T is *High* and its weight factor is *Medium* THEN the similarity coefficient is 0.8

Rule 3: IF $\mu^{I/D}$ is *Medium* and its weight factor is *Low* THEN the similarity coefficient is 0.2

Table 4.6: IF-THEN rules

w / μ	VL	L	M	H	VH
VL	0	0	0.2	0.2	0.2
L	0	0	0.4	0.4	$\underline{0.4}$
M	0.2	$\underline{0.2}$	0.6	0.6	0.6
H	0.4	0.4	$\underline{0.8}$	0.8	0.8
VH	0.6	0.6	1.0	1.0	1.0
$\mu^* = \mu^L = \mu^T = \mu^{I/D}$					

Step 7: Using the minimum operator; Rule1 results in similarity coefficient of 0.4 with membership value of 0.666 [Minimum {1, 0.666}]. Similarly, Rule 2 results in similarity coefficient of 0.8 with membership value of 0.5, and Rule 3 results in similarity coefficient of 0.2 with membership value of 0.866.

Step 8: The crisp value of similarity coefficient for part pair 1-3 using the Centre of Area (COA) method is:

$$\frac{0.4 \times 0.666 + 0.8 \times 0.5 + 0.2 \times 0.866}{0.666 + 0.5 + 0.866} = 0.413$$

This process is repeated for all pair of parts and subsequently the similarity coefficient matrix generated is shown in table 4.7.

Step 9: The maximum value of similarity coefficient in table 4.7 is 0.855 for part pair 1-5. Cluster these parts together and the modify similarity matrix. (For example, $S_{(1,5)6} = \max(S_{16}, S_{56}) = 0.418$)

Case I: The importance rating of different attributes is:

L over T = 2, L over L/D = 5, and T over L/D = 1

Table 4.7: Similarity matrix for parts

	1	2	3	4	5	6
1		0.353	0.413	0.462	0.855	0.367
2			0.8	0.283	0.353	0.638
3				0.316	0.413	0.855
4					0.462	0.367
5						0.418
6						

Table 4.7a: Updated similarity matrix for joining parts 1 and 5

	1,5	2	3	4	6
1,5		0.353	0.413	0.462	0.418
2			0.8	0.283	0.638
3				0.316	0.855
4					0.367
6					

Table 4.7b: Updated similarity matrix for joining parts 3 and 6

	1,5	2	3,6	4
1,5		0.353	0.418	0.462
2			0.8	0.283
3,6				0.367
4				

Table 4.7c: Updated similarity matrix for joining part 2 and (3,6)

	1,5	2,3,6	4
1,5		0.418	0.462
2,3,6			0.367
4			

Table 4.7d: Updated similarity matrix for joining part 4 and (1,5)

	1,5,4	2,3,6
1,5,4		<u>0.418</u>
2,3,6		

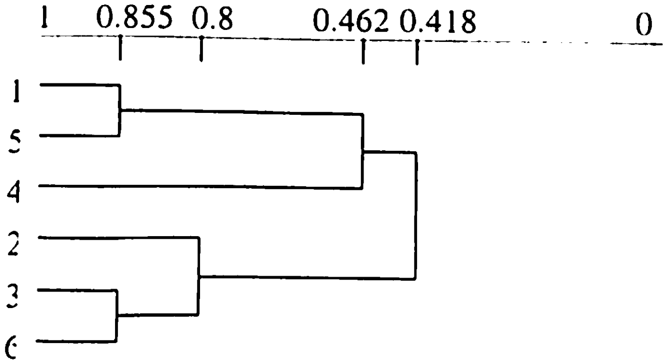

Figure 4.4a: Dendogram showing the clustering of parts (not to scale) for example 1(case I)

Part families formed at different levels of similarity are:

α = 0.855
Part family 1: [1, 5]
Part family 2: [3, 6]
Part family 3: [2]
Part family 4: [4]

α = 0.8
Part family 1: [1, 5]
Part family 2: [3, 6, 2]
Part family 3: [4]

α = 0.462
Part family 1: [1, 5, 4]
Part family 2: [3, 6, 2]

α = 0.418
Part family 1: [1, 5, 4, 3, 6, 2]

These results are also shown in figure 4.4a using a simple dendogram

Case II: The importance rating of different attributes is:

L over T = ½, L over L/D = 1/3, and T over L/D = 1. The similarity matrix generated is shown in table 4.8.

Table 4.8: Similarity matrix for parts

	1	2	3	4	5	6
1		0.432	0.575	0.445	0.828	0.580
2			0.7	0.493	0.432	0.669
3				0.526	0.575	0.828
4					0.445	0.579
5						0.580
6						

Table 4.8a: Updated similarity matrix for joining parts 1 and 5

	1,5	2	3	4	6
1,5		0.432	0.575	0.445	0.580
2			0.7	0.493	0.669
3				0.526	0.828
4					0.579
6					

Table 4.8b: Updated similarity matrix for joining parts 3 and 6

	1,5	2	3,6	4
1,5		0.432	0.58	0.445
2			0.7	0.493
3,6				0.579
4				

Table 4.8c: Updated similarity matrix for joining parts 2 and (3,6)

	1,5	2,3,6	4
1,5		0.58	0.445
2,3,6			0.579
4			

Table 4.8d: Updated similarity matrix for joining parts (1,5) and (2,3,6)

	1,5, 2,3,6	4
1,5, 2,3,6		0.579
4		

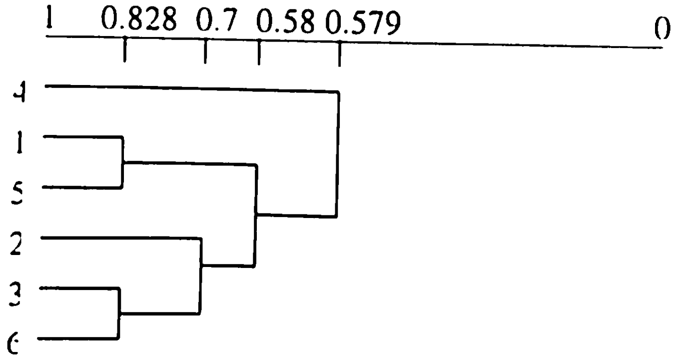

Figure 4.4b: Dendogram showing the clustering of parts (not to scale) for example1 (case II)

Part families formed at different levels of similarity are:

α = 0.828
Part family 1: [1, 5]
Part family 2: [3, 6]
Part family 3: [2]
Part family 4: [4]

α = 0.7
Part family 1: [1, 5]
Part family 2: [2, 3, 6]
Part family 3: [4]

α = 0.58
Part family 1: [1, 5, 2, 3, 6]
Part family 2: [4]

α = 0.579
Part family 1: [1, 5, 2, 3, 6, 4]

These results are also shown in figure 4.4b using a simple dendogram

Case III: The importance rating of different attributes is:

L over T = 1, L over L/D = 1, and T over L/D = 1. The similarity matrix generated is shown in table 4.9.

Table 4.9: Similarity matrix for parts

	1	2	3	4	5	6
1		0.497	0.583	0.467	1.0	0.54
2			0.888	0.47	0.497	0.8
3				0.47	.583	1.0
4					0.467	.539
5						0.611
6						

Table 4.9a: Updated similarity matrix for joining parts 1 and 5

	1,5	2	3	4	6
1,5		0.497	0.583	0.467	0.611
2			0.888	0.47	0.8
3				0.47	1.0
4					0.539
6					

Table 4.9b: Updated similarity matrix for joining parts 3 and 6

	1,5	2	3,6	4
1,5		0.497	0.611	0.467
2			0.888	0.47
3,6				0.539
4				

Table 4.9c: Updated similarity matrix for joining parts 2 and (3,6)

	1,5	2,3,6	4
1,5		0.611	0.467
2,3,6			0.539
4			

Table 4.9d: Updated similarity matrix for joining parts (1,5) and (2,3,6)

	1,5, 2,3,6	4
1,5, 2,3,6		0.539
4		

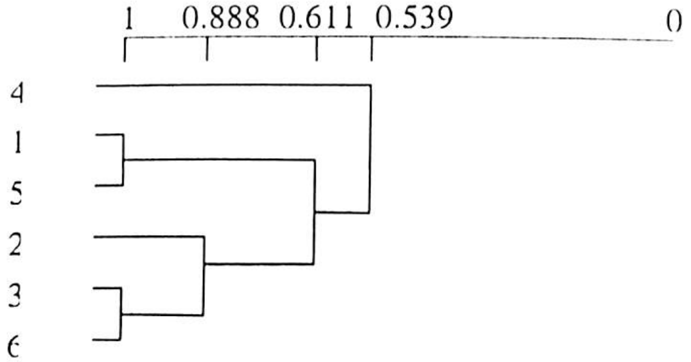

Figure 4.4c: Dendogram showing the clustering of parts (not to scale) for example1(case III)

Part families formed at different levels of similarity are:

$\alpha = 1.0$
Part family 1: [1, 5]
Part family 2: [3, 6]
Part family 3: [2]
Part family 4: [4]

$\alpha = 0.888$
Part family 1: [1, 5]
Part family 2: [2, 3, 6]
Part family 3: [4]
$\alpha = 0.611$
Part family 1: [1, 5, 2, 3, 6]
Part family 2: [4]

$\alpha = 0.539$
Part family 1: [1, 5, 2, 3, 6, 4]

These results are also shown in figure 4.4c using a simple dendogram

Example 2: This example has been extracted from Singh and Rajamani (1996). Here six parts are to be classified into families based on the eight-digit classification code. In this example the eight digits of code are taken as eight attributes and the code values are assumed as attribute values. The data is given in table 4.10. The problem is solved by taking the same weightage for all the eight attributes. The similarity relation matrix is shown in table 4.11. The dendogram showing the clustering of parts is shown in figure 4.5. The solution is similar to the one given in Singh and Rajamani (1996)

Table 4.10: Input data for example 2

Attributes / Parts	*1*	2	*3*	*4*	*5*	*6*	*7*	*8*
1	3	1	1	6	3	8	0	7
2	4	3	1	5	1	8	1	4
3	4	2	1	5	1	8	0	4
4	5	1	1	6	3	7	0	7
5	4	2	1	5	1	5	1	4
6	3	1	1	6	3	6	2	7

Table 4.11: Similarity matrix for equal weightage of all attributes

	1	2	3	4	5	6
1		0.375	0.500	0.833	0.312	0.792
2			0.875	0.333	0.813	0.292
3				0.458	0.813	0.292
4					0.292	0.292
5						0.396
6						

Table 4.11a: Updated similarity matrix for joining parts 2 and 3

	1	2,3	4	5	6
1		0.500	0.833	0.312	0.792
2,3			0.458	0.813	0.292
4				0.292	0.292
5					0.396
6					

Table 4.11b: Updated similarity matrix for joining parts 1 and 4

	1,4	2,3	5	6
1,4		0.500	0.312	0.792
2,3			0.813	0.292
5				0.396
6				

Table 4.11c: Updated similarity matrix for joining parts 5 and (2,3)

	1,4	2,3,5	6
1,4		0.500	0.792
2,3,5			0.396
6			

Table 4.11d: Updated similarity matrix for joining parts 6 and (1,4)

	1,4,6	2,3,5
1,4,6		0.500
2,3,5		

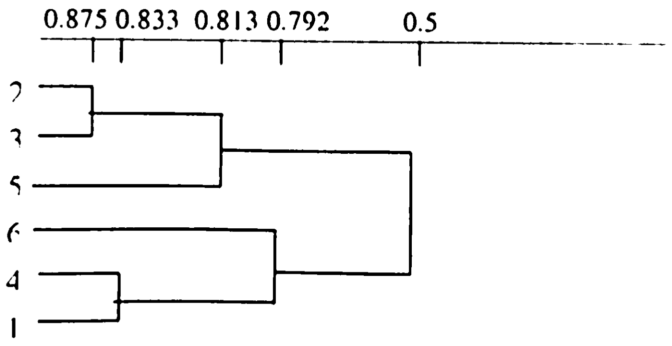

Figure 4.5: Dendogram showing the clustering of parts (not to scale) for example 2

Part families formed at different levels of similarity are:

α = 0.875
Part family 1: [2, 3]
Part family 2: [1]
Part family 3: [4]
Part family 4: [5]
Part family 5: [6]

α = 0.833
Part family 1: [2, 3]
Part family 2: [1, 4]
Part family 3: [5]
Part family 4: [6]

α = 0.813
Part family 1: [2, 3, 5]
Part family 2: [1, 4]
Part family 3: [6]

α = 0.792
Part family 1: [2, 3, 5]
Part family 2: [1, 4, 6]

α = 0.5
Part family 1: [2, 3, 5, 1, 4, 6]

These results are also shown in figure 4.5 using a simple dendogram

4.3.3 Development of model (Model 2) using fuzzy equivalence relations and AHP for part family formation

In each equivalence relation on a given set X, elements of X are related if they are equivalent in terms of a specified characteristic. There are three properties of fuzzy equivalence relations: reflexivity, symmetry, and transitivity.

A fuzzy relation R on X is reflexive if and only if

$$R(x,x) = 1 \qquad \forall\ x \in X;$$

It is symmetric if and only if

$$R(x, y) = R(y, x) \quad \forall\ x, y \in X.$$

A fuzzy relation is transitive if and only if

$$R(x, z) \geq \max_{y \in Y} \min [R(x, y), R(y, z)] \qquad \forall x, z \in X$$

The formula on the right hand side of this inequality expresses the composition R o R of the relation R with itself. This is possible since R is defined on the Cartesian product X×X and, hence, it is compatible with itself. By performing the composition R o R, one can obtain for each pair $\langle x, z \rangle \in X^2$ its membership grade representing the indirect connection of elements x and z via all possible chains with two links. For a fuzzy relation to be transitive it is required that for any pair $\langle x, z \rangle \in R$, the direct membership grade R (x, z) be not smaller than the membership grade obtained indirectly. In some applications, a fuzzy relation that should be transitive on intuitive ground is actually not transitive. This unsatisfactory situation may be caused by a deficiency in the data from which the relation was derived, inconsistent opinions of experts, or other shortcomings. Transitivity is essential if the relation is intuitively an equivalence relation. In such cases, it is desirable to convert the given fuzzy relation R to a transitive one that is as close as possible to R. Such a relation is called the transitive closure of R. To obtain transitivity, some degrees of membership in R must be properly increased. The transitive closure of R is thus the smallest fuzzy relation that is transitive and contains R. Equivalence relation clearly groups elements that are equivalent under the relation into disjoint classes. Figure 4.6 shows the characteristics of reflexivity, symmetry, and transitivity.

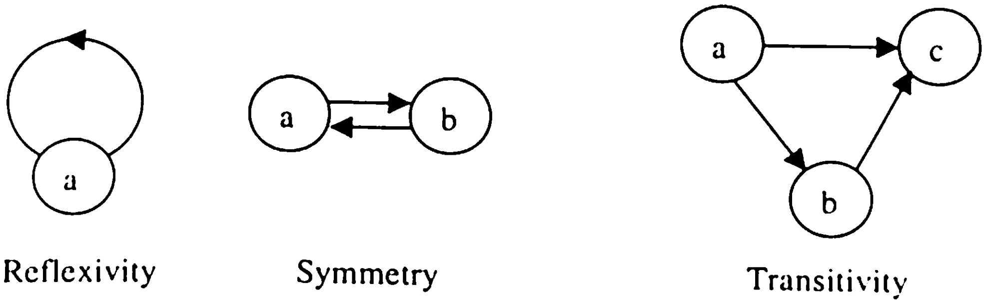

Figure 4.6: Characteristic components of reflexive, symmetric, and transitive relations

Compositions of fuzzy relations are conveniently performed in terms of their matrix representation. Let

$$P = [p_{ij}],\ Q = [q_{jk}],\ \text{and } R = [r_{ik}]$$

be matrix representation of fuzzy relations for which $P \circ Q = R$. then by using matrix notation, one can write

$$[r_{ik}] = [p_{ij}] \circ [q_{jk}]$$

where $r_{ik} = \max_{j} \min (p_{ij}, q_{jk})$

Observe that the same entries in matrices P and Q are used to calculate matrix R as would be used in the regular matrix multiplication, but the product and sum are replaced here with the *min* and *max* operations, respectively.

As an example, consider a set of six experts who are asked to express their opinion on some policy issue. Assume that the similarity in their opinions is captured by the fuzzy relation R expressed by the matrix R given below

$$R = \begin{bmatrix} 1 & 1 & 0 & 0.8 & 0.9 & 0 \\ 1 & 1 & 0.8 & 0.9 & 0.5 & 0 \\ 0 & 0.8 & 1 & 0 & 0 & 0.8 \\ 0.8 & 0.9 & 0 & 1 & 1 & 0 \\ 0.9 & 0.5 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0.8 & 0 & 0 & 1 \end{bmatrix}$$

$$R \circ R = \begin{bmatrix} 1 & 1 & 0.8 & 0.9 & 0.9 & 0 \\ 1 & 1 & 0.8 & 0.9 & 0.9 & 0.8 \\ 0.8 & 0.8 & 1 & 0.9 & 0.5 & 0.8 \\ 0.9 & 0.9 & 0.8 & 1 & 1 & 0 \\ 0.9 & 0.9 & 0.5 & 1 & 1 & 0 \\ 0 & 0.8 & 0.8 & 0 & 0 & 1 \end{bmatrix}$$

For example 0.8 (=r_{13}) = max [min (r11, r13), min (r12, r23), min (r13, r33), min (r14, r43), min (r15, r53), min (r16, r63)]

= max [min (1,0), min (1,0.8), min (0,1), min (0.8,0), min (0.9,0), min (0,0.8)]

= max [0,0.8, 0,0, 0, 0]

= 0.8

4.3.3.1 Algorithm

Step 1: Input the number of parts, number of attributes, their weightage and values.

Step 2: Compute the weight factors of attributes using AHP.

Step 3 : Compute the membership value of the individual attributes between the parts as:

$$\mu_{1-2}^{a} = 1 - \frac{(x_1 - y_2)}{(x-y)_{\max}^{a}}$$

Where x and y are values of the attribute a for parts 1 and 2 respectively.

Step 4 : Compute weighted similarity relation matrix (R) between parts as:

$$\mu_{1-2} = w_a \mu_{1-2}^{a} + w_b \mu_{1-2}^{b} + \ldots + w_n \mu_{1-2}^{n}$$

Step 5 : Compute R′ = R o R [R (x, z) ≥ $\max_{y \in Y}$ min [R (x, y), R (y, z)] $\forall x, z \in X$]

Step 6 : If R′ ≠ R, set R= R′ and go to step 5

else R_T = R′ and go to step 7

Step 7 : Stop

The flow chart of the developed algorithm is shown in figure 4.7

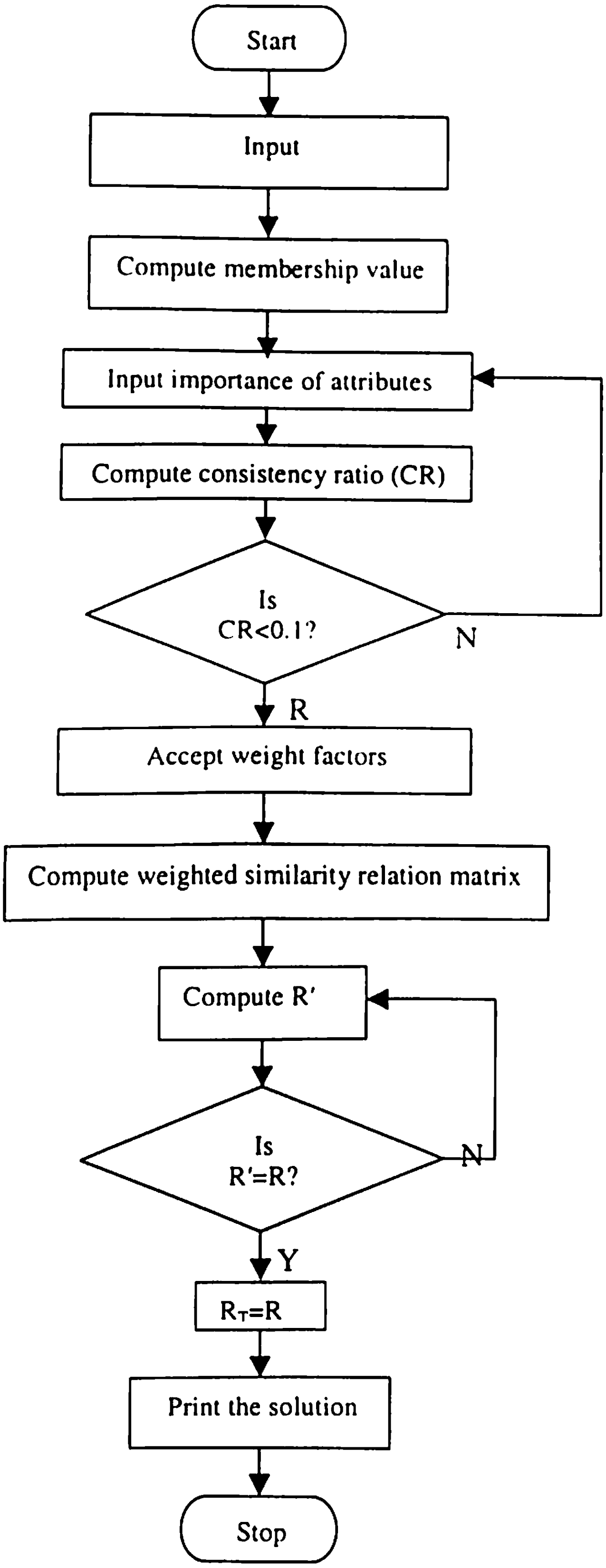

Figure 4.7: Flow chart of the model (model 2) using fuzzy equivalence relations and AHP for part family formation

4.3.3.2 Validation

The model is validated by solving three examples - one from literature and other two generated with hypothetical values.

Example 1: To validate this algorithm, we have taken the example 1 given in section 4.3.2.2 and also further divided the problem in three sub problems as done in section 4.3.2.2.

Tables 4.12, 4.13, and 4.14 show the similarity matrix and transitive closure obtained for Case I, Case II, and Case III respectively. The results are shown in figures 4.8a, 4.8b, and 4.8c for Case I, Case II, and Case III respectively.

Table 4.12a: Similarity matrix for Case I

	1	2	3	4	5	6
1	1.0	0.243	0.358	0.5	1.0	0.329
2		1.0	0.8	0.257	0.243	0.829
3			1.0	0.343	0.357	0.971
4				1.0	0.5	0.371
5					1.0	0.329
6						1.0

Table 4.12b: Transitive closure for Case I

	1	2	3	4	5	6
1	1.0	0.371	0.371	0.5	1.0	0.371
2		1.0	0.83	0.371	0.371	0.83
3			1.0	0.371	0.371	0.971
4				1.0	0.5	0.371
5					1.0	0.371
6						1.0

Table 4.13a: Similarity matrix for Case II

	1	2	3	4	5	6
1	1.0	0.525	0.541	0.142	1.0	0.492
2		1.0	0.764	0.333	0.525	0.813
3			1.0	0.374	0.541	0.951
4				1.0	0.142	0.423
5					1.0	0.492
6						1.0

Table 4.13b: Transitive closure for case II

	1	2	3	4	5	6
1	1.0	0.54	0.54	0.423	1.0	0.54
2		1.0	0.813	0.423	0.54	0.813
3			1.0	0.423	0.54	0.951
4				1.0	0.423	0.423
5					1.0	0.54
6						1.0

Table 4.14a: Similarity matrix for Case III

	1	2	3	4	5	6
1	1.0	0.417	0.472	0.278	1.0	0.431
2		1.0	0.778	0.306	0.417	0.819
3			1.0	0.361	0.472	0.958
4				1.0	0.278	0.403
5					1.0	0.431
6						1.0

Table 4.14b: Transitive closure for Case III

	1	2	3	4	5	6
1	1.0	0.472	0.472	0.403	1.0	0.472
2		1.0	0.819	0.403	0.473	0.819
3			1.0	0.403	0.473	0.958
4				1.0	0.403	0.403
5					1.0	0.473
6						1.0

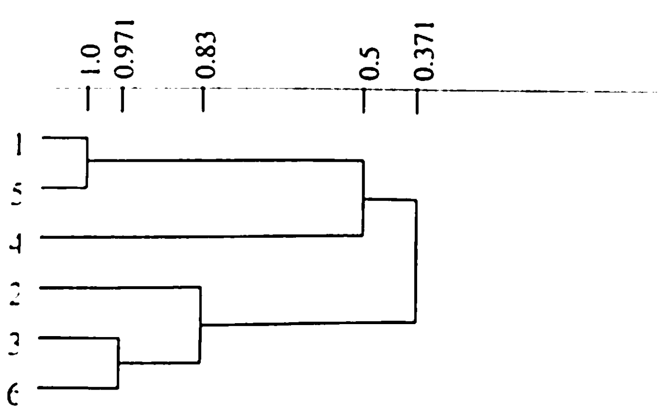

Figure 4.8a: Dendogram showing the clustering of parts by fuzzy equivalence (not to scale) for Case I

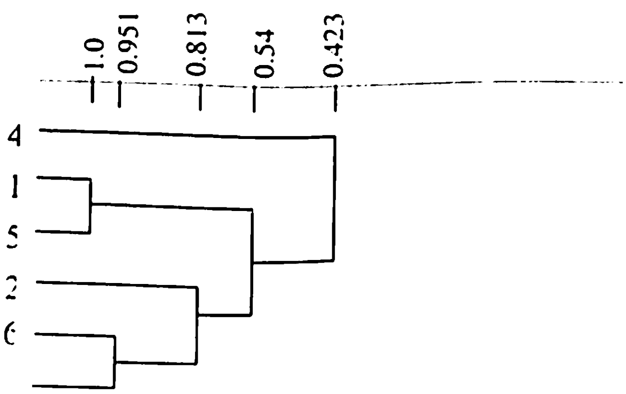

Figure 4.8b: Dendogram showing the clustering of parts by fuzzy equivalence (not to scale) for Case II

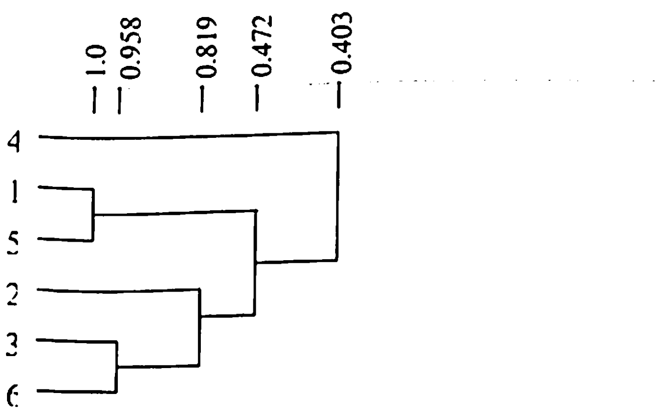

Figure 4.8c: Dendogram showing the clustering of parts by fuzzy equivalence (not to scale) for Case III

Example 2: An example for clustering 25 parts using 15 attributes is taken from Xu and Wang (1989). The data is given in table 4.15. In this example equal weightage for all attributes has been considered. The similarity matrix and transitive closures obtained are given in tables 4.16a and 4.16b respectively.

Table 4.15: The part feature data for example 2

Features/attributes†

Parts	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	5.514	1.1600	0.560	4.7534	2	0.0008	8	0.0001	0	0	0.00005	0.010	0	0	0
2	5.96	0.9996	0.39	5.9624	3	0.0001	32	0.0005	0.0001	0	0	0	0	0	0
3	5.96	0.996	0.39	5.9624	3	0.0001	32	0.0005	0.0001	0	0	0	0	0	0
4	5.96	0.9996	0.39	5.9624	3	0.0001	32	0.0005	0.0001	0	0	0	0	0	0
5	4.687	0.718	0.3762	6.5279	6	0.0005	3	0	0.00005	0	0.0002	0	0	0	0
6	4.687	0.718	0.3762	0.6279	6	0.0005	3	0	0.00005	0	0.0002	0	0	0	0
7	4.09	0.504	0.329	8.115	2	0.0002	32	0.0008	0.00003	0.02	0.005	0.003	0	0	0
8	3.928	0.7509	0.29	5.231	4	0.001	8	0.0002	0	0	0	0	0	0	0
9	6.31	1.06	0.875	5.9547	0	0.00005	63	0.001	0	0	0.00003	0.03	0	0	0.005
10	2.51	0.3165	0.159	7.9305	4	0	0	0.0006	0	0	0.002	0	0	0.01	0
11	5.96	0.9997	0.39	5.9618	0	0.0001	16	0.0005	0.0001	0	0	0	0	0	0
12	11.481	0.878	0.5	13.0763	5	0.001	125	0	0	0	0.002	0	0.0003	0.002	0
13	4.687	0.718	0.3762	6.5279	6	0.0005	5	0	0	0	0.0001	0	0	0	0
14	11.281	0.875	0.5	12.8926	7	0.0001	8	0.002	0	0	0	0	0.0003	0.002	0
15	3.7	0.38	0.2	9.7368	2	0.001	5	0	0	0	0.0002	0	0	0	0
16	3.7	0.59	0.275	6.2712	2	0.00005	5	0.0005	0.00005	0	0.002	0	0	0.015	0
17	2.174	0.18	0.109	12.0778	0	0.0001	5	0	0	0	0.005	0.002	0	0.01	0
18	3.7	0.6252	0.3	5.9181	2	0.001	5	0.0005	0.00005	0	0.005	0	0	0	0
19	5.512	0.75	0.35	7.3493	2	0.00015	16	0.0001	0.00005	0	0	0	0	0	0
20	3.6	0.3849	0.188	9.3531	2	0.0001	5	0.0008	0	0	0	0.003	0	0	0
21	4.076	0.504	0.4	8.0873	2	0.0001	5	0.0008	0.00003	0.02	0.002	0	0	0	0
22	5.512	1.1873	0.55	4.6425	2	0.0001	8	0.0001	0	0	0.00005	0.01	0	0	0
23	2.174	0.3125	0.159	6.9568	4	0.00005	5	0	0	0	0.005	0	0	0.01	0
24	6.388	0.9377	0.44	6.8124	2	0.0002	5	0	0	0	0.0005	0.002	0	0	0
25	4.687	0.718	0.355	6.5279	6	0.0002	16	0	0.00005	0	0.0001	0	0	0	0

[† Various attributes considered are: 1-overall length, 2-maximum diameter, 3-minimum diameter, 4-length/maximum diameter ratio, 5-number of grooves, 6-minimum diameter, 7-tightest dimensional tolerance, 8-best surface finish, 9-perpendicularity, 10-cylindricity, 11-parallelisim, 12-round out, 13-position, 14-straightness, 15-symmetry]

Table 4.16a: Similarity matrix for example 2

1.000000	0.793040	0.792801	0.793040	0.817672	0.805082	0.663921	0.876904	0.714072	0.684761	0.792059	0.657384	0.853406	0.634954	0.834874	0.703193	0.633869	0.772923	0.836849	0.790159	0.708014	0.950048	0.666637	0.888845	0.795561
0.793040	1.000000	0.999762	1.000000	0.844643	0.819103	0.724110	0.797374	0.685739	0.725065	0.962885	0.590530	0.813710	0.663833	0.736131	0.791116	0.619570	0.767038	0.901306	0.799416	0.767530	0.838162	0.680274	0.858899	0.871065
0.792801	0.999762	1.000000	0.999762	0.844881	0.819341	0.724348	0.797612	0.685500	0.725303	0.962647	0.590768	0.813948	0.664072	0.736369	0.791355	0.619808	0.767277	0.901544	0.799654	0.767769	0.837923	0.680513	0.859137	0.871303
0.793040	1.000000	0.999762	1.000000	0.844643	0.819103	0.724110	0.797374	0.685739	0.725065	0.962885	0.590530	0.813710	0.663833	0.736131	0.791116	0.619570	0.767038	0.901306	0.799416	0.767530	0.838162	0.680274	0.858899	0.871065
0.817672	0.844643	0.844881	0.844643	1.000000	0.968403	0.718058	0.880224	0.597849	0.755660	0.824595	0.654088	0.964267	0.680436	0.832211	0.797781	0.662317	0.823729	0.910931	0.803496	0.774542	0.809490	0.742069	0.865259	0.969888
0.805082	0.819103	0.819341	0.819103	0.968403	1.000000	0.686460	0.862518	0.572391	0.724063	0.799061	0.622491	0.932670	0.648839	0.800614	0.768933	0.630720	0.798663	0.879334	0.771899	0.742945	0.798087	0.710472	0.833662	0.938291
0.663921	0.724110	0.724348	0.724110	0.718058	0.686460	1.000000	0.698478	0.556363	0.726597	0.706043	0.513792	0.711124	0.540826	0.717354	0.749207	0.724348	0.810496	0.779071	0.795305	0.925839	0.695738	0.744711	0.748243	0.745503
0.876904	0.797374	0.797612	0.797374	0.880224	0.862518	0.698478	1.000000	0.616529	0.779857	0.777333	0.696381	0.915957	0.655681	0.911875	0.760194	0.675314	0.854850	0.855380	0.835160	0.743748	0.828721	0.755066	0.856733	0.861802
0.714072	0.685739	0.685500	0.685739	0.597849	0.572391	0.556363	0.616529	1.000000	0.558270	0.705787	0.467630	0.633582	0.540400	0.575050	0.570036	0.505473	0.539374	0.672759	0.670869	0.588191	0.757454	0.506813	0.720425	0.624270
0.684761	0.725065	0.725303	0.725065	0.755660	0.724063	0.726597	0.779857	0.558270	1.000000	0.705017	0.576263	0.786593	0.628897	0.797206	0.870456	0.850124	0.738504	0.771378	0.864697	0.788400	0.729911	0.926114	0.776728	0.769238
0.792059	0.962885	0.962647	0.962885	0.824595	0.799061	0.706043	0.777333	0.705787	0.705017	1.000000	0.553415	0.793662	0.643786	0.735130	0.790116	0.656664	0.766044	0.900305	0.798415	0.766530	0.837181	0.660226	0.857898	0.851017
0.657384	0.590530	0.590768	0.590530	0.654088	0.622491	0.513792	0.696381	0.467630	0.576263	0.553415	1.000000	0.687155	0.762604	0.675184	0.538827	0.529474	0.613664	0.622786	0.575692	0.545323	0.609172	0.554377	0.674895	0.637843
0.853406	0.813710	0.813948	0.813710	0.964267	0.932670	0.711124	0.915957	0.633582	0.786593	0.793662	0.687155	1.000000	0.716169	0.865278	0.764181	0.695383	0.790129	0.879998	0.839230	0.767609	0.845223	0.775136	0.898326	0.938955
0.634954	0.663833	0.664072	0.663833	0.680436	0.648839	0.540826	0.655681	0.540400	0.628897	0.643786	0.762604	0.716169	1.000000	0.615818	0.584795	0.542108	0.539632	0.680220	0.694993	0.611290	0.680076	0.567011	0.713798	0.698324
0.834874	0.736131	0.736369	0.736131	0.832211	0.800614	0.717354	0.911875	0.575050	0.797206	0.735130	0.675184	0.865278	0.615818	1.000000	0.757014	0.763439	0.840618	0.834825	0.899860	0.765526	0.786691	0.775320	0.845508	0.807923
0.703193	0.791116	0.791355	0.791116	0.797781	0.768933	0.749207	0.760194	0.570036	0.870456	0.790116	0.538827	0.764181	0.584795	0.757014	1.000000	0.777342	0.823604	0.844930	0.814966	0.811010	0.748344	0.825666	0.789364	0.813493
0.633869	0.619570	0.619808	0.619570	0.662317	0.630720	0.724348	0.675314	0.505473	0.850124	0.656664	0.529474	0.695383	0.542108	0.763439	0.777342	1.000000	0.732057	0.711597	0.795709	0.696965	0.679019	0.913581	0.732503	0.678029
0.772923	0.767038	0.767277	0.767038	0.823729	0.798663	0.810496	0.854850	0.539374	0.738504	0.766044	0.613664	0.790129	0.539632	0.840618	0.823604	0.732057	1.000000	0.824211	0.778570	0.778965	0.724740	0.773714	0.775312	0.799440
0.836849	0.901306	0.901544	0.901306	0.910931	0.879334	0.779071	0.855380	0.672759	0.771378	0.900305	0.622786	0.879998	0.680220	0.834825	0.844930	0.711597	0.824211	1.000000	0.864777	0.825929	0.875333	0.749050	0.913616	0.941043
0.790159	0.799416	0.799654	0.799416	0.803496	0.771899	0.795305	0.835160	0.670869	0.864697	0.798415	0.575692	0.839230	0.694993	0.899860	0.814966	0.795709	0.778570	0.864777	1.000000	0.843478	0.835310	0.802811	0.865682	0.821875
0.708014	0.767530	0.767769	0.767530	0.774542	0.742945	0.925839	0.743748	0.588191	0.788400	0.766530	0.545323	0.767609	0.611290	0.765526	0.811010	0.696965	0.778965	0.825929	0.843478	1.000000	0.753165	0.726514	0.799982	0.786564
0.950048	0.838162	0.837923	0.838162	0.809490	0.798087	0.695738	0.828721	0.757454	0.729911	0.837181	0.609172	0.845223	0.680076	0.786691	0.748344	0.679019	0.724740	0.875333	0.835310	0.753165	1.000000	0.711788	0.920634	0.827378
0.666637	0.680274	0.680513	0.680274	0.742069	0.710472	0.744711	0.755066	0.506813	0.926114	0.660226	0.554377	0.775136	0.567011	0.775320	0.825666	0.913581	0.773714	0.749050	0.802811	0.726514	0.711788	1.000000	0.765271	0.757781
0.888845	0.858899	0.859137	0.858899	0.865259	0.833662	0.748243	0.856733	0.720425	0.776728	0.857898	0.674895	0.898326	0.713798	0.845508	0.789364	0.732503	0.775312	0.913616	0.865682	0.799982	0.920634	0.765271	1.000000	0.877281
0.795561	0.871065	0.871303	0.871065	0.969888	0.938291	0.745503	0.861802	0.624270	0.769238	0.851017	0.637843	0.938955	0.698324	0.807923	0.813493	0.678029	0.799440	0.941043	0.821875	0.786564	0.827378	0.757781	0.877281	1.000000

Table 4.16b: Transitive closure for example 2

1.000000	0.901544	0.901544	0.901544	0.913616	0.913616	0.843478	0.913616	0.757454	0.864697	0.901544	0.716169	0.913616	0.716169	0.911875	0.864697	0.864697	0.854850	0.913616	0.899860	0.843478	0.950048	0.864697	0.920634	0.913616
0.901544	1.000000	0.999762	1.000000	0.901544	0.901544	0.843478	0.901544	0.757454	0.864697	0.962885	0.716169	0.901544	0.716169	0.901544	0.864697	0.864697	0.854850	0.901544	0.899860	0.843478	0.901544	0.864697	0.901544	0.901544
0.901544	0.999762	1.000000	0.999762	0.901544	0.901544	0.843478	0.901544	0.757454	0.864697	0.962885	0.716169	0.901544	0.716169	0.901544	0.864697	0.864697	0.854850	0.901544	0.899860	0.843478	0.901544	0.864697	0.901544	0.901544
0.901544	1.000000	0.999762	1.000000	0.901544	0.901544	0.843478	0.901544	0.757454	0.864697	0.962885	0.716169	0.901544	0.716169	0.901544	0.864697	0.864697	0.854850	0.901544	0.899860	0.843478	0.901544	0.864697	0.901544	0.901544
0.913616	0.901544	0.901544	0.901544	1.000000	0.968403	0.843478	0.915957	0.757454	0.864697	0.901544	0.716169	0.964267	0.716169	0.911875	0.864697	0.864697	0.854850	0.941043	0.899860	0.843478	0.913616	0.864697	0.913616	0.969888
0.913616	0.901544	0.901544	0.901544	0.968403	1.000000	0.843478	0.915957	0.757454	0.864697	0.901544	0.716169	0.964267	0.716169	0.911875	0.864697	0.864697	0.854850	0.941043	0.899860	0.843478	0.913616	0.864697	0.913616	0.968403
0.843478	0.843478	0.843478	0.843478	0.843478	0.843478	1.000000	0.843478	0.757454	0.843478	0.843478	0.716169	0.843478	0.716169	0.843478	0.843478	0.843478	0.843478	0.843478	0.843478	0.925839	0.843478	0.843478	0.843478	0.843478
0.913616	0.901544	0.901544	0.901544	0.915957	0.915957	0.843478	1.000000	0.757454	0.864697	0.901544	0.716169	0.915957	0.716169	0.911875	0.864697	0.864697	0.854850	0.915957	0.899860	0.843478	0.913616	0.864697	0.913616	0.915957
0.757454	0.757454	0.757454	0.757454	0.757454	0.757454	0.757454	0.757454	1.000000	0.757454	0.757454	0.716169	0.757454	0.716169	0.757454	0.757454	0.757454	0.757454	0.757454	0.757454	0.757454	0.757454	0.757454	0.757454	0.757454
0.864697	0.864697	0.864697	0.864697	0.864697	0.864697	0.843478	0.864697	0.757454	1.000000	0.864697	0.716169	0.864697	0.716169	0.864697	0.870456	0.913581	0.854850	0.864697	0.864697	0.843478	0.864697	0.926114	0.864697	0.864697
0.901544	0.962885	0.962885	0.962885	0.901544	0.901544	0.843478	0.901544	0.757454	0.864697	1.000000	0.716169	0.901544	0.716169	0.901544	0.864697	0.864697	0.854850	0.901544	0.899860	0.843478	0.901544	0.864697	0.901544	0.901544
0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	1.000000	0.716169	0.762604	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169
0.913616	0.901544	0.901544	0.901544	0.964267	0.964267	0.843478	0.915957	0.757454	0.864697	0.901544	0.716169	1.000000	0.716169	0.911875	0.864697	0.864697	0.854850	0.941043	0.899860	0.843478	0.913616	0.864697	0.913616	0.964267
0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.762604	0.716169	1.000000	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169	0.716169
0.911875	0.901544	0.901544	0.901544	0.911875	0.911875	0.843478	0.911875	0.757454	0.864697	0.901544	0.716169	0.911875	0.716169	1.000000	0.864697	0.864697	0.854850	0.911875	0.899860	0.843478	0.911875	0.864697	0.911875	0.911875
0.864697	0.864697	0.864697	0.864697	0.864697	0.864697	0.843478	0.864697	0.757454	0.870456	0.864697	0.716169	0.864697	0.716169	0.864697	1.000000	0.870456	0.854850	0.864697	0.864697	0.843478	0.864697	0.870456	0.864697	0.864697
0.864697	0.864697	0.864697	0.864697	0.864697	0.864697	0.843478	0.864697	0.757454	0.913581	0.864697	0.716169	0.864697	0.716169	0.864697	0.870456	1.000000	0.854850	0.864697	0.864697	0.843478	0.864697	0.913581	0.864697	0.864697
0.854850	0.854850	0.854850	0.854850	0.854850	0.854850	0.843478	0.854850	0.757454	0.854850	0.854850	0.716169	0.854850	0.716169	0.854850	0.854850	0.854850	1.000000	0.854850	0.854850	0.843478	0.854850	0.854850	0.854850	0.854850
0.913616	0.901544	0.901544	0.901544	0.941043	0.941043	0.843478	0.915957	0.757454	0.864697	0.901544	0.716169	0.941043	0.716169	0.911875	0.864697	0.864697	0.854850	1.000000	0.899860	0.843478	0.913616	0.864697	0.913616	0.941043
0.899860	0.899860	0.899860	0.899860	0.899860	0.899860	0.843478	0.899860	0.757454	0.864697	0.899860	0.716169	0.899860	0.716169	0.899860	0.864697	0.864697	0.854850	0.899860	1.000000	0.843478	0.899860	0.864697	0.899860	0.899860
0.843478	0.843478	0.843478	0.843478	0.843478	0.843478	0.925839	0.843478	0.757454	0.843478	0.843478	0.716169	0.843478	0.716169	0.843478	0.843478	0.843478	0.843478	0.843478	0.843478	1.000000	0.843478	0.843478	0.843478	0.843478
0.950048	0.901544	0.901544	0.901544	0.913616	0.913616	0.843478	0.913616	0.757454	0.864697	0.901544	0.716169	0.913616	0.716169	0.911875	0.864697	0.864697	0.854850	0.913616	0.899860	0.843478	1.000000	0.864697	0.920634	0.913616
0.864697	0.864697	0.864697	0.864697	0.864697	0.864697	0.843478	0.864697	0.757454	0.926114	0.864697	0.716169	0.864697	0.716169	0.864697	0.870456	0.913581	0.854850	0.864697	0.864697	0.843478	0.864697	1.000000	0.864697	0.864697
0.920634	0.901544	0.901544	0.901544	0.913616	0.913616	0.843478	0.913616	0.757454	0.864697	0.901544	0.716169	0.913616	0.716169	0.911875	0.864697	0.864697	0.854850	0.913616	0.899860	0.843478	0.920634	0.864697	1.000000	0.913616
0.913616	0.901544	0.901544	0.901544	0.969888	0.968403	0.843478	0.915957	0.757454	0.864697	0.901544	0.716169	0.964267	0.716169	0.911875	0.864697	0.864697	0.854850	0.941043	0.899860	0.843478	0.913616	0.864697	0.913616	1.000000

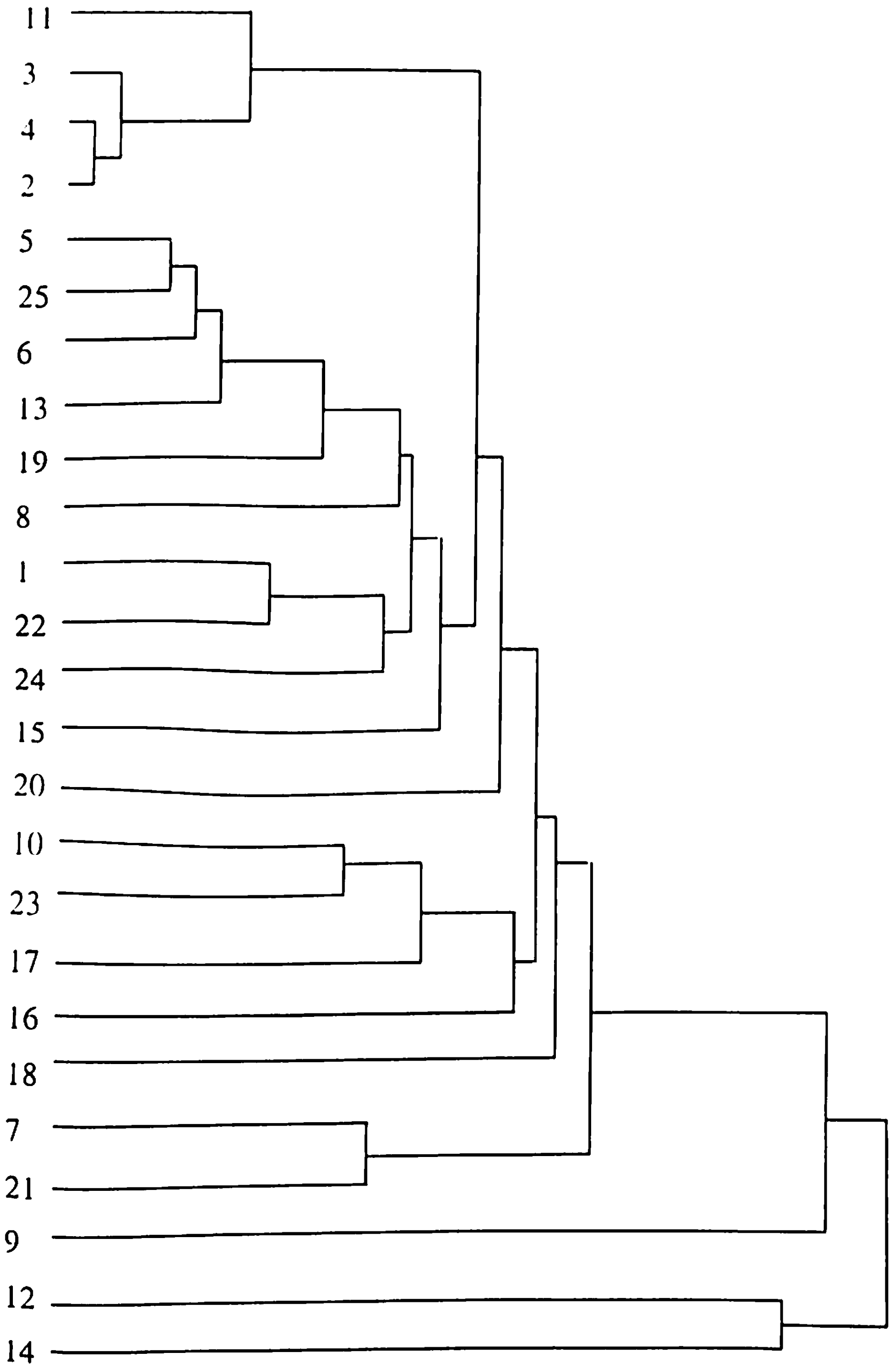

Figure 4.9: Dendogram showing the clustering of parts (not to scale) for example 2

Part families formed at different levels of similarity are:

$\alpha = 1.0$
Part family 1: [2, 4]
Part family 2-24: each part in individual family

$\alpha = 0.999762$
Part family 1: [2, 4, 3]
Part family 2-23: each part in individual family

$\alpha = 0.969888$
Part family 1: [2, 4, 3]
Part family 2: [5, 25]
Part family 3-22: each part in individual family

$\alpha = 0.968403$
Part family 1: [2, 4, 3]
Part family 2: [5, 25, 6]
Part family 3-21: each part in individual family

$\alpha = 0.964267$
Part family 1: [2, 4, 3]
Part family 2: [5, 25, 6, 13]
Part family 3-20: each part in individual family

$\alpha = 0.962885$
Part family 1: [2, 4, 3, 11]
Part family 2: [5, 25, 6, 13]
Part family 3-19: each part in individual family

$\alpha = 0.950048$
Part family 1: [2, 4, 3, 11]
Part family 2: [5, 25, 6, 13]
Part family 3: [1, 22]
Part family 4-18: each part in individual family

$\alpha = 0.941043$
Part family 1: [2, 4, 3, 11]
Part family 2: [5, 25, 6, 13, 19]
Part family 3: [1, 22]
Part family 4-17: each part in individual family

$\alpha = 0.926119$
Part family 1: [2, 4, 3, 11]
Part family 2: [5, 25, 6, 13, 19]
Part family 3: [1, 22]
Part family 4: [10, 23]
Part family 5-16: each part in individual family

$\alpha = 0.925839$
Part family 1: [2, 4, 3, 11]
Part family 2: [5, 25, 6, 13, 19]
Part family 3: [1, 22]
Part family 4: [7, 21]
Part family 5: [10, 23]
Part family 6-15: each part in individual family

$\alpha = 0.920634$
Part family 1: [2, 4, 3, 11]
Part family 2: [5, 25, 6, 13, 19]
Part family 3: [1, 22, 24]
Part family 4: [7, 21]
Part family 5: [10, 23]
Part family 6-14: each part in individual family

$\alpha = 0.915957$
Part family 1: [2, 4, 3, 11]
Part family 2: [5, 25, 6, 13, 19, 8]
Part family 3: [1, 22, 24]
Part family 4: [7, 21]
Part family 5: [10, 23]
Part family 6-13: each part in individual family

$\alpha = 0.913616$
Part family 1: [2, 4, 3, 11]
Part family 2: [5, 25, 6, 13, 19, 8, 1, 22, 24]
Part family 3: [7, 21]
Part family 4: [10, 23]
Part family 5-12: each part in individual family

$\alpha = 0.913581$
Part family 1: [2, 4, 3, 11]
Part family 2: [5, 25, 6, 13, 19, 8, 1, 22, 24]
Part family 3: [7, 21]
Part family 4: [10, 23, 17]
Part family 5-11: each part in individual family

$\alpha = 0.911875$
Part family 1: [2, 4, 3, 11]
Part family 2: [5, 25, 6, 13, 19, 8, 1, 22, 24, 15]
Part family 3: [7, 21]
Part family 4: [10, 23, 17]
Part family 5-10: each part in individual family

$\alpha = 0.901544$
Part family 1: [2, 4, 3, 11, 5, 25, 6, 13, 19, 8, 1, 22, 24, 15]
Part family 2: [7, 21]
Part family 3: [10, 23, 17]
Part family 4-9: each part in individual family

α = 0.89986
Part family 1: [2, 4, 3, 11, 5, 25, 6, 13, 19, 8, 1, 22, 24, 15, 20]
Part family 2: [7, 21]
Part family 3: [10, 23, 17]
Part family 4-8: each part in individual family

α = 0.870456
Part family 1: [2, 4, 3, 11, 5, 25, 6, 13, 19, 8, 1, 22, 24, 15, 20]
Part family 2: [7, 21]
Part family 3: [10, 23, 17, 16]
Part family 4-7: each part in individual family

α = 0.864697
Part family 1: [2, 4, 3, 11, 5, 25, 6, 13, 19, 8, 1, 22, 24, 15, 20, 10, 23, 17, 16]
Part family 2: [7, 21]
Part family 3-6: each part in individual family

α = 0.854850
Part family 1: [2, 4, 3, 11, 5, 25, 6, 13, 19, 8, 1, 22, 24, 15, 20, 10, 23, 17, 16, 18]
Part family 2: [7, 21]
Part family 3-5: each part in individual family

α = 0.843478
Part family 1: [2, 4, 3, 11, 5, 25, 6, 13, 19, 8, 1, 22, 24, 15, 20, 10, 23, 17, 16, 18, 7, 21]
Part family 2: [9]
Part family 3: [12]
Part family 4: [14]

α = 0.762604
Part family 1: [2, 4, 3, 11, 5, 25, 6, 13, 19, 8, 1, 22, 24, 15, 20, 10, 23, 17, 16, 18, 7, 21]
Part family 2: [12, 14]
Part family 3: [9]

α = 0.757454
Part family 1: [2, 4, 3, 11, 5, 25, 6, 13, 19, 8, 1, 22, 24, 15, 20, 10, 23, 17, 16, 18, 7, 21, 9]
Part family 2: [12, 14]

α = 0.716169
All parts in one family

These results are also shown in figure 4.9 using a simple dendogram

Example 3: A hypothetical example for clustering 25 parts using 22 attributes is considered. The data is given in table 4.17. In this example also equal weightage for all attributes has been considered. The similarity matrix and transitive closures obtained are given in table 4.18a and 4.18b respectively.

Table 4.17: The part feature data for example 3

Features/Attributes[†] →

Parts ↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	0.000	0.000	0.000	0.000	1.000	0.000	90.000	10.000	2.000	20.000	0.000	1.000	0.000	0.050	10.000	0.000	0.000	0.500	1.000	0.000	1.000	2.000
2	0.000	1.000	1.000	1.000	0.000	1.000	40.000	5.000	0.500	0.000	0.000	0.000	0.000	0.010	90.000	0.000	1.000	1.000	1.000	1.000	2.000	1.000
3	1.000	2.000	2.000	0.000	0.000	2.000	50.000	15.000	1.500	0.000	0.000	0.000	0.000	0.010	10.000	5.000	2.000	10.000	0.000	2.000	0.000	3.000
4	0.000	1.000	3.000	2.000	0.000	35.000	15.000	20.000	0.500	0.000	0.000	0.000	0.000	0.010	90.000	0.000	3.000	50.000	0.000	0.000	1.000	1.000
5	1.000	0.000	1.000	1.000	0.000	2.000	90.000	5.000	0.500	0.000	0.000	0.000	0.000	0.050	10.000	0.000	0.000	10.000	0.000	1.000	2.000	3.000
6	1.000	3.000	0.000	0.000	0.000	6.000	90.000	15.000	1.500	0.000	0.000	0.000	1.000	0.010	10.000	0.000	2.000	10.000	0.000	2.000	3.000	0.000
7	0.000	2.000	2.000	2.000	3.000	2.000	40.000	10.000	0.500	0.000	4.000	0.000	0.000	0.010	10.000	9.000	0.000	10.000	0.000	2.000	0.000	1.000
8	1.000	0.000	3.000	1.000	3.000	0.000	90.000	10.000	0.500	0.000	0.000	1.000	0.000	0.050	90.000	0.000	1.000	10.000	2.000	2.000	1.000	3.000
9	1.000	1.000	0.000	2.000	2.000	1.000	90.000	15.000	0.500	0.000	0.000	0.000	0.000	0.010	10.000	0.000	3.000	10.000	2.000	2.000	2.000	1.000
10	0.000	3.000	1.000	0.000	1.000	4.000	90.000	15.000	0.500	0.000	0.000	0.000	0.000	0.010	10.000	0.000	0.000	10.000	0.000	1.000	3.000	2.000
11	0.000	2.000	2.000	1.000	0.000	3.000	90.000	15.000	1.500	0.000	0.000	0.000	0.000	0.010	10.000	5.000	2.000	5.000	0.000	1.000	0.000	2.000
12	1.000	0.000	3.000	2.000	3.000	0.000	80.000	20.000	0.500	0.000	0.000	0.000	0.000	0.001	90.000	0.000	0.000	5.000	1.000	1.000	2.000	2.000
13	1.000	0.000	0.000	1.000	2.000	1.000	75.000	15.000	1.000	0.000	8.000	0.000	0.000	0.010	10.000	0.000	4.000	5.000	2.000	1.000	3.000	1.000
14	0.000	1.000	1.000	0.000	1.000	4.000	40.000	10.000	1.000	0.000	0.000	0.000	0.000	0.010	10.000	0.000	0.000	5.000	0.000	2.000	3.000	3.000
15	1.000	3.000	2.000	2.000	0.000	2.000	35.000	10.000	1.000	25.000	0.000	0.000	0.000	0.001	10.000	0.000	2.000	5.000	1.000	0.000	3.000	2.000
16	1.000	0.000	0.000	1.000	3.000	3.000	45.000	15.000	1.000	0.000	0.000	0.000	0.000	0.010	90.000	0.000	3.000	5.000	2.000	1.000	0.000	0.000
17	0.000	1.000	3.000	0.000	2.000	0.000	90.000	10.000	1.000	0.000	0.000	0.000	0.000	0.010	10.000	0.000	0.000	5.000	0.000	2.000	2.000	1.000
18	1.000	3.000	0.000	2.000	1.000	6.000	55.000	15.000	0.500	0.000	0.000	0.000	1.000	0.010	10.000	0.000	1.000	10.000	1.000	0.000	2.000	2.000
19	1.000	0.000	1.000	2.000	0.000	0.000	85.000	10.000	0.500	0.000	0.000	0.000	0.000	0.050	10.000	0.000	4.000	50.000	2.000	1.000	1.000	2.000
20	1.000	1.000	3.000	1.000	3.000	1.000	75.000	15.000	1.500	0.000	2.000	0.000	0.000	0.010	90.000	0.000	0.000	5.000	0.000	2.000	2.000	2.000
21	1.000	0.000	0.000	0.000	2.000	0.000	65.000	10.000	0.500	0.000	0.000	0.000	0.000	0.010	10.000	0.000	3.000	5.000	1.000	0.000	3.000	1.000
22	0.000	3.000	0.000	1.000	0.000	5.000	55.000	15.000	0.500	0.000	0.000	0.000	0.000	0.010	10.000	0.000	3.000	5.000	0.000	1.000	0.000	3.000
23	0.000	0.000	2.000	0.000	1.000	6.000	30.000	10.000	2.000	0.000	0.000	0.000	1.000	0.010	10.000	0.000	2.000	5.000	1.000	2.000	1.000	2.000
24	0.000	0.000	0.000	1.000	2.000	0.000	80.000	15.000	0.500	0.000	0.000	0.000	0.000	0.010	10.000	0.000	0.000	5.000	2.000	0.000	3.000	1.000
25	0.000	0.000	3.000	2.000	3.000	1.000	90.000	10.000	1.000	30.000	0.000	0.000	1.000	0.050	90.000	0.000	2.000	5.000	0.000	2.000	1.000	0.000

[[†] various attributes considered are: 1-overall shape, 2-external shape, 3-internal shape, 4-initial shape, 5-raw material type, 6-type of material, 7-maximum external diameter, 8-minimum external diameter, 9-dimensional envelope, 10-gear teeth, 11-auxiliary holes, 12-spherical surfaces, 13-plane surfaces, 14-tolerance, 15-surface finish, 16-complexity, 17-size, 18- weight, 19-personnel requirement, 20-material handling, 21-annual production, 22-machine tool requirement]

Table 4.18a: Similarity matrix for example 3

1.000000	0.616440	0.553594	0.436379	0.678073	0.537288	0.497028	0.631428	0.562720	0.676249	0.641735	0.542838	0.562009	0.673264	0.596301	0.537442	0.678459	0.580469	0.618182	0.543069	0.682247	0.601511	0.694909	0.710277	0.570327
0.616440	1.000000	0.637154	0.713879	0.752574	0.602666	0.676043	0.635149	0.703857	0.749203	0.722265	0.731377	0.660721	0.776522	0.691983	0.733123	0.748816	0.688272	0.658267	0.709963	0.729877	0.754768	0.699682	0.762453	0.606948
0.553594	0.637154	1.000000	0.559553	0.708854	0.763492	0.716162	0.588832	0.680267	0.720635	0.863807	0.600119	0.612797	0.772104	0.695141	0.651433	0.723619	0.659704	0.619525	0.730221	0.666801	0.785199	0.733143	0.570589	0.498418
0.436379	0.713879	0.559553	1.000000	0.531033	0.474849	0.590867	0.486769	0.585780	0.593464	0.638079	0.649571	0.488007	0.581297	0.596108	0.595907	0.606405	0.583183	0.613652	0.597855	0.572314	0.668202	0.559652	0.589738	0.563022
0.678073	0.752574	0.708854	0.531033	1.000000	0.662245	0.606834	0.720888	0.715383	0.770903	0.712055	0.714023	0.675186	0.758736	0.666621	0.622913	0.728433	0.690275	0.798551	0.701701	0.732221	0.732437	0.613714	0.714796	0.577443
0.537288	0.602666	0.763492	0.474849	0.662245	1.000000	0.540260	0.481617	0.724567	0.770130	0.708684	0.541389	0.669218	0.712508	0.660653	0.619543	0.707313	0.762879	0.566856	0.665430	0.711101	0.703958	0.709045	0.633071	0.573022
0.497028	0.676043	0.716162	0.590867	0.606834	0.540260	1.000000	0.554994	0.669156	0.694372	0.746635	0.634462	0.571383	0.727660	0.605242	0.600928	0.757963	0.610714	0.547808	0.681231	0.595084	0.698331	0.643244	0.650387	0.608519
0.631428	0.635149	0.588832	0.486769	0.720888	0.481617	0.554994	1.000000	0.688868	0.552396	0.546579	0.758287	0.603216	0.585684	0.516296	0.699861	0.651485	0.539951	0.698875	0.743368	0.617394	0.536658	0.569450	0.622697	0.672140
0.562720	0.703857	0.680267	0.585780	0.715383	0.724567	0.669156	0.688868	1.000000	0.712013	0.668316	0.748640	0.838591	0.684694	0.683488	0.783720	0.747898	0.775325	0.781683	0.721166	0.819868	0.711426	0.630582	0.810019	0.583303
0.676249	0.749203	0.720635	0.593464	0.770903	0.770130	0.694372	0.552396	0.712013	1.000000	0.802191	0.680350	0.671816	0.866621	0.693553	0.591837	0.831123	0.752706	0.630059	0.698331	0.744002	0.825171	0.691296	0.802335	0.530164
0.641735	0.722265	0.863807	0.638079	0.712055	0.708684	0.746635	0.546579	0.668316	0.802191	1.000000	0.630684	0.637302	0.738600	0.689342	0.648232	0.766306	0.653381	0.646969	0.709271	0.633730	0.848665	0.729942	0.692064	0.586559
0.542838	0.731377	0.600119	0.649571	0.714023	0.541389	0.634462	0.758287	0.748640	0.680350	0.630684	1.000000	0.684292	0.628881	0.674675	0.750634	0.712863	0.702753	0.675344	0.847171	0.713621	0.602582	0.589920	0.726500	0.651732
0.562009	0.660721	0.612797	0.488007	0.675186	0.669218	0.571383	0.603216	0.838591	0.671816	0.637302	0.684292	1.000000	0.656710	0.655504	0.801191	0.671429	0.677552	0.724819	0.685606	0.837338	0.668290	0.602597	0.821429	0.491682
0.673264	0.776522	0.772104	0.581297	0.758736	0.712508	0.727660	0.585684	0.684694	0.866621	0.738600	0.628881	0.656710	1.000000	0.690569	0.613095	0.873593	0.661751	0.593650	0.728680	0.741017	0.773701	0.794372	0.750866	0.572635
0.596301	0.691983	0.695141	0.596108	0.666621	0.660653	0.605242	0.516296	0.683488	0.693553	0.689342	0.674675	0.655504	0.690569	1.000000	0.609292	0.629963	0.784138	0.668201	0.621413	0.739811	0.691543	0.642517	0.658751	0.541126
0.537442	0.733123	0.651433	0.595907	0.622913	0.619543	0.600928	0.699861	0.783720	0.591837	0.648232	0.750634	0.801191	0.613095	0.609292	1.000000	0.616558	0.652119	0.677524	0.729221	0.764286	0.703463	0.619589	0.736255	0.618630
0.678459	0.748816	0.723619	0.606405	0.728433	0.707313	0.757963	0.651485	0.747898	0.831123	0.766306	0.712863	0.671429	0.873593	0.629963	0.616558	1.000000	0.614132	0.592784	0.804004	0.746212	0.695779	0.758875	0.774243	0.696444
0.580469	0.688272	0.659704	0.583183	0.690275	0.762879	0.610714	0.539951	0.775325	0.752706	0.653381	0.702753	0.677552	0.661751	0.784138	0.652119	0.614132	1.000000	0.669129	0.635885	0.761859	0.751686	0.681015	0.733829	0.517718
0.618182	0.658267	0.619525	0.613652	0.798551	0.566856	0.547808	0.698875	0.781683	0.630059	0.646969	0.675344	0.724819	0.593650	0.668201	0.677524	0.592784	0.669129	1.000000	0.569516	0.716269	0.665836	0.600143	0.676117	0.560409
0.543069	0.709963	0.730221	0.597855	0.701701	0.665430	0.681231	0.743368	0.721166	0.698331	0.709271	0.847171	0.685606	0.728680	0.621413	0.729221	0.804004	0.635885	0.569516	1.000000	0.659307	0.626623	0.644264	0.666126	0.669712
0.682247	0.729877	0.666801	0.572314	0.732221	0.711101	0.595084	0.617394	0.819868	0.744002	0.633730	0.713621	0.837338	0.741017	0.739811	0.764286	0.746212	0.761859	0.716269	0.659307	1.000000	0.707143	0.686905	0.850758	0.518414
0.601511	0.754768	0.785199	0.668202	0.732437	0.703958	0.698331	0.536658	0.711426	0.825171	0.848665	0.602582	0.668290	0.773701	0.691543	0.703463	0.695779	0.751686	0.665836	0.626623	0.707143	1.000000	0.676732	0.724567	0.516033
0.694909	0.699682	0.733143	0.559652	0.613714	0.709045	0.643244	0.569450	0.630582	0.691296	0.729942	0.589920	0.602597	0.794372	0.642517	0.619589	0.758875	0.681015	0.600143	0.644264	0.686905	0.676732	1.000000	0.651299	0.654886
0.710277	0.762453	0.570589	0.589738	0.714796	0.633071	0.650387	0.622697	0.810019	0.802335	0.692064	0.726500	0.821429	0.750866	0.658751	0.736255	0.774243	0.733829	0.676117	0.666126	0.850758	0.724567	0.651299	1.000000	0.546444
0.570327	0.606948	0.498418	0.563022	0.577443	0.573022	0.608519	0.672140	0.583303	0.530164	0.586559	0.651732	0.491682	0.572635	0.541126	0.618630	0.696444	0.517718	0.560409	0.669712	0.518414	0.516033	0.654886	0.546444	1.000000

Table 4.18b: Transitive closure for example 3

1.000000	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.710277	0.696444
0.710277	1.000000	0.776522	0.713879	0.776522	0.770130	0.757963	0.758287	0.776522	0.776522	0.776522	0.776522	0.776522	0.776522	0.775325	0.776522	0.776522	0.775325	0.776522	0.776522	0.776522	0.776522	0.776522	0.776522	0.696444
0.710277	0.776522	1.000000	0.713879	0.781683	0.770130	0.757963	0.758287	0.802335	0.825171	0.863807	0.804004	0.802335	0.825171	0.775325	0.801191	0.825171	0.775325	0.781683	0.804004	0.802335	0.848665	0.794372	0.802335	0.696444
0.710277	0.713879	0.713879	1.000000	0.713879	0.713879	0.713879	0.713879	0.713879	0.713879	0.713879	0.713879	0.713879	0.713879	0.713879	0.713879	0.713879	0.713879	0.713879	0.713879	0.713879	0.713879	0.713879	0.713879	0.696444
0.710277	0.776522	0.781683	0.713879	1.000000	0.770130	0.757963	0.758287	0.781683	0.781683	0.781683	0.781683	0.781683	0.781683	0.775325	0.781683	0.781683	0.775325	0.798551	0.781683	0.781683	0.781683	0.781683	0.781683	0.696444
0.710277	0.770130	0.770130	0.713879	0.770130	1.000000	0.757963	0.758287	0.770130	0.770130	0.770130	0.770130	0.770130	0.770130	0.770130	0.770130	0.770130	0.770130	0.770130	0.770130	0.770130	0.770130	0.770130	0.770130	0.696444
0.710277	0.757963	0.757963	0.713879	0.757963	0.757963	1.000000	0.757963	0.757963	0.757963	0.757963	0.757963	0.757963	0.757963	0.757963	0.757963	0.757963	0.757963	0.757963	0.757963	0.757963	0.757963	0.757963	0.757963	0.696444
0.710277	0.758287	0.758287	0.713879	0.758287	0.758287	0.757963	1.000000	0.758287	0.758287	0.758287	0.758287	0.758287	0.758287	0.758287	0.758287	0.758287	0.758287	0.758287	0.758287	0.758287	0.758287	0.758287	0.758287	0.696444
0.710277	0.776522	0.802335	0.713879	0.781683	0.770130	0.757963	0.758287	1.000000	0.802335	0.802335	0.802335	0.838591	0.802335	0.775325	0.801191	0.802335	0.775325	0.781683	0.802335	0.837338	0.802335	0.794372	0.837338	0.696444
0.710277	0.776522	0.825171	0.713879	0.781683	0.770130	0.757963	0.758287	0.802335	1.000000	0.825171	0.804004	0.802335	0.866621	0.775325	0.801191	0.866621	0.775325	0.781683	0.804004	0.802335	0.825171	0.794372	0.802335	0.696444
0.710277	0.776522	0.863807	0.713879	0.781683	0.770130	0.757963	0.758287	0.802335	0.825171	1.000000	0.804004	0.802335	0.825171	0.775325	0.801191	0.825171	0.775325	0.781683	0.804004	0.802335	0.848665	0.794372	0.802335	0.696444
0.710277	0.776522	0.804004	0.713879	0.781683	0.770130	0.757963	0.758287	0.802335	0.804004	0.804004	1.000000	0.802335	0.804004	0.775325	0.801191	0.804004	0.775325	0.781683	0.847171	0.802335	0.804004	0.794372	0.802335	0.696444
0.710277	0.776522	0.802335	0.713879	0.781683	0.770130	0.757963	0.758287	0.838591	0.802335	0.802335	0.802335	1.000000	0.802335	0.775325	0.801191	0.802335	0.775325	0.781683	0.802335	0.837338	0.802335	0.794372	0.837338	0.696444
0.710277	0.776522	0.825171	0.713879	0.781683	0.770130	0.757963	0.758287	0.802335	0.866621	0.825171	0.804004	0.802335	1.000000	0.775325	0.801191	0.873593	0.775325	0.781683	0.804004	0.802335	0.825171	0.794372	0.802335	0.696444
0.710277	0.775325	0.775325	0.713879	0.775325	0.770130	0.757963	0.758287	0.775325	0.775325	0.775325	0.775325	0.775325	0.775325	1.000000	0.775325	0.775325	0.784138	0.775325	0.775325	0.775325	0.775325	0.775325	0.775325	0.696444
0.710277	0.776522	0.801191	0.713879	0.781683	0.770130	0.757963	0.758287	0.801191	0.801191	0.801191	0.801191	0.801191	0.801191	0.775325	1.000000	0.801191	0.775325	0.781683	0.801191	0.801191	0.801191	0.794372	0.801191	0.696444
0.710277	0.776522	0.825171	0.713879	0.781683	0.770130	0.757963	0.758287	0.802335	0.866621	0.825171	0.804004	0.802335	0.873593	0.775325	0.801191	1.000000	0.775325	0.781683	0.804004	0.802335	0.825171	0.794372	0.802335	0.696444
0.710277	0.775325	0.775325	0.713879	0.775325	0.770130	0.757963	0.758287	0.775325	0.775325	0.775325	0.775325	0.775325	0.775325	0.784138	0.775325	0.775325	1.000000	0.775325	0.775325	0.775325	0.775325	0.775325	0.775325	0.696444
0.710277	0.776522	0.781683	0.713879	0.798551	0.770130	0.757963	0.758287	0.781683	0.781683	0.781683	0.781683	0.781683	0.781683	0.775325	0.781683	0.781683	0.775325	1.000000	0.781683	0.781683	0.781683	0.781683	0.781683	0.696444
0.710277	0.776522	0.804004	0.713879	0.781683	0.770130	0.757963	0.758287	0.802335	0.804004	0.804004	0.847171	0.802335	0.804004	0.775325	0.801191	0.804004	0.775325	0.781683	1.000000	0.802335	0.804004	0.794372	0.802335	0.696444
0.710277	0.776522	0.802335	0.713879	0.781683	0.770130	0.757963	0.758287	0.837338	0.802335	0.802335	0.802335	0.837338	0.802335	0.775325	0.801191	0.802335	0.775325	0.781683	0.802335	1.000000	0.802335	0.794372	0.850758	0.696444
0.710277	0.776522	0.848665	0.713879	0.781683	0.770130	0.757963	0.758287	0.802335	0.825171	0.848665	0.804004	0.802335	0.825171	0.775325	0.801191	0.825171	0.775325	0.781683	0.804004	0.802335	1.000000	0.794372	0.802335	0.696444
0.710277	0.776522	0.794372	0.713879	0.781683	0.770130	0.757963	0.758287	0.794372	0.794372	0.794372	0.794372	0.794372	0.794372	0.775325	0.794372	0.794372	0.775325	0.781683	0.794372	0.794372	0.794372	1.000000	0.794372	0.696444
0.710277	0.776522	0.802335	0.713879	0.781683	0.770130	0.757963	0.758287	0.837338	0.802335	0.802335	0.802335	0.837338	0.802335	0.775325	0.801191	0.802335	0.775325	0.781683	0.802335	0.850758	0.802335	0.794372	1.000000	0.696444
0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	0.696444	1.000000

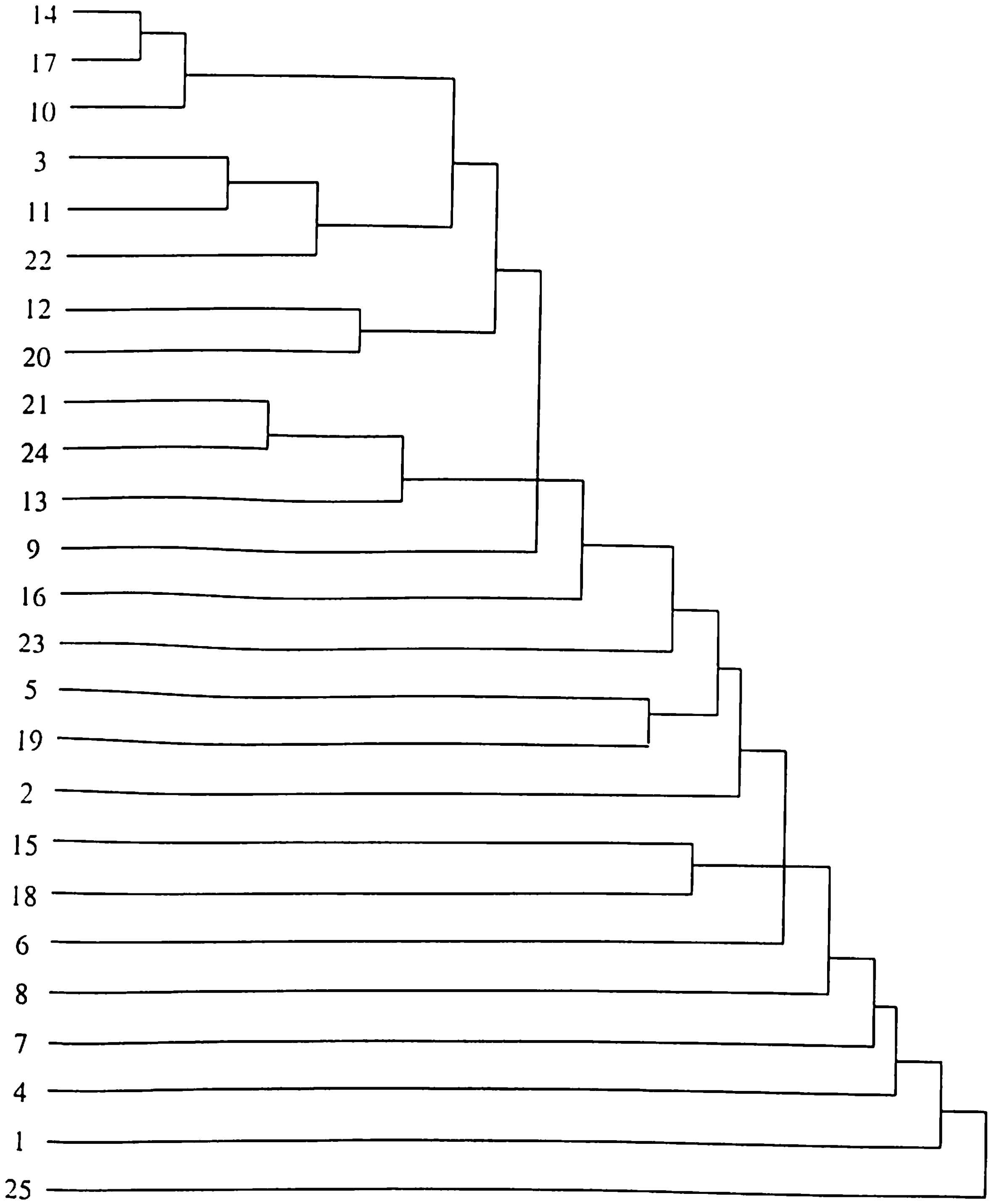

Figure 4.10: Dendogram showing the clustering of parts (not to scale) for example 3

Part families formed at different levels of similarity are:

$\alpha = 0.873593$
Part family 1: [14, 17]
Part family 2-24: each part in individual family

$\alpha = 0.866621$
Part family 1: [14, 17, 10]
Part family 2-23: each part in individual family

$\alpha = 0.863807$
Part family 1: [14, 17, 10]
Part family 2: [3, 11]
Part family 3-22: each part in individual family

$\alpha = 0.850758$
Part family 1: [14, 17, 10]
Part family 2: [3, 11]
Part family 3: [21, 24]
Part family 4-21: each part in individual family

$\alpha = 0.848665$
Part family 1: [14, 17, 10]
Part family 2: [3, 11, 22]
Part family 3: [21, 24]
Part family 4-20: each part in individual family

$\alpha = 0.847171$
Part family 1: [14, 17, 10]
Part family 2: [3, 11, 22]
Part family 3: [21, 24]
Part family 4: [12, 20]
Part family 5-19: each part in individual family

$\alpha = 0.837328$
Part family 1: [14, 17, 10]
Part family 2: [3, 11, 22]
Part family 3: [21, 24, 13]
Part family 4: [12, 20]
Part family 5-18: each part in individual family

$\alpha = 0.825171$
Part family 1: [14, 17, 10, 3, 11, 22]
Part family 2: [21, 24, 13]
Part family 3: [12, 20]
Part family 4-17: each part in individual family

$\alpha = 0.804004$
Part family 1: [14, 17, 10, 3, 11, 22, 12, 20]
Part family 2: [21, 24, 13]
Part family 3-16: each part in individual family

α = 0.802335
Part family 1: [14, 17, 10, 3, 11, 22, 12, 20, 21, 24, 13, 9]
Part family 2-14: each part in individual family

α = 0.801191
Part family 1: [14, 17, 10, 3, 11, 22, 12, 20, 21, 24, 13, 9, 20]
Part family 2-13: each part in individual family

α = 0.798551
Part family 1: [14, 17, 10, 3, 11, 22, 12, 20, 21, 24, 13, 9, 20]
Part family 2: [5, 19]
Part family 3-12: each part in individual family

α = 0.794372
Part family 1: [14, 17, 10, 3, 11, 22, 12, 20, 21, 24, 13, 9, 20, 23]
Part family 2: [5, 19]
Part family 3-11: each part in individual family

α = 0.784183
Part family 1: [14, 17, 10, 3, 11, 22, 12, 20, 21, 24, 13, 9, 20, 23]
Part family 2: [5, 19]
Part family 3: [15, 18]
Part family 4-10: each part in individual family

α = 0.781683
Part family 1: [14, 17, 10, 3, 11, 22, 12, 20, 21, 24, 13, 9, 20, 23, 5, 19]
Part family 2: [15, 18]
Part family 3-9: each part in individual family

α = 0.776522
Part family 1: [14, 17, 10, 3, 11, 22, 12, 20, 21, 24, 13, 9, 20, 23, 5, 19, 2]
Part family 2: [15, 18]
Part family 3-8: each part in individual family

α = 0.770130
Part family 1: [14, 17, 10, 3, 11, 22, 12, 20, 21, 24, 13, 9, 20, 23, 5, 19, 2, 15, 18, 6]
Part family 2-6: each part in individual family

α = 0.758287
Part family 1: [14, 17, 10, 3, 11, 22, 12, 20, 21, 24, 13, 9, 20, 23, 5, 19, 2, 15, 18, 6, 8]
Part family 2-5: each part in individual family

α = 0.757963
Part family 1: [14, 17, 10, 3, 11, 22, 12, 20, 21, 24, 13, 9, 20, 23, 5, 19, 2, 15, 18, 6, 8, 7]
Part family 2-4: each part in individual family

α = 0.713879
Part family 1: [14, 17, 10, 3, 11, 22, 12, 20, 21, 24, 13, 9, 20, 23, 5, 19, 2, 15, 18, 6, 8, 7, 4]
Part family 2: [1]
Part family 3: [25]

$\alpha = 0.710277$
Part family 1: [14, 17, 10, 3, 11, 22, 12, 20, 21, 24, 13, 9, 20, 23, 5, 19, 2, 15, 18, 6, 8, 7, 4, 1]
Part family 2: [25]

$\alpha = 0.696444$
All parts in one family

These results are also shown in figure 4.10 using a simple dendogram

4.4 Conclusions

Literature review of the part family formation approaches indicates that there are two main methodologies for part family formation - one based on the coding and classification and the other based on production flow analysis. Moreover, part families can be formed based on the design attributes or manufacturing attributes or using a combination of both. Two models for part family formation are developed in this chapter, which do not force a part dichotomously to fall in a cluster but allow it to belong to a part family with certain membership. Model 1 is based on the fuzzy logic and AHP and model 2 is based on fuzzy equivalence and AHP. Both these models eliminate the scaling problem of different attributes and can be integrated with the existing coding systems in the organizations to form the part families. However, in model 1 AHP is used to assign the weightages to the attributes for each relationship of part pairs and in model 2 AHP is used to assign the weightages to the different attributes, which are same for all parts. Both the models show that different importance for the different attributes changes the part clustering.

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Chapter 5

Cell Formation

5.1. Introduction

The cell formation problem is of crucial importance when implementing a cellular manufacturing system because the success of the system depends greatly on the initial grouping of machines and parts (Chen *et al.* 1995a). A considerable amount of research has been directed at the cell formation problem. The Group Technology (GT) problem was originally tackled, although not in an algorithmic approach, by Burbidge's production flow analysis (1963, 1971, 1975, 1991). Burbidge's pioneering work is based on parts routing information and consists of an exhaustive analysis of production flow. His approach takes the binary machine-part incidence matrix and rearranges it so that blocks of machine-part combinations are grouped into cells along the diagonal of the matrix. The early cell formation methods like array clustering methods and similarity coefficient based methods used the binary machine-part incidence matrix and ignored issues such as operation sequence of parts, demand of parts, alternate routes, and size of the cells. Mathematical programming approaches can cope with the cell formation problem in a more comprehensive way since they can incorporate more complicated features of the problem. Such approaches vary greatly in objectives and constraints, resulting in extremely complex formulations that are non-polynomial (NP)-complete. Therefore, usually heuristics are employed to solve these problems. Simulated annealing algorithms, genetic algorithms, and tabu search based heuristics have been employed to solve these problems.

This chapter presents a literature review on cell formation and three models developed to solve the cell formation problem. The first model is ART1 neural network (NN) based which considers various practical factors like production volume, processing time of parts on machines, number of cells, minimum acceptable utilization of individual machines, machine downtime, desirable machine utilization, maximum permissible workload on machines and other management constraints like number of shifts, working days, maximum and effective time available on machines. Intercell material handling cost and cost of voids are also considered. Model 2 and model 3 are random search heuristics based on simulated annealing. These two models consider the alternate process plans for the parts. However, model 2 considers the binary part-machine incidence matrix and solves the cell formation problem with the objective of minimizing weighted sum of exceptional elements and voids and model 3 considers the operation sequence, production volume (demand), and batch size of parts and solves the cell formation problem with the objective of minimizing intercell moves.

5.2. Literature Review

Cell formation problem has attracted considerable attention of researchers during past three decades. Many research papers have appeared during this period. In this section, cell formation literature is reviewed. Due to the large number of cell formation methods and the diversity in approaches adopted it is difficult to classify all the approaches without overlap. Therefore, few references are referred more than once according to the requirement of the proposed classification scheme. The literature in cell formation has been classified on the basis of various approaches followed by the researchers as:

- Array clustering
- Similarity coefficient methods
- Heuristics
- Mathematical programming
- Fuzzy clustering
- Graph theory and network based methods
- Neural networks
- Simulated annealing
- Genetic algorithms
- Expert systems/Knowledge-based systems
- Simulation
- Multiobjective models

5.2.1 Array clustering

Array based clustering method is based on production flow analysis, which primarily uses routing information. The approach is based on sorting rows and columns of the part-machine incidence matrix to generate block diagonal forms. McCormick *et al.* (1972) developed bond energy algorithm (BEA) to identify and display natural variable groups or clusters that occur in complex data arrays. They proposed a measure of effectiveness (ME) such that an array that possesses dense clumps of numerically large elements will have a large ME when compared with the same array if the rows and columns have been permuted so that its numerically large elements are more uniformly distributed throughout the array. King (1980) proposed the rank order clustering (ROC) algorithm for block diagonalising the binary part-machine incidence matrix. This algorithm provides a simple, effective and efficient technique, which can be easily computerized. In this method each row (column) in the part-machine matrix is read as a binary word. The procedure converts these binary words for each row (column) into decimal equivalents. The algorithm successively rearranges the rows (columns) iteratively in order of descending values until there is no change. ROC algorithm had a limitation of computational complexity as for large-scale problems the binary weight increases, creating computational problems. This method was improved by developing a modified version (ROC2) by King and Nakornchai (1982). ROC2 algorithm begins by identifying in the right-most column all rows that have an entry of 1. These rows are moved to the top of the column, keeping the relative order among rows. This procedure is then applied to the rows by beginning at the last row. The use of binary words was eliminated in this procedure. Waghodekar (1994) proposed ROC3, in which column-row reordering is suggested instead of row-column reordering, which is done in ROC2. Chandrasekharan and Rajagopalan (1986a) presented modified rank ordering clustering (MODROC), an improved ROC algorithm incorporating the block and slice method. In this method the block of columns form left is removed and ROC is applied again to get another block of 1's in the top left hand corner. This process is continued until no elements are left in the matrix. This method identifies mutually exclusive groups but may contain overlapping machines. Chan and Milner (1982) proposed the direct clustering algorithm (DCA), which rearranges the rows with the left-most positive cells (i.e. 1's) to the top and the column with the top-most positive cells to the left of the matrix. This method may not necessarily always produce diagonal solutions even if one exists. Iri (1968) suggested a method to identify perfect block diagonals if they exist. In this method, starting from any row, mask all the columns, which have an entry in this row, then proceed to mask all the rows, which have an entry of 1 in these columns. Repeat this process until the number of rows and columns stop increasing. These rows and columns constitute a block. If perfect block diagonals do not exist, the entire matrix is masked as one group. Kusiak and Chow (1987b) presented a cluster identification algorithm (CIA) as an implementation of this method to solve the machine-part grouping problem. A cost analysis was developed to solve the augmented formulation of the problem, which associates the cost with part and restricts the number of machines in the cell. In later paper (1987b) they developed a modified cluster analysis to tackle the presence of exceptional parts or machines. Chandrasekharan and Rajagopalan (1986b, 1987) presented a three step non-hierarchical algorithm, ZODIAC, for simultaneous design of part families and machine groups. In the first step the grouping problem is formulated as a bipartite graph with the nodes in the first layer representing machines and the nodes in the second layer representing the parts. The upper bound to number of groups is determined. In the second step, the machine part incidence matrix is rearranged with the cell having maximum clustering efficiency. Finally groups are adjusted by defining 'ideal' seeds (centroids of the groups) for the groups. Grouping efficiency is then used to evaluate the goodness of the solution. Srinivasan and Narendran (1991) developed an algorithm called GRAPHICS based on non-hierarchical clustering algorithm. In this algorithm the initial seed is obtained from the assignment method. The authors found that the results obtained with this method are better than those obtained by ZODIAC.

5.2.2 Similarity coefficient based methods

Similarity coefficient based methods are one of the most frequently used techniques in cell formation. It can incorporate production data. The approach is easy for the computer application. Similarity coefficient, dissimilarity coefficient, and resemblance coefficient are the various measures used in this category. These are used to compare two objects such as parts/machines. The aim is to select a larger similarity/resemblance coefficient or a smaller dissimilarity coefficient.

McAuley (1972) used Jaccard similarity coefficient in cluster analysis for machine cell formation. The similarity measure is determined by the ratio of number of parts visiting both machines and number of parts visiting at least one of the machines. Using single linkage clustering analysis (SLCA), groups of machines with the highest similarity coefficient are formed. In order that the similarity coefficients are meaningful, all machines must process nearly the same number of parts (DeBeers *et al.* 1976). For two machines, which are processing an identical set of parts and if one of the machines also processes an additional large number of parts, this similarity would be artificially low (Luong 1993). SLCA requires a large number of data storage and computation of similarity matrices and does not form part families and machine groups simultaneously. It also suffers from chaining problem (Adil *et al.* 1997). Carrie (1973) used numerical taxonomy for similarity between parts for the cell formation. Like McAuley (1972), this method also needs a threshold level of similarity or pre-specified number of cells. Similarity level is gradually reduced for grouping. The membership of each family is determined at such level. Rajagopalan and Batra (1975) have also used Jaccard similarity coefficient for representing arcs in their graph theoretic model. They used cliques of machine-graph to identity machine cells. Strongly related vertices form the preliminary cells. With limitation on the cell sizes, some of the vertices are merged so as to minimize intercellular movement. In this approach, large cliques do not get disjoint- vertex due to high density of graphs. Another limitation of this method is that part-families are not formed concurrently. DeWitte (1980) used operation routing, machine time and divisibility of operations between machines. The method uses three types of similarity coefficients to explore the interdependence of machine types. These are (i) absolute similarity coefficient, (sa_{ij}), (ii) mutual similarity coefficient, (sm_{ij}), and (iii) single similarity coefficient, (ss_{ij}). Cells are formed using single linkage cluster analysis and arbitrary selection of threshold value for similarity coefficients. DeWitte concluded that for clustering one should first use sa_{ij} and sm_{ij} and then for allocating the remaining unassigned machines, ss_{ij} should be used. Waghodekar and Sahu (1984) proposed a heuristic, MACE, in which they used three similarity coefficients of additive type or product type. Their method is simple and yields minimum number of exceptional elements. Grouping is based on the flow and sequence of parts. Panneerselvam and Balasubramanian (1985) used the parts grouping, which is based on similar process sequence. This facilitates the processing in the same line. Seifoddini and Wolfe (1985) proposed average linkage clustering algorithm (ALCA) to overcome the chaining problem resulting from the duplication of bottleneck machines. Machine duplication starts with the machine, which is generating largest number of intercellular moves and continues until a specified threshold is reached. Average linkage clustering method is preferred as a means of reducing chances of improper machine assignments, though it does not always do so (Seifoddini and Wolfe 1986, Seifoddini 1989b). In a similar development, Seifoddini (1989a) compared the SCLA and ALCA and found that ALCA gives better results. In further study in this area, Seifoddini (1990) observed that machine-component group analysis methods are suitable when there is no bottleneck machine and similarity coefficient methods are suitable when bottleneck machines are present. Mosier and Taube (1985) used similarity coefficient, which is weighed by the size of two member clusters. Weighted average linkage clustering algorithm, (WLCA), which is an extension of average linkage clustering algorithm (ALCA) is used for cell formation. Mosier (1989) has done experimental investigation of application of similarity coefficients in clustering problems. Steudel and Ballakur (1987) introduced a similarity measure based on the part routing and production requirement data. The similarity measure, called cell bond strength, is used in a two-stage heuristic. Optimum chain maximising the sum of the bonds among the machines is determined and it is then partitioned to form machine groups. Wei and Kern (1989, 1991) used a commonality score for evaluating similarity of parts. The commonalty score not only recognizes the parts, which require the two machines for processing, but also the parts, which do not require both the machines. An algorithm based on single linkage cluster method is used to form cells. Gupta and Seifoddini (1990) used a similarity coefficient based on production data such as part type, production volume, routing sequence, and unit operation time. On the basis of percentage utilization in each cell, their algorithm identifies bottleneck machines for duplication. Vakharia and Wemmerlov (1990) used an index to assess to similarity of parts on the basis of their operation sequences. Flow line cells are generated through iterative sequential manner. Shafer and Roger (1993a) have compared similarity and distance measures. They observed that the research devoted to machine grouping procedures out numbers the research devoted to part grouping procedures. Shafer and Roger (1993b) have proposed a similarity measure to remove this bias, which occurs when the part requires different number of machines in their processing. Similar bias also occurs when machines process different number of parts. Loung (1993) developed a similarity coefficient, which is based on the similarity between the two cells. Coding system is used to identify machines needed for processing the parts. A heuristic is used to form cells. In this approach, appropriate value for maximum number of machines in a cell and minimum acceptable value of similarity coefficient need to be specified beforehand. Sarker (1996) compared the similarity/dissimilarity coefficients in literature. Mosier *et al.* (1997) have surveyed the similarity coefficient based methods. They emphasised the need for development of similarity matrices with some desirable properties such as, controlling the placement of matrices on a numeric continuum and incorporation of weights and sequence-order into the matrix. Offodile and Grznar (1997) used similarity coefficient method for converting weighted code of coding and classification into similarity measures. An algorithm involving single linkage clustering and average linkage clustering is also proposed. Askin and Zhou (1998) have defined a similarity coefficient based on longest common operation sequence between part type and used it to group parts into independent flow-line families. The optimum machine sequence and capacity for each cell are then determined by solving shortest path problem on an augmented graph. Nair and Narendran (1998) proposed CASE (Clustering Algorithm for Sequence Data) to cluster machines and components on the basis of sequence data. Islam and Sarker (2000) developed relative similarity coefficient, which uses a set of important characteristic properties for grouping, for use as an intermediate tool to form cohesive cells. They developed a mathematical model and a heuristic to form cohesive cells using the similarity coefficient developed. Yin and Yasuda (2002) developed a similarity coefficient that incorporates alternate process routing, operation sequence, operation time and production volume factors. They developed a two stage heuristic for cell formation. The developed similarity coefficient is used in stage I to obtain basic machine cells. Stage II solves the machine-capacity violated issue, assigns parts to cells, selects process routing for each part and refines the final cell formation solution. A major disadvantage of most of the similarity coefficient methods is their arbitrary choice of threshold value.

5.2.3 Heuristics

Since the cell formation problem is NP-complete, many procedures developed in this area are heuristic based. These methods attempt for efficient yet effective solution approaches. This often leads to sub-optimal results.

Purcheck (1985) suggested a heuristic for cell formation. He defined the most complex part that has to be processed in one cell as master. His heuristic forms groups of minimum difference between masters and maximum combination of masters. Integrating it with workload the combination of master set is revised through acceptability tests. Waghodekar and Sahu (1984) developed a heuristic algorithm MACE (Machine Component Cell Formation) based on the similarity coefficient between parts to form machine part groups. The heuristic determines the intercell flows and groups machines based on the flow and assigns the parts as per the sequence of machines. Askin and Subramanian (1987) used a three-stage heuristic with economic considerations. Part routing similarity is coupled with the economic benefits of group technology. This forms the basis of the heuristic for cell formation. Ballakur and Steudel (1987) applied within-cell-utilization, workload restrictions and cell-size restrictions in two-stage procedure involving heuristic for cell formation. Tabucanon and Ojha (1987) developed heuristic for minimizing intercell flow of material in CMS. Harhalakis *et al.* (1990a) used a two-step procedure in the heuristic for minimizing intercell movement of parts. The first step is a bottom-up aggregation procedure to minimize the normalized intercell traffic. The second step involves a refinement procedure, which validates the significance of each machine in a cell to which it is assigned. They also considered the sequence of operations. Kusiak (1991) used a branching algorithm, which is a modification over his previous heuristic. Branching schemes for exceptional elements and bottleneck machines were proposed. The algorithm does not recommend any objective criteria to determine exceptional elements. Logendran (1991) has developed heuristic solution algorithm for the identification of key machines in the cell formation. Total moves of the parts are considered as the weighted sum of both intercell and intracell moves. Chen and Irani (1993) developed two effective clustering heuristics that generate compact block diagonal form. These heuristics are based on the minimal spanning tree (MST) of machines and parts. Kang and Wemmerlov (1993) proposed a heuristic that incorporates the concept of reallocating operations to alternative machines, while meeting capacity constraints. The proposed heuristic is user interactive that allows the user to intervene at several points during the cell formation process. Verma and Ding (1995) developed a sequence based material flow heuristic to solve cell formation problem. This heuristic is designed to consider operation sequence in accurately determining the costs of intercell movement as well as forward and backward intracell movements. Beaulieu *et al.* (1997) proposed a heuristic algorithm for cell formation. They considered machine capacity, alternate routing and constraints on cell size. The heuristic consists of two phases. In the first phase independent cell is formed using an aggregation procedure. In the second phase, intercell flow is introduced to eliminate the under-utilization of machines. Del Valle *et al.* (1994) developed a workload-based heuristic to minimize the intercell movements. Wu and Salvendy (1999) proposed a merging-and-breaking heuristic to solve the traditional cell formation problem and the assignments of the identical machines to different cells. Yin and Yasuda (2002) developed a heuristic algorithm that consists of two stages. They developed a similarity coefficient that is used in stage I to obtain basic machine cells. Stage II solves the machine-capacity violated issue, assigns parts to cells, selects process routing for each part and refines the final cell formation solution.

5.2.4 Mathematical programming

Two main research schools are identified in the area of CMS, namely: ‘pragmatic’ and ‘optimal’ (Cantamessa and Turroni, 1997). According to ‘pragmatic’ school of research benefits of CMS come from mere existence of cellular structure with realistic features rather than mere optimal composition of cells, pursued by so called optimal school of research. Therefore, there is a growing need to address some of the practical manufacturing and managerial considerations mentioned above. Lenstra (1972) showed that cell formation problem is NP-complete problem. Therefore, research has focussed in this area to solve a truncated version of the much larger and intractable problem under certain assumptions to simplify the model. A large variety of mathematical programming approaches have been used to solve cell formation problems. Linear programming (LP), Zero-One Linear Integer Programming (ZOLIP), Dynamic Programming (DP), Goal Programming (GP), Mixed Integer Programming (MIP), Zero-One Non-Linear Integer Programming (ZONLIP), Zero-One Non-Linear Fractional Programming (ZONLFP), assignment model, network model, *etc.* have been adopted for this purpose. Majority of mathematical programming models have used objective functions, which are based on either maximizing similarity measures or minimizing dissimilarity measures. Some other models use minimization of various associated costs or maximizing/minimizing the operation related measures. The constraints are selected on the basis of cell size, physical constraints, logical constraints or modelling constraints. Chu (1995) has reviewed and compiled 34 objectives and 44 constraints on the basis of 58 models selected from literature in this category.

Purcheck (1975) used mathematical programming for cell formation. Two kinds of classification schemes using exclusive membership and non-exclusive membership are adopted. Kusiak *et al.* (1986) used quadratic programming model for cell formation. Cluster size is constrained. The model is solved using an eigenvector-based algorithm. Steudel and Ballakur (1987) used a similarity measure called 'cell bond strength'. Using dynamic programming formulation, optimum chain of machines is found. Later, these chains are partitioned on the basis of cell restrictions. Kusaik (1987c) used p-median model for maximising the sum of similarity coefficients for a fixed number of groups.

Additional constraint for assigning each part to only one family is modelled. The approach involves initially selecting *p* of parts to serve as median or seeds for the clusters. Subsequently, the remaining parts are assigned to this seed such that the sum of part similarity in each cluster is maximized. In another integer programming model he considered more than one process-routes for every part. In the p-median formulation, additional constraints are added so that each part uses one process plan. The approach is significant in the sense that it was one of the earlier approaches to process a similarity matrix into a mathematical programming framework. The major limitation is that there is no simultaneous identification of machine cells in the model. Viswanathan (1996) proposed a new approach for solving the p-median problem in GT wherein the number of cells are not required to be given *a priori*. Wang and Roze (1997) used modified *p-median* approach for cell formation that allows the control of size of machine cells or part families by introducing an upper bound on the maximal number of machines per cell or maximal number of parts per family. Won (2000) developed two new p-median approaches to cell formation with alternate process plans: one with the prespecified number of cells and the other without the prespecified number of cells. Choobineh (1988) used proximity measure for manufacturing operations and sequence of operation. A zero/one integer programming formulation is used for cell formation. It is assumed that an operation can be performed on more than one machine type. Objective function minimizes the cost of producing parts in each cell and cost of purchasing new equipment. The model makes a significant contribution as the fund availability for machine acquisition has been considered. The formulation has a limitation that some coefficients of model can be known exactly only after the solution is known. For example, cost of producing a part in a cell can be known exactly only after the cell is formed through the final result of the formulation. Co and Araar (1988) used a three-stage methodology for cell formation. Initially zero/one integer programming is used to minimize the deviation between available capacity and workloads assigned to each machine. The resulting incidence matrix is manipulated by using King's algorithm. In the third stage, a direct search algorithm is employed for the composition of cells. The most significant limitation of this model is that the two parts that require similar processing in terms of tooling and set-ups can be assigned to different machines in order to achieve a balance of capacity for each machine type (Shafer and Rogers 1991). Gunasingh and Lashkari (1989) developed zero/one integer programming for maximizing similarity between machines and parts for minimizing the difference in cost of machines and saving due to intercellular material handling. The major contributions are: consideration for tooling-based similarity; differentiating situations of reorganizing the manufacturing system and setting up a new system; and consideration for cell size limitations. The information regarding total budgetary limit for the purchase of each machine is considered. Shtub (1989) used generalised assignment problem to minimize the cost of assigning the parts in the cells subject to minimum and maximum usage in each cell. Several process plans are also considered for the parts in each model. Askin and Chiu (1990) considered minimization of four costs: (i) machine cost; (ii) overhead associated with establishing a cell; (iii) tooling cost; and (iv) parts intercell transfer cost. Cell size restriction and limits on workers hour are also considered in the 0/1 integer programming formulation. Offodile (1992) has tackled the cell formation problem as a generalized assignment problem. This model advocates the adoption of dissimilarity measures and incorporates a weighted incidence matrix for production volume of parts. Rajamani *et al.* (1992a) have developed an integer program for a sequence dependent cell formation problem. The trade-off between saving on sequence dependent setup costs and additional investment on new machines is considered for determining the economic number of cells. Nagi *et al.* (1990), Singh *et al.* (1992) have considered the issue of alternate routing in the mathematical programming model for cell formation and route selection. A weighted criteria for minimizing intercell and intracell part movement is considered by Logendran (1990). Sankaran and Kasilingam (1993) have tackled the issue of cell size and machine requirement planning in the integer-programming model for cell formation. They also presented a simplified computational heuristic. It was observed that the interplay between sum of spatial and machine amortizing cost, and the sum of the processing and the material handling costs are the crucial factors in deciding capacity planning investments. Shanker and Agarwal (1997) considered a generalized framework of cell formation where an operation can be performed on more than one machine. Non-binary part-operation-machine incidence matrix is used for both hierarchical and non-hierarchical approaches. With multiple route plans, it is possible to reduce number of bottleneck machines by selecting a suitable process plan out of several alternatives available for each part. Lee and Chen (1997) have developed a mathematical formulation weighted approach for cell formation. The objectives are minimizing intercell movement and workload balancing among duplicate machines. Cell size, machine types and capacities, routing sequence, processing data, setup time, cycle demand, batch size, and pallet size are considered in the model. It has been assumed in the model that each part type has one unique routing sequences and total workload of each machine is within capacity limit. A three-phase strategy has been adopted to solve the model. They have also concluded that a singular objective of either minimizing intercell movement or maximizing process similarity is not effective in real life cell formation problem. Important performance including throughout time, number of in-process parts, and complexity of operation and control must be considered in the cell formation process. Askin and Zhou (1998) proposed an operation-sequence-based method for forming flow-line cells. The objective of the method is to find the minimum cost set of flow line cells that is capable of producing desired part mix. Shortest path problem is solved as an augmented graph to find optimal machine sequence/requirement for each cell. Baykasoglu and Gindy (2000) developed a goal programming formulation for concurrently forming independent cells. Machine independent capability unit, which are known as resource elements, are used to define processing requirements of parts and processing capabilities of machine tools. Representation of unique and shared capability boundaries by resource elements increases the opportunity to form independent cells and efficient utilization of them. The model was solved using tabu search algorithm. Won and Lee (2001) proposed a 0-1 linear formulation for solving the cell formation problem considering operation sequences and production volume to minimize the total intercell flows. The upper and lower limits on the part family and machine cell size were considered in the algorithm. Many other researchers have also adopted mathematical programming approaches in cell formation, for example: quadratic programming (Srivastava and Chen 1995), integer programming (Gunasingh and Lashkari 1991), mixed integer programming (Rajamani *et al.* 1990, 1992b, 1996, Adil *et al.* 1993, and 1996), *etc.* There has been some criticism of the mathematical programming models. This is because most of these methods are computationally intractable for large size problems (Vakharia and Chang 1997). Wei and Gaither (1990) have however pointed out that these models allow researchers to compare solution quality of heuristics used for cell formation. These models also provide the insight into development of near-optimal heuristic procedure. Another feature of some recent research is to exploit the potential of these methods in conjunction with a heuristic, i.e., adopting a two-phase methodology for cell formation.

5.2.5 Fuzzy clustering

Fuzzy approach provides a more accurate presentation of problem in the environment of uncertainty or inexact information (Bezdek 1981). It effectively tackles those parts/machines whose lineages to a cell are less evident. Batra and Rajagopalan (1977) used fuzzy clustering. Their approach first forms fuzzy component families and decides membership grades of each component with reference to every family. An alternative algorithm is used for cell formation by considering the requirements of high-grade members subject to constraint on cell size and machine utilization. They also introduced the concept of super cell, which is a collection of adjacent cells forming single administrative unit. Chu and Hayya (1991) used fuzzy c-means clustering algorithm to formulate the cell formation problem. Each part is associated with a degree of membership to the part families. It provides flexibility in part assignment to cells so that the workload balance among machine cells is maintained. Zhang and Wang (1992) showed that degree of match between each part-machine pair could be calculated using fuzzy set theory. They provide a fuzzy version of single linkage clustering and rank order clustering considering a non-binary machine-component matrix. This method is more flexible as compared to the binary matrix approach. It provides a mechanism to capture a number of other relationships between part machine pair such as cost of processing a part on machine, processing time, *etc.* Fuzzy clustering approach has also been used for cell formation by Ponnambalam and Arvindan (1993a), Ponnambalam *et al.* (1993). They proposed a heuristic algorithm, which uses a similarity measure proposed by Kusiak (1987b) and Hungarian method to solve the travelling salesman formulation for sequential fuzzy clustering problem. The algorithm has weaknesses such as - artificial restriction on number of groups and data structure of incidence matrix is in no way related to the heuristic. They (Ponnambalam and Arvindan 1993b) proposed the modification by incorporating commonality score (Wei and Kern 1989) and labelling algorithm (Lotfi 1989). Gindy *et al.* (1995) used fuzzy c-means clustering algorithm and defined a validity measure for cell formation. Component partitioning is based upon assessing the compactness of component within a group and overlapping between component groups. Venogopal (1999) provides a review of the fuzzy models for solving group technology problem. He divided the models in four categories: (i) fuzzy clustering; (ii) fuzzy heuristics; (iii) fuzzy mathematical programming; and (iv) fuzzy ART neural networks.

5.2.6 Graph theory and network based methods

Rajagopalan and Batra (1975) used graph theory for machine group formation. This problem is represented in the form of a graph, whose vertices represent machines and edges represent relationships created between the machines and components using them. In order to identify the machine cells a graph-partitioning method was developed, which identifies cliques. Vannelli and Kumar (1986) used minimum cut nodes of graph to model the minimum number of bottlenecks machines (or parts). When duplicated (or subcontracted) this results in perfect clustering. Faber and Carter (1986) used networks in which nodes represent machines/components. This is decomposed into dense sub-graphs. Heuristic is used to decide duplication of bottleneck machines and cell formation. Ballakur and Steudel (1987) used bipartite graph search algorithm to select key machine/part and within cell utilization of machines is used as the criterion for machine assignment. Askin and Chiu (1990) used graph partitioning to assign components to specific machines and then grouping into cells. Vohra *et al.* (1990) used network approach for cell formation for minimum intercellular transfer. Modified Gomory-Hu algorithm is used to partition the incidence matrix with machining time figures.

Askin *et al.* (1991) used Hamiltonian path approach for cell formation. Distance measure based on the similarity coefficients is used in the heuristic for deleting edges on tour. Agarwal *et al.* (1994) have also considered use of graph theory in cell formation. Vannelli and Hall (1993) used a graph partitioning technique for finding part-machine families to optimize machine replication and part sub-contracting strategies in economical sense. The limit on part-machine families was considered to address the issue of load imbalance between cells. Hadley (1996) extended this work to improve the accuracy of the graphical models. Shanker and Agarwal (1997) have reviewed some graph partitioning approaches-based papers and concluded that this approach has been successfully employed for simple grouping and has potential for generalized grouping with non-binary part-machine associations. Wu (1998) developed a network based model by which the cell formation and assignment of identical machines are solved concurrently. The machine type which has only one machine is represented by a simple node and the machine which has two or more than two machines is represented by a complex node. By using the information of operation sequences for each part type, Wu and Salvendy (1999) developed a graphical model that can describe the part families with respect to the machine types of multiple machines. This model can assign identical machines to different cells based on part families without involving complex computation. Mukhopadhyay *et al.* (2000) proposed an algorithm based on modified Hamiltonian chain (MHC) and consists of two stages. Stage I forms the graph from the machine part incidence matrix. Stage II generates a modified Hamiltonian chain which is a subgraph of the main graph developed in stage I, and it gives machine sequence and part sequence directly. A major drawback of graph theoretic approach is due to non-consideration of practical issues such as, production volume and alternative plans (Singh 1993).

5.2.7 Neural networks

Various paradigms of neural network have been used for cell formation during recent years. The rapid parallel processing of these networks and pattern classification are very useful in this area. Back propagation, self-organising mapping, competitive learning, adaptive learning techniques (ART, ART-I and ART-II), and interactive action and competition learning, have been employed for cell formation problem (Chu 1995). Malave and Ramachandran (1991) and Chu (1993) have applied the competitive learning rule to the parts and machines formation problem but the problem with these models is that there is no threshold to define the level of similarity between the patterns which are clustered together. So the presence of an unusual pattern which is only slightly similar to the members of an existing cluster can wash away the cluster's information about the previously learned patterns. Dagli and Huggahalli (1991) used the ART1 neural network for part family and machine cell formation and noticed that the outputs of ART1 are dependent on the sequence of the inputs. Kaparthi and Suresh (1992) also used ART1 to group parts or machines wherein they suggested reversing the ones and zeros in the incidence matrix and restoring the original values after the clustering to reduce the data dependency of ART1. This algorithm didn't produce very satisfactory results for ill-structured problems such as Burbidge (1975). Kaparathi *et al.* (1993) proposed a robust neural network based algorithm for part-machine grouping problem in group technology by modifying the normal Carpenter and Grossberg's ART1 neural network. The robustness of the modified algorithm to random ordering of the input data was tested using industry-size data set (10000 parts and 100 machine types). Venugopal and Narendran (1994) tested the competitive learning algorithm, ART1 and Kohonen's self-organising feature map for cell formation. Kusiak and Lee (1996), Chen and Cheng (1995), Chen *et al.* (1995b) have also used neural network approach for cell formation problem. Malakooti and Yang (1995) have used unsupervised learning neural network, having features to incorporate variable parameters in cell formation. V[illegible] and Ali (1995), and Zolfaghari and Liang (1997) have used Hopfield neural network for cell design. Burke and Kamal (1992) have introduced an application of the fuzzy-ART neural network to the cell formation problem. Suresh and Kaparthi (1994) investigated the performance of fuzzy-ART for cell formation. Using large data set, a series of replicated clustering experiments are performed. It is shown that the fuzzy-ART performs better than ART1, DCA, ROC3 and modified ART1 approaches in terms of consistency and better identification of block diagonalised structures. Execution time in fuzzy-ART is more than ART1 and modified ART1 but less than DCA and ROC2. Suresh *et al.* (1999) included the operation sequence of parts in a Fuzzy-ART model. Kamal (1995) and Kamal and Burke (1996) also presented FACT (Fuzzy ART with Add Clustering Technique) algorithm for GT application. FACT can be trained to cluster machines and parts for cellular manufacturing under a multiple objective environment. Rao and Gu (1995) proposed a multi-constrained neural network that is capable to develop alternate cell designs taking into consideration the duplicate machine availability and the capacity available on each of the machines. Venugopal (1999) provides a review of the neural network models for solving group technology problem. He divided the various neural network models in eight categories: (i) competitive learning/modification; (ii) interactive activations and competition (IAC); (iii) self-organizing feature map/modification; (iv) ART-1/modification; (v) Fuzzy ART; (vi) back propagation; (vii) stochastic learning; and (viii) Hopfield networks. Dobado *et al.* (2002) proposed the application of a Fuzzy Min-Max neural network for the part family formation in a CMS. They used a minimum cost flow model to form the machine cells. The input data are in the form of a binary part-machine incidence matrix.

5.2.8 Simulated annealing

Boctor (1991) used simulated annealing for minimum number of exceptional elements (EE) when rearranging the part-machine matrix. Its potential is however limited to single objective. Boctor (1996) has further used mixed linear program where the objective is to minimise the total manufacturing cost (material handling cost and the annual operating cost). He used simulated annealing to solve cell formation problem. Proth (1991) proposed an algorithm based on simulated annealing for cell formation. The algorithm is used to minimize the inter-cell movements. He concluded that the convergence of the algorithm is highly dependent on the annealing parameters and the initial incident matrix. Harhalakis *et al.* (1990b) used simulated annealing-based heuristic for cell formation for an industrial problem. Venugopal and Narendran (1992a) used a simulated annealing algorithm to solve the cell formation problem wherein the grouping problem is modelled mathematically with the objective of minimizing the load variations of machines in a cell, subjected to the constraints of assigning one machine type to only one cell and where cell is not empty. Chen and Srivastava (1994) have used simulated annealing for solving part-family problem in discrete part manufacturing. Cell formation was modelled as quadratic programming with the objective of minimizing the sum of similarity of machines within a cell. It produces solutions of comparable quality and could handle realistically large problem instances. Chen *et al.* (1995a) used simulated annealing-based heuristic for cell formation. They outlined three advantages of their approach: (i) flexibility in maximum number of machines allowed; (ii) ability to solve non-binary problems; and (iii) ability to solve large size problems. Adil *et al.* (1997) have also used simulated annealing for cell formation with alternate routing considerations. Vakharia and Chang (1997) have used simulated annealing and tabu search for cell formation. They concluded that simulated annealing is preferred above tabu search procedure in terms of solution quality and computational effort for the selected problem. Sofianopoulou (1997,1999) proposed simulated annealing algorithms for cell formation problem considering alternate process plans and multiple machines of each type with an objective to minimize the intercellular moves. Adil and Rajamani (2000) developed a simulated annealing algorithm that minimizes the total intercell and intracell costs. Sangwan and Kodali (2002) formulated the cell formation problem as a non-linear programming (NLP) problem with the objective to minimize intercellular and intracellular moves cost. A simulated annealing algorithm was proposed to solve the formulation. Various practical factors like alternate routes, operation sequence of parts, production volume, transfer batch size and upper limit on the number of machines in the cells were considered.

5.2.9 Genetic algorithms

Venugopal and Narendran (1992b) used bi-criteria mathematical model with a solution procedure on genetic algorithm. Two objectives are considered: (i) minimisation of the volume of intercell moves; and (ii) total within-cell load variation. Gupta *et al.* (1995) used genetic algorithm for a formulation, which minimises the weighted sum of intercell and intracell part movement. Minimum acceptable level of machine utilisation is defined. Cheng *et al.* (1998) have also used genetic algorithm to solve a "travelling salesman problem" (TSP) formulation for cell design. Lee *et al.* (1997) developed a genetic algorithm based method for cell formation. This method takes into account the production volume, alternate routing, and process sequences. It also has the ability to select the best alternate routing in terms of cell formation for each part before attempting to cluster the machines and parts. The cell formation has been treated as a minimization problem according to a defined cost function. The cost function consists of material handling costs, operation and non-operation (loading and unloading) costs of machines, fixed machine costs, and machine duplication costs. Cheng *et al.* (1998) formulated the cell formation problem as a travelling salesman problem (TSP) and a solution methodology based on genetic algorithms is proposed to minimize the intercellular movements. Binary part-machine incidence matrix is the input. Zhao and Wu (2000) developed a genetic algorithm approach to the cell formation problem with multiple objectives: minimizing costs due to intercell and intracell part movements; minimizing the total within cell load variation; and minimizing exceptional elements. Cells are formed based on production data. They also suggested a method to deal with alternate routing. Brown and Sumichrast (2001) presented a grouping genetic algorithm for solving the machine-part cell formation problem. The algorithm was tested using the measurements of efficiency and efficacy. The input data are in the form of a binary part-machine incidence matrix. Dimopoulos and Mort (2001) also proposed a genetic programming model to solve the simple versions of the problem. The input data are in the form of a binary part-machine incidence matrix.

5.2.10 Expert systems/knowledge-based systems

Kusiak (1987a, 1988, 1990) used knowledge-based approach with expert system and optimization. Information regarding machine capacity, material handling capabilities, technical requirements and cell dimensions are used to form cells. The knowledge-based approach EXGT-S allows taking advantage of the user's expertise. Kusiak (1987c) discussed the role of artificial intelligence and operations research in the GT cell formation. El-Maraghy and Gu (1988) developed a system considering syntactic pattern and knowledge rule to form cells. In a similar development, they used a technique for direct and automatic assignment of parts. They used the integration of feature-based modelling system and cellular manufacturing with the help of expert part/cell assignment. El-Maraghy and Gu (1989) has also used expert system approach for cell formation.

Chow and Hawaleshka (1993) developed a knowledge-based system to consider three types of practical constraints in cellular manufacturing: maximum size of machine cells, technological constraints, and desired total number of machine cells. Basu *et al.* (1995) proposed an expert system approach to cell formation. The starting point for their expert systems is the initial solution generated by traditional mathematical techniques. Based on a flexible set of user-driven quantitative and qualitative factors, the expert system evaluates these preliminary solutions for feasibility and quality. If the solutions are not satisfactory (infeasible or of low quality), the system suggests modification.

5.2.11 Simulation

In the contemporary research in manufacturing, simulation studies have been carried out to establish the effectiveness of manufacturing systems (Lyu and Gunasekaran 1992). Gupta and Tompkins (1982) analysed the impact of variables such as demand, cell size, setup time, *etc.* on the group technology shop. Ang and Willey (1984) compared the pure and hybrid group technology systems. The effects of the changes in job mix and of increase in demand and intercell workload transfer were examined. It was established that hybrid group technology with approximate configuration may perform significantly better than pure group technology system. Flynn and Jacobs (1987) compared group technology and traditional job shop for average move time and average setup time. Superiority of group technology-based system is established. Banarjee and Flynn (1987) studied the group technology system for maintenance policies. They found that combined policy of preventive maintenance and equipment redundancy is superior to individual policies. Hanumante *et al.* (1988) have considered the effectiveness of cellular manufacturing through simulation study. Flynn (1987) used critical machine concept in the group technology and evolved a set of maintenance policies. Simulation study of group technology by Sassani (1990) suggested that the performance improve through sub-batch work transfer. Morris and Tersine (1990) analysed the factor influencing the attractiveness of group technology layouts. They identified the ideal environment for CMS as one in which: (i) there is high ratio of setup to processing time; (ii) demand is stable; (iii) the work has a unidirectional flow within a cell; and (iv) there is a significant time delay in moving parts between departments. Suresh (1991) investigated how much setup times must decrease in CMS to offset the loss in routing flexibility that exists because of the substitutability of machines in functional layout. Suresh (1992) further studied CMS under a comprehensive set of conditions involving the setup reduction factor, the batch quantity, the cell size, and the allowance of intercell movements. Shafar and Meredith (1993) carried simulation study of functional and cellular layouts with overlapping operations. They suggested that following five factors might influence the relative benefits of adopting a cellular layout: (i) mean batch size; (ii) number of different machine parts required; (iii) processing times; (iv) machine capacity; and (v) existence of natural part family. Shafer and Charnes (1993) used a simulation model to study the performance of a completely cellular layout, which is different from Shafer and Meredith (1993) due to hybrid cellular layout studied in the later. Shafer and Charnes (1995) simulated the loading procedures for cellular and functional layouts in a variety of operating environments. Factors such as, part family flow, shop congestion, delay in moving batches, and labour are considered.

5.2.12 Multi-objective models

Any manufacturing system design is basically a multiple criteria decision making problem (Tabucanon 1998), a fact ignored in many contemporary research papers in CMS design. This is mainly due to computational effort to tackle such formulations. However, there are some important contributions in this area. Wei and Gaither (1990) considered capacity constrained, linear integer, multi objective cell formation problem. Objective functions are: bottleneck costs; average cell utilisation; intercell load imbalance and intracell imbalance. Limits on cell size were also considered in the model. Frazier *et al.* (1991) used best of random seed heuristic to generate a large number of alternatives for a multiobjective, cell formation problem. Non-dominated solution theory, and preference cone theory were used to select a solution out of potentially useful alternatives. In this model the active participation of the decision-maker is required. Vakharia and Wemmerlov (1990) used four-stage cell formation algorithm, which is based on the operation sequences with restrictions on capital for machine acquisition and acceptable threshold value for cell utilization. Shafer and Rogers (1991) used goal programming for a multi-objective cell formation problem. Objectives are divided in four major categories: (i) reducing the number of set-ups; (ii) producing parts completely within the cell; (ii) minimizing investments in new equipment; and (iv) maintaining acceptable utilisation levels. Min and Shin (1993) have developed multi-objective model for simultaneous formation of machine cell and human cell. Akturk and Balkose (1996) proposed a more comprehensive multi-objective approach for part-machine grouping and considered both design and manufacturing attributes and operation sequences simultaneously.

5.3 Neural Networks Approach for Cell Formation

Neural networks, sometimes referred to as artificial neural networks or parallel processing systems, are developed to model the way in which the human brain processes information. As the human brain is extremely effective as regards problems involving large amount of uncertain and noisy data, neural networks attempt to mimic the functioning of biological neurons and generate intelligent decisions. The fundamental processing unit in a neural network is called a neuron, which can posses a local memory and carry out localized information processing operations. They are interconnected with unidirectional signal channels (called connections) into multilevel networks. Each neuron has a single output, which branches into as many collateral connections as desired. Each neuron carries the same signal - the neuron output signal. This signal can be of any mathematical type desired. The processing that takes place within each neuron must be completely local - it must depend only upon the current values of the input signal arriving at the neuron through impinging connections and upon the values stored in the neuron's local memory. Generally, a neural network has an input layer to receive data from the outside world and an output layer to send information to users or external devices. Layers that lie between the input and output are called hidden layers and have no direct contact with the environment. Neural networks may or may not have hidden layers. The structure of a neural network could be characterized by the interconnection architecture among neurons, the activation function for conversion of inputs into outputs, and the learning algorithm. To date, many kinds of neural network architectures including the ART models, Hopfield models, Back-Propagation models, Kohonen's model, *etc.*, have been developed. The basic principles of neural networks are given in Lippmann (1987), Zurada (1999).

Artificial Resonance Theory 1 (ART1)

ART1 network was developed by Carpenter and Grossberg (1987, 1988). It serves the purpose of cluster discovery. The network produces clusters by itself, if such clusters are identified in the input data, and stores the clustering information about patterns or features without *a priori* information about the possible number and type of clusters. Essentially the network "follows the leader" after it originates the first cluster with the first input pattern received. It then creates the second cluster if the distance (dissimilarity) of the second pattern exceeds a certain threshold, otherwise the pattern inspection followed by either new cluster origination or acceptance of the pattern to the old cluster is the main step of ART1 network production. The basic idea in ART1 is that the input vector is compared to the prototype vectors in order of decreasing similarity until a prototype vector close enough to the input vector (vigilance ratio) is found. Prototype vectors are stored in the network as connection weight vectors. Connection weight vectors that have not been used for any cluster at a certain stage are all set to '1', the vector of all ones (exemplar). The flow chart of the basic ART1 algorithm is shown in figure 5.1.

The ART1 neural network is based on unsupervised learning. Learning in neural networks can be supervised, unsupervised or based on combined unsupervised-supervised learning. In supervised learning, the correct output for an input pattern has to be specified when the input pattern is presented. In an unsupervised learning, the network has no knowledge about what the correct or desired output should be. The system learns on its own without external guidance. The ART1 network includes two layers of neurons: the input (comparison) layer and the output (recognition) layer as shown in figure 5.2. In part family formation problem, the input layer is representative of the part characteristic vector and the output layer represents the number of part families.

The comparison layer elements accept inputs from the environment and the recognition layer elements each represents a pattern class. Every node in the input layer is totally connected to every node in the output layer with top down and bottom up connections. The ART1 algorithm employs a competitive learning approach in the sense that ART1 learns to cluster the input pattern by making the output neurons compete with each other for the right to react to a particular input pattern. The output neuron which has the weight vector that is most similar to the input vector claims this input pattern by producing an output of '1' and at the same time inhibits other output neurons by forcing them to produce '0's. In ART1, only the winning node is permitted to alter its weight vector, which is modified in such a way that it is brought even near to the representative input pattern in the cluster concerned. ART1 attempts to associate an input pattern to a cluster pattern. The output of ART1 is an indication of membership of the input pattern in a group with similar characteristics.

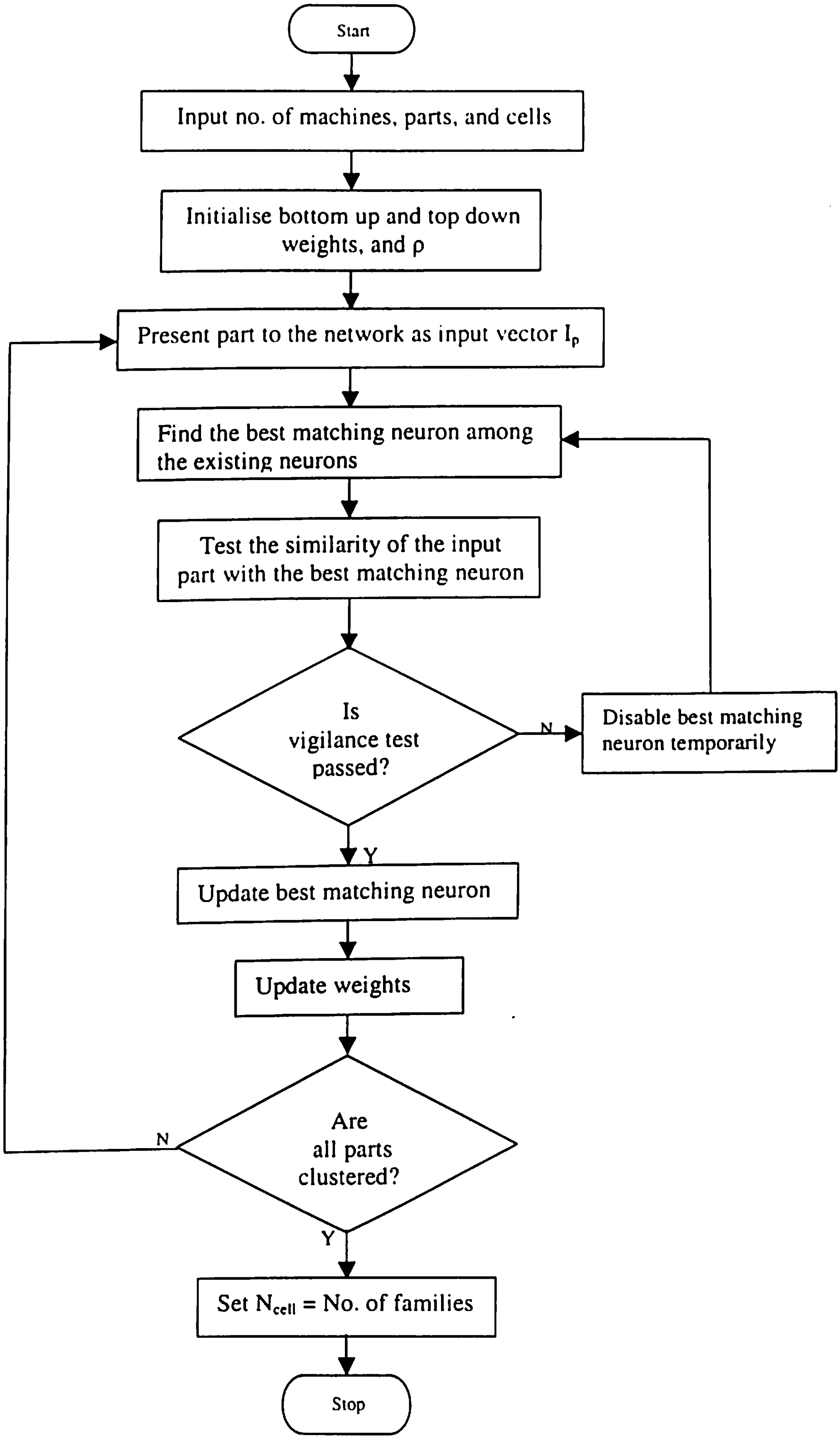

Figure 5.1: Flow chart of the basic ART1 algorithm

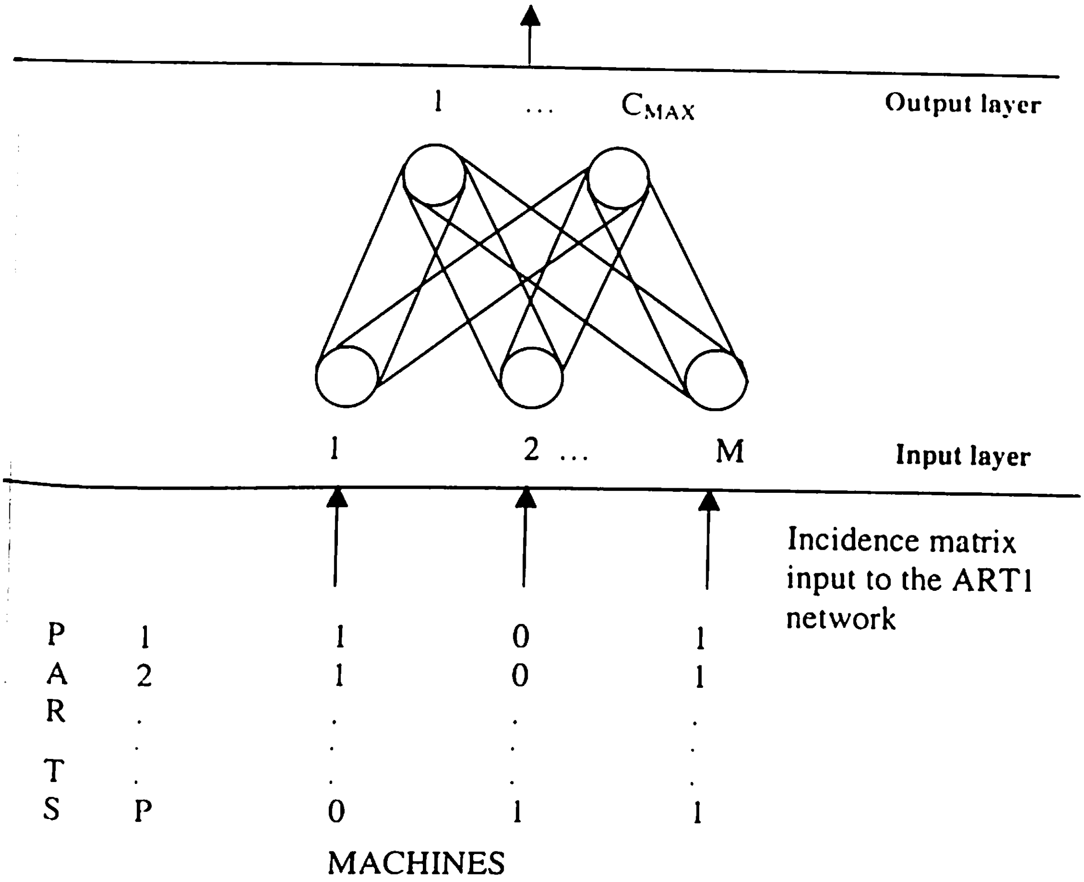

Figure 5.2: The architecture of the ART1 neural network

5.3.1 Development of model (Model 1) using ART1 for cell formation

In this section a user interactive five-stage ART1 based model is presented to solve the cell formation problem by satisfying the specified design criteria as deemed fit by the user/organization. The five stages of the framework for the model - the parameter input, ART1 part family formation, allocation of machines, examination of the cell design constraints, and finally the selection of the best solution from the feasible set on the basis of a cost function - are shown in figure 5.3.

Stage 1: *The parameter input stage*

In this stage the following problem inputs are required to define the problem.

Notation:

M : Number of machines

P : Number of parts

I_{pm} : Part-machine incidence matrix

UC : An upper bound on the number of cells

C_{MAX} : Number of output neurons

ρ : The vigilance threshold for the formation of part families

ρ_{MIN} : Least permissible degree of similarity between parts in each family

PTM_{pm} :Processing time, in minutes, of part p on machine type m

$CVOID$:Cost associated with a void

$CICM_p$:Cost associated with an inter-cell move for each unit of part type p

$PVOL_p$:Annual demand for part p

$UTIL_m$:Minimum acceptable utilization levels for machine m

NS :Number of shifts

HPS :Hours per shift

WD :Number of working days in a year

m_u :Utilization of machine m

m_{usage} :Time (in minutes) for which the machine is engaged

DUM :Desirable utilization levels for each machine

ν_{MAX} :Available time reduction factor for machines

$\Psi_i(C_{MAX}, \rho)$:The i^{th} feasible cell configuration corresponding to ρ and C_{MAX}

ξ :Cost function (the sum of the costs of voids and inter-cell material handling)

Φ :Feasible set of solutions

MGCmc :Machine to cell assignment

PCC_{pc} :Part to cell allocation

NCELLS :Number of cells formed

Stage 2: *Formation of part families*

In this stage ART1 neural network is used to form part families based on the network parameters, C_{MAX} and ρ, which play an important role in determining the quality of the resulting partitions. Here C_{MAX} is the expected number of clusters and thus corresponds to an upper bound on the number of cells that can be formed. The initial value of C_{MAX}, chosen arbitrarily, does not impact the efficiency of the solution provided it is high enough. In our algorithm this parameter is changed from 2 to UC in various iterations. This technique has the advantage that all feasible solutions are identified. This parameter can be used to limit the number of cells formed and, ρ, the vigilance threshold, is a measure of the minimum desired similarity between parts in each part family and as ρ is increased the network tends to increase the number of clusters formed. The advantages of using this methodology for the formation of part families is that computational times are low, the entire part-machine matrix need not be stored and as only one row is processed at a time, product flexibility in the CMS is maintained. The network treats each part on the basis of its processing characteristics, which is a marked improvement over traditional clustering techniques, which would solve the entire problem if a new part is to be added.

Stage 3: *Machine assignment*

At this stage of the algorithm the neural network has formed part families corresponding to the network parameters C_{MAX} and ρ. We now use the weighted sum of exceptional elements and voids to allocate machines for the processing of these part families.

Stage 4: *Satisfaction of cell design constraints*

When the machines in the manufacturing system have all been assigned for the processing of part families the cell configuration has been completely determined. Most conventional approaches to the cellular manufacturing problem terminate at this stage. However, this model investigates the feasibility of the resulting solution by ascertaining if all specified cell design constraints are met.

Stage 5: *Selection of the best solution corresponding to the minimum total cost*

The total cost for each element of the feasible set, i.e. the $\Psi_i(C_{MAX}, \rho)$, will now determine the best solution corresponding to the least cell configuration cost. It must be noted that the total cost function ξ is a function of Ψ alone and does not depend on the level of similarity at which it is formed.

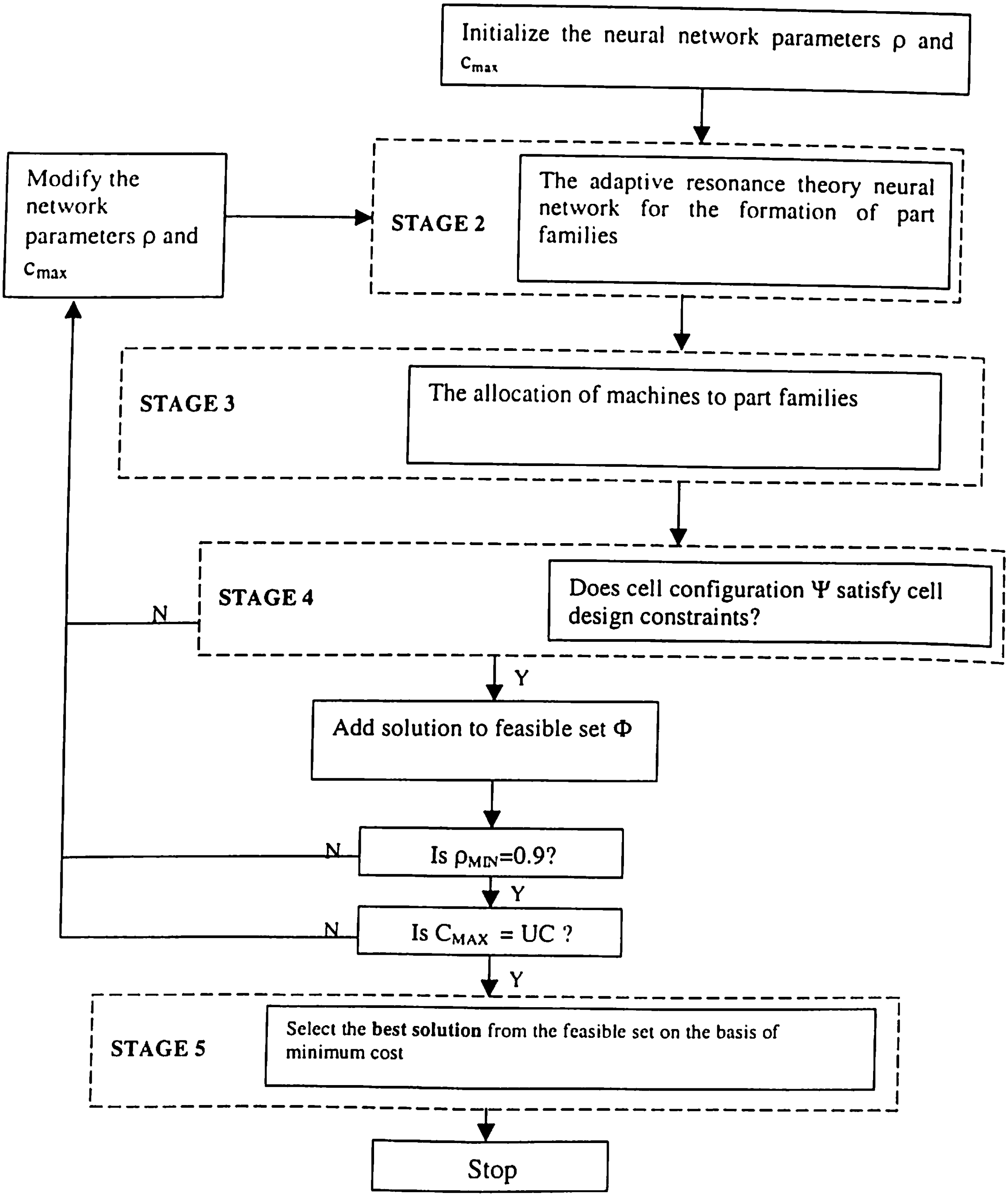

Figure 5.3: Framework for the model (model 1) using ART1 for cell formation

5.3.1.1 Algorithm

Step 1: Part data, costs and cell design parameters are input to the algorithm

Step 2: Initialize $C_{MAX} = 2$

Step 3: Initialize $\rho = \rho_{MIN}$

Step 4: Initialize top-down and bottom-up weights

Step 4a: Top down connection weights: $t_{ij}(0) = 1$

Step 4b: Bottom-up connection weights: $b_{ij}(0) = 1/(1+M)$

Step 5: Input nodes $i=1$ to M and output node $j = 1$ to C_{MAX}

Step 6: Apply a new input vector I_p, corresponding to the p^{th} row of the part-machine incidence matrix

Step 7: Compute matching scores

The output μ_j of every node j is calculated as:

$$\mu_j = \sum_i b_{ij}(t) x_i \quad \forall \quad j = 1 \ to \ C_{\max}$$

$$\mu_\theta = \max_j \{\mu_j\}$$

Step 8: Select best matching score, i.e. node (θ) with maximum output. The output of all other neurons is suppressed (lateral inhibition). In the case of a tie choose the one with a lower j.

Step 9: Test the similarity of the input vector with the best matching exemplar

$$\|I_p\| = \sum_i x_i = the\ number of\ 1s\ \ in the input\ vector$$

$$\|T \cdot I_p\| = \sum_i t_{i\theta} \cdot x_i = the number\ matching\ 1s\ \ between\ the\ input\ vector\ and$$

$$the\ best\ matching\ exemplar$$

$$If\ (\|T \cdot I_P\| / \|I_P\|) \geq \rho\ go\ to\ step\#11\ else\ go\ to\ step\#10$$

Step 10: Disable best matching exemplar temporarily

The output of the best matching node selected is temporarily set to zero. Other outputs have already been suppressed due to lateral inhibition. Go to step 7 and select a new neuron in the output layer

Step 11: Update best matching exemplar

Reverse the exemplar X and the input vector I_p to X' and I_p' respectively, with the ones being made zeros and vice versa. The elements of the modified exemplar are then given by $\| X'. I_p' \|$ which is in turn reversed to yield the updated exemplar.

Case 11a: $X= I_p$. The input vector is identical to the exemplar and the input is classified under the category of matching exemplar and the exemplar remains unchanged, regardless of reversal of digits.

Case 11b: $X\neq I_p$, $\|X\| < \| I_p \|$ and $X \subseteq I_p$. The number of ones in the exemplar is lower than in the input vector that has been found to be similar. Also, the exemplar is fully included in the input vector. It is desired that the exemplar absorb new elements from the input vector. This does not occur with regular notation.

Case 11c: $X\neq I_p$, $\| X \| > \| I_p \|$ and $I_p \subseteq X$. In this case, the number of elements in the exemplar is more than in the input. The input vector is fully included in the exemplar that has been found to be similar within the limits of ρ. Reversal ensures that the exemplar remain the same without contracting.

Case 11d: $X\neq I$ and $\| X \| = \| I_p \|$. In this case the two vectors are similar, but not the same, and the number of elements in both are same, but their positions differ. In such a case it is desired that the exemplar merely absorb new elements without losing any existing element.

$$b_{i\theta} = \frac{t_{i\theta}(t) \cdot x_i}{(0.5 + \sum_i t_{i\theta}(t) \cdot x_i)}$$

Step 12: Update the bottom-up weight connections

Step 13: If all parts are assigned go to step 14; else Go to step 5, after enabling any nodes disabled in step 10

Step 14: Set NCELLS = Number of part families identified

Step 15: Assignment of machines to part families by minimizing the weighted sum of exceptional elements and voids

$$\textit{Contribution of Exceptional elements:}\quad w\sum_{c=1}^{NCELLS}\sum_{p=1}^{P}\sum_{m=1}^{M} I_{pm}\, PCC_{pc}\,(1-MGC_{mc})$$

$$\textit{Void contribution:}\quad (1-w)\sum_{c=1}^{NCELLS}\sum_{p=1}^{P}\sum_{m=1}^{M}(1-I_{pm})\, PCC_{pc}\, MGC_{mc}$$

Subject to:

$$\sum_{c=1}^{NCELLS} PCC_{pc} = 1, \forall\ p = 1\ to\ P$$

$$\sum_{c=1}^{NCELLS} MGC_{mc} = 1, \forall\ m = 1\ to\ M$$

where

$$PCC_{pc} = \begin{cases} 1 & \text{if part } p \text{ is assigned to cell } c \\ 0 & \text{otherwise} \end{cases}$$

$$MGC_{mc} = \begin{cases} 1 & \text{if machine } m \text{ is assigned to cell } c \\ 0 & \text{otherwise} \end{cases}$$

Step16 Examine the feasibility of the solution by checking if all cell design constraints are satisfied

Step 16a: Calculate the available time (in minutes per year) of each machine as follows

$$TIME_{avail} = 60 \times NPS \times HPS \times W \times v_{MAX}$$

Step 16b: Find total time for which each machine 'm' is engaged

$$m_{usage} = \sum_{p=1}^{P} I_{pm} \; PVOL_p \; PTM_{pm} \qquad \forall m = 1 \; to \; M$$

$$m_u = \left(m_{usage} / TIME_{avail}\right) \qquad \forall m = 1 \; to \; M$$

Step 16c: Find the utilization of all machines m = 1 to M

Step 16d: Compute machine workloads in each cell:

The number of shifts, hours per shift and the number of working days in a year govern the operation time available for machines in each cell. While forming cells we need to ensure that the total time for which the machine needs to be engaged does not exceed the available time of the machine. We also need to account for the downtime of the machine for maintenance, breakdowns, tooling and set-ups. Implementing philosophies like TPM in the workplace can increase the available time of machines.

$$m_{usage} \leq TIME_{avail} \quad \forall \quad m \quad = \quad 1 \; to \; M$$

Step 16e: Utilization of machines in each cell: On the basis of the capital investment in each machine and the management philosophies being implemented it will be necessary that every machine be used to varying levels of utilization

$$m_u \geq ACCPU_m \; \forall \; m = 1 \; to \; M$$

If all the cell design constraints are met go to step 17 else go to step 18

Step 17: Add solution to the feasible set Φ

Calculate the total cost ξ for this cell configuration Ψ(C_{MAX}, ρ) by finding out the inter-cell material handling cost for parts in various cells and the cost associated with the voids.

$$\textit{Inter cell material handling cost}: \quad \sum_{c=1}^{NCELLS}\sum_{p\in c}\sum_{m\notin c} I_{pm} \;\; CICM_p \;\; PVOL_p$$

$$\textit{Cost associated with voids in cells}: \quad \sum_{c=1}^{NCELLS}\sum_{p\in c}\sum_{m\in c}(1-I_{pm})\, CVOID \;\; \delta(x)$$

$$\textit{where} \qquad x = m_u - DUM$$

$$\textit{and} \qquad \delta(x)=\begin{cases} 0 & \forall \quad x \ge 0 \\ |x| & \forall \quad x < 0 \end{cases}$$

Step 18 If ρ = 0.9 go to step 19; else update ρ = ρ + 0.1 and go to step 5

Step 19 If C_{MAX} = *UC* go to step 20; else update C_{MAX} = C_{MAX} + 1, ρ = ρ_{MIN} and go to step 5

Step 20 Select the best solution Ψ^*, corresponding to the least cost ξ^*, from the feasible set Φ

Step 21 Stop

5.3.1.2 Validation

The model is validated using example 1 and example 2 (given below) from literature. For both examples the feasible set of solutions is obtained and for these cell configurations the total cost of inter-cell material handling and voids in the manufacturing cells, is computed. The best solution is then the cell configuration corresponding to the minimum cost. Both examples use the following values for the parameters specified:

NS = 2
HPS = 8
WD = 6
v_{MAX} = 0.95
DUM = 0.6
CVOID = $ 1000
UC = 3

Example 1: This is a six machines and eight parts matrix (Singh and Rajamani 1996). The input data for the problem is given in the table 5.1. The upper bound on the number of cells is set to 3. The network parameters, C_{MAX} and ρ initially set to 2 and 0.1 respectively. Then each row of the incidence matrix is fed to the network, part-wise and the network assigns them to part families on the basis of the similarity threshold ρ. The steps of the ART1 algorithm for part family formation at $\rho = 0.5$ are given below:

Table 5. 1: Input data for example 1

Parts	Unit cost of inter-cell move ($)	Demand	Processing times on machines [minutes]
1	10	4000	M1(10), M3(14), M6(13)
2	10	3500	M1(23), M3(9), M6(9)
3	30	4750	M2(5), M3(11), M5(9)
4	10	2500	M2(18), M4(18), M5(13)
5	20	6500	M1(9), M3(8)
6	9	5000	M2(19), M3(8), M6(10)
7	10	6700	M2(9), M4(20), M5(10)
8	13	5000	M1(16), M3(3), M4(16)

Step 1: consider the upper limit on the number of families as 2 (C = 2)

The weights are initiated as:

$b_{ij} = 1/1+M = 1/7$

$t_{ij} = 1, i = 1,\ldots, 6; j = 1,2$

Step 2: When part 1 is presented to the network, one of the two neurons has the largest output. It is arbitrarily denoted as neuron 1. The vigilance test is unconditionally passed as the vigilance in the first pass is unity as all top down weights are initialised as unity. This results in the unconditional definition of the first cluster. Figure 5.4 shows the ART1 network after completion of the first training step. Note that from among 12 weights, t_{ij}, 3 are set to unity and others are set to zero.

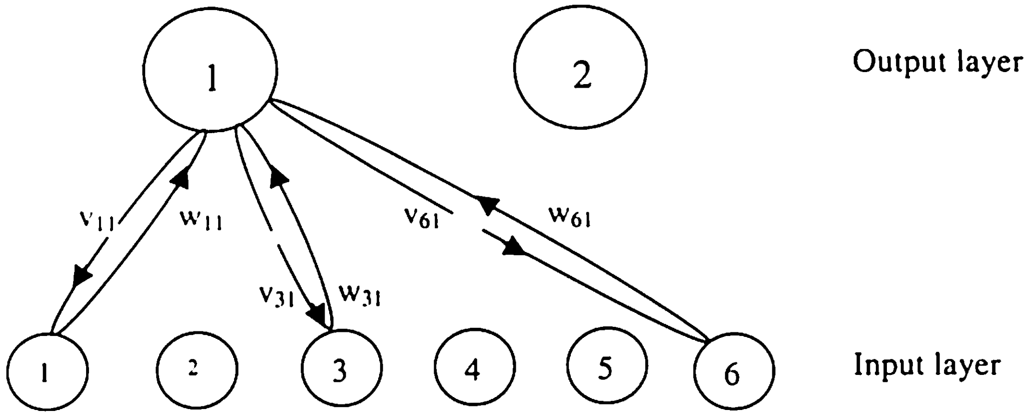

Figure 5.4: The ART1 network for example 1 after the first training step

Summary of first pass of ART1 algorithm, after part 1 is input is:

$b_{11} = b_{31} = b_{61} = 2/7\ (1/0.5+3)$,

the remaining bottom up weights are 1/7 as initialised.

$t_{11} = t_{31} = t_{61} = 1$,

the remaining top down weights are set to zero.

Step 3: During the presentation of part 2, there is no output layer node competing for clustering, since the only active node is 1. The vigilance test results in

$$\left(\|T \cdot I_P\| / \|I_P\|\right) = 3(1/3) = 1 > 0.5$$

As this input is exactly similar to the neuron 1, this part is clustered in family 1. Summary of second pass of ART1 algorithm, after part 2 is input is:

$b_{12} = b_{32} = b_{62} = 2/7\ (1/0.5+3)$,

the remaining bottom weights are 1/7 as initialised.

$t_{12} = t_{32} = t_{62} = 1$,

the remaining top down weights are set to zero.

Step 4: During the presentation of part 3 also there is only one active top layer node. The vigilance test results in:

$$\left(\|T \cdot I_P\| / \|I_P\|\right) = 1(1/3) = 1/3 < 0.5$$

Due to the failure of the vigilance test and the absence of other nodes for further evaluation and for potential disabling, part 3 is treated as a new cluster (family). This family is represented by another neuron, neuron 2.

Summary of third pass of ART1 algorithm, after part 3 is input is:

$b_{23} = b_{33} = b_{53} = 2/7$,

the remaining bottom weights are 1/7 as initialised.

$t_{23} = t_{33} = t_{53} = 1$,

the remaining top down weights are set to zero.

Step 5: During the presentation of part 4, there are two neuron competitors. The matching score computed are:

$\mu_1 = 0(2/7) + 3(1/7) = 3/7$

$\mu_2 = 2(2/7) + 1(1/7) = 5/7$

Thus, neuron 2 results as a winner and the vigilance test results in:

$$\left(\|T \cdot I_P\| / \|I_P\|\right) = 2(1/3) = 2/3 > 0.5$$

The vigilance test is passed and the part is clustered in family 2.

Summary of fourth pass of algorithm, after part 4 is input is:

$b_{24} = b_{34} = b_{44} = b_{54} = 2/9$ (1/0.5+4),

the remaining bottom weights are 1/7 as initialised.

$t_{24} = t_{34} = t_{44} = t_{54} = 1$,

the remaining top down weights are set to zero.

Step 6: During the presentation of part 5, the matching score computed are:

$\mu_1 = 2(2/7) + 0(1/7) = 4/7 = 0.571$

$\mu_2 = 1(2/9) + 1(1/7) = 23/63 = 0.365$

Thus, neuron 1 results as a winner and the vigilance test results in:

$$\left(\|T \cdot I_P\| / \|I_P\|\right) = 2(1/2) = 1 > 0.5$$

The vigilance test is passed and the part is clustered in family 1

The summary of fifth pass of ART1 algorithm, part 5 is input is:

$b_{15} = b_{35} = b_{65} = 2/7$,

the remaining bottom weights are 1/7 as initialised.

$t_{15} = t_{35} = t_{65} = 1$,

the remaining top down weights are set to zero.

Step 7: During the presentation of part 6, the matching score computed are:

$\mu_1 = 2(2/7) + 1(1/7) = 5/7 = 0.714$

$\mu_2 = 2(2/9) + 1(1/7) = 37/63 = 0.587$

Thus, neuron 1 results as a winner and the vigilance test results in:

$$\left(\|T \cdot I_P\| / \|I_P\|\right) = 2(1/3) = 2/3 > 0.5$$

The vigilance test is passed and the part is clustered in family 1

The summary of fifth pass of algorithm, part 6 is input is:

$b_{16} = b_{26} = b_{36} = b_{66} = 2/9$,

the remaining bottom weights are 1/7 as initialised.

$t_{16} = t_{26} = t_{36} = t_{66} = 1$,

the remaining top down weights are set to zero.

Step 8: During the presentation of part 7, the matching score computed are:

$\mu_1 = 1(2/9) + 2(1/7) = 23/63$

$\mu_2 = 3(2/9) + 0(1/7) = 2/3$

Thus, neuron 2 results as a winner and the vigilance test results in:

$$\left(\|T \cdot I_P\| / \|I_P\|\right) = 3(1/3) = 1 > 0.5$$

The vigilance test is passed and the part is clustered in family 2

The summary of sixth pass of ART1 algorithm, part 7 is input is:

$b_{27} = b_{37} = b_{47} = b_{57} = 2/9$,

the remaining bottom weights are 1/7 as initialised.

$t_{27} = t_{37} = t_{47} = t_{57} = 1$,

the remaining top down weights are set to zero.

Step 9: During the presentation of part 8, the matching score computed are:

$\mu_1 = 2(2/9) + 1(1/7) = 37/63$

$\mu_2 = 2(2/9) + 1(1/7) = 37/63$

Both the neurons have same score, but the selected winner is neuron 1 (lower j), the vigilance test results in:

$$\left(\|T \cdot I_P\| / \|I_P\|\right) = 2(1/3) = 2/3 > 0.5$$

The vigilance test is passed and the part is clustered in family 1

Thus, at this stage, the part families formed are:

Part family 1: 1, 2, 5, 6, 8

Part family 2: 3, 4, 7

After the network has successfully assigned all parts, the weighted sum of exceptional elements and voids is minimized and the machines are allocated as shown in table 5.2. We have used a weight of w=0.7, as exceptional elements are usually more problematic from a material-handling perspective than voids. The current cell configuration $\Psi(2, 0.1)$ is then examined to check if all cell design constraints are met. The rearranged matrix, machine utilization levels, inter-cell material handling costs and cost of cell voids are shown in tables 5.3 - 5.6. This cell configuration is found to satisfy all cell design constraints and is added to the feasible set Φ.

The network parameters are then updated to $C_{MAX}=2$ and $\rho=0.2$, and it is found that the solution is the same as $\Psi(2, 0.1)$. In fact, this solution is found to remain stable for all values of ρ ranging from 0.1 to 0.6, for C_{MAX}=2.Finally, at C_{MAX}=2, ρ=0.7, the network is unable to retain all parts in two clusters and no solution is obtained. No solution is obtained for all subsequent values of ρ, for the same value of C_{MAX}=2. Now the network parameters are set to C_{MAX}=3, ρ=0.1, and the original feasible solution of Ψ(2, 0.1) reappears. In this way by altering the parameters of the network the feasible set of solutions if obtained as follows:

$$\Phi = \{\Psi_i(C_{MAX}, \rho)\}$$

$$= \{\Psi_1(2, 0.1), \Psi_2(2, 0.2), \Psi_3(2, 0.3), \Psi_4(2, 0.4), \Psi_5(2, 0.5), \Psi_6(2, 0.6), \Psi_7(3, 0.1), \Psi_8(3, 0.2), \Psi_9(3, 0.3), \Psi_{10}(3, 0.4), \Psi_{11}(3, 0.5), \Psi_{12}(3, 0.5), \Psi_{13}(3, 0.6)\}$$

As mentioned above, the total cost function ξ depends of the cell configuration alone and is independent of the level of similarity at which the cells are formed, thus the total cost for all these solutions is the same. The various costs for the cells and the overall cell configuration cost are shown in table 5. 7. The minimum cost for this solution is seen to be ξ^* = $ 278,500.

Table 5.2: Change in solutions with variations in the network parameters

C_{max}	ρ_{min}	CELL CONFIGURATION (Ψ)	
		Machine Group	Part Family
2	0.1-0.6	M1, M3, M6 M2, M4, M5	1, 2, 5, 6, 8 3, 4, 7
2	0.7-0.9	No feasible solution	
3	0.1-0.6	Same as Ψ(C_{MAX} =2, ρ=0.1-0.6)	
3	0.7-0.9	No feasible solution	

Table 5.3: Rearranged part machine matrix for cell configuration Ψ1

	Machines					
Parts	1	3	6	2	4	5
1	1	1	1			
2	1	1	1			
5	1	1	*			
6	*	1	1	1		
8	1	1	*		1	
3		1		1	*	1
4				1	1	1
7				1	1	1

Table 5.4: Utilization of machines

Cell	Machine	Minimum acceptable utilization	Utilization	Operation time [minutes]
1	1	0.75	0.91	259000
	3	0.5	0.47	133500
	6	0.4	0.50	142250
2	2	0.4	0.68	194500
	4	0.4	0.45	129050
	5	0.4	0.63	179000

Table 5.5: Calculation of costs associated with inter-cell moves for parts

Cell	Inter-cell move	Demand of part	Cost for 1 unit ($)	Total cost ($)
1	P6 to M2	5000	9	45000
	P8 to M4	5000	13	65000
2	P3 to M3	4750	30	142500

Table 5.6: Calculation of costs associated with voids in cells

Cell	Void at [part/machine]	Machine utilization	Cost of void [CVOID * (DUM – m_u)]
1	P5/M6	0.47	13000
	P8/M6	0.47	13000
2		No voids	

Table 5.7: Inter-cell movement, void and total costs (All costs in $)

Cell	Inter-cell movement cost	Void cost	Total cost
1	11000	26000	136000
2	142500	0	142500
	Total cost for this cell configuration =		278500

Example 2: This problem involves ten machines and twenty-five parts (Masnata and Settineri 1997). The data for the problem is given in table 5.8. The feasible set is obtained as follows:

$$
\begin{aligned}
\Phi &= \{\Psi_i(C_{MAX}, \rho)\} \\
&= \{\Psi_1(4,\ 0.1),\ \Psi_2(4,\ 0.2),\ \Psi_3(4,\ 0.3),\ \Psi_4(4,\ 0.4),\ \Psi_5(5,\ 0.1),\ \Psi_6(5,\ 0.2), \\
&\quad \Psi_7(5, 0.3),\ \Psi_8(5,\ 0.4)\}
\end{aligned}
$$

The configurations Ψ_1, Ψ_2, Ψ_3, Ψ_5, Ψ_6 and Ψ_7 correspond to the same cell configuration, say Ψ', while the configurations Ψ_4 and Ψ_8 are the also the same, say Ψ''. It is found that the minimum total cost corresponds to the cell configuration Ψ' and is equal to \$607,500 while the solution Ψ'' corresponds to a total cost of \$984,800. The best solution Ψ^*, thus corresponds to a minimum cost ξ^* of \$607,500. Various feasible solutions at different network parameters are given in table 5. 9. Tables 5.10 to 5.14 show the rearranged matrix, utilization of machines, and calculation of inter-cell, void and total cost for the best solution respectively.

Table 5.8: Input data for example 2

Parts	Unit cost of inter-cell move ($)	Annual demand	Processing times on machines [minutes]
1	10	4000	M1(9), M7(9), M9(5)
2	10	3500	M1(7), M5(9), M7(8)
3	10	4750	M4(23), M10(1)
4	10	2500	M3(10), M5(20)
5	10	6500	M2(12), M6(7), M8(16)
6	10	5000	M3(10), M5(21), M10(7)
7	10	6700	M4(2), M6(11), M8(9)
8	10	5000	M1(13), M7(9), M9(14)
9	10	4000	M4(12), M8(11)
10	10	3500	M4(6), M8(12)
11	10	4750	M3(14), M7(9)
12	10	2500	M2(14), M10(4)
13	10	6500	M1(8), M7(16)
14	10	5000	M4(12), M10(17)
15	10	6700	M2(19), M6(2), M8(7)
16	10	5000	M1(9), M7(10)
17	10	4000	M2(2), M6(14), M8(1)
18	10	3500	M2(9), M9(11)
19	10	4750	M2(10), M6(9)
20	10	2500	M2(5), M6(12), M8(9)
21	10	6500	M1(5), M5(3), M9(5)
22	10	5000	M1(8), M7(5), M9(7)
23	10	6700	M4(5), M10(8)
24	10	5000	M3(6), M7(12), M9(3)
25	10	1500	M3(7), M5(12)

Table 5.9: Change in solutions with variations in the network parameters

C_{max}	ρ_{min}	Cell configuration (Ψ)	
		Machine Group	Part Family
2	0.1-0.9	No feasible solution	
3	0.1-0.9	No feasible solution	
4	0.1-0.3	M1, M7, M9 M4, M5, M10 M3 M2, M6, M8	1, 2, 8, 12, 16, 18, 21, 22 3, 6, 12, 14, 23, 25 4, 11, 24 5, 7, 9, 10, 15, 17, 19, 20
4	0.4	M1, M7, M9 M4, M10 M5, M5 M2, M6, M8	1, 2, 8, 22 3, 9, 10, 14, 23 4, 6, 11, 12, 13, 16, 18, 19, 21, 24, 25 5, 7, 15, 17, 20
4	0.5-0.9	No feasible solution	
5	0.1-0.3	Same as Ψ(C_{MAX}=4, ρ=0.1 to 0.3)	
5	0.4	Same as Ψ(C_{MAX} =4, ρ=0.4)	
5	0.5-0.9	No feasible solution	

Table 5.10: Rearranged part machine matrix

	Machines									
Parts	1	7	9	4	5	10	3	2	6	8
1	1	1	1							
2	1	1	*		1					
8	1	1	1							
13	1	1	*							
16	1	1	*							
18	*	*	1					1		
21	1	*	1		1					
22	1	1	1							
3				1	*	1				
6				*	1	1	1			
12				*	*	1		1		
14				1	*	1				
23				1	*	1				
25				*	1	*	1			
4					1		1			
11		1					1			
24		1	1				1			
5								1	1	1
7				1				*	1	1
9				1				*	*	1
10				1				*	*	1
15								1	1	1
17								1	1	1
19								1	1	*
20								1	1	1

Table 5.11: Utilization of machines

Cell	Machine	Minimum acceptable utilization	Utilization	Operation time [minutes]
1	1	0.4	0.86	245000
	7	0.4	0.78	223000
	9	0.4	0.69	196000
2	4	0.4	0.71	202750
	5	0.4	0.43	123000
	10	0.4	0.66	188350
3	3	0.4	0.43	121500
4	2	0.4	0.96	273300
	6	0.4	0.92	261350
	8	0.4	0.79	223700

Table 5.12: Calculation of costs associated with inter-cell moves for parts

Cell	Inter-cell move	Demand of part	Cost for 1 unit ($)	Total cost ($)
1	P2 to M5	3500	10	35000
	P21 to M5	6500	10	65000
	P18 to M2	3500	10	35000
2	P6 to M3	5000	10	50000
	P25 to M3	1500	10	15000
	P12 to M2	2500	10	25000
3	P11 to M7	4750	10	47500
	P24 to M7	5000	10	50000
	P24 to M9	5000	10	50000
	P4 to M5	2500	10	25000
4	P7 to M4	6700	10	67000
	P9 to M4	4000	10	40000
	P10 to M4	3500	10	35000

Table 5.13: Calculation of costs associated with voids in cells

Cell	Void at [part/machine]	Machine utilization (M_u)	Cost of void [CVOID * (DUM – m_u)]
1	P18/M1	M1 - 0.86	-
	P18/M7	M7 - 0.78	-
	P21/M7	M7 - 0.78	-
	P2/M9	M9 - 0.69	-
	P13/M9	M9 - 0.69	-
	P16/M9	M9 - 0.69	-
2	P6/M4	M4 - 0.71	-
	P12/M4	M4 - 0.71	-
	P25/M4	M4 - 0.71	-
	P3/M5	M5 - 0.43	17000
	P12/M5	M5 - 0.43	17000
	P14/M5	M5 - 0.43	17000
	P23/M5	M5 - 0.43	17000
	P25/M10	M10 -0.66	
3		No voids	
4	P7/M2	M2 - 0.96	-
	P9/M2	M2 - 0.96	-
	P10/M2	M2 - 0.96	-
	P9/M6	M6 - 0.92	-
	P10/M6	M6 - 0.92	-
	P19/M8	M8 - 0.79	-

Table 5.14: Inter-cell movement, void and total costs (All costs in $)

Cell	Inter-cell movement cost	Void cost	Total cost
1	135000	0	135000
2	90000	68000	158000
3	172500	0	172500
4	142000	0	142000
Total cost for this cell configuration =			607500

5.4 Simulated Annealing (SA) Approach for Cell Formation

Simulated Annealing Algorithm is a powerful random search algorithm based on iterative improvement originally introduced by Metropolis *et al.* (1953) and later implemented by Kirkpatrick *et al.* (1983) to solve combinatorial problems. The algorithm starts with an initial random feasible solution Sol_0 and by applying the perturbation scheme to this and any subsequent solution, Sol_t, neighbouring feasible solution, Sol_{t+1}, is obtained. If the change in the objective function E (obj_{t+1}-obj_t) ≤ 0, the solution is accepted otherwise the case is treated probabilistically; if a random number, R, between (0, 1) $\leq e^{-E/T}$, the solution is accepted otherwise rejected. The probability of accepting such solutions is reduced as the value of T decreases and the change E in the objective values increases. It is this ability to probabilistically accept 'retrogressive' solutions that distinguishes the SAA from the classic iterative improvement methods and enables it to escape from a local optimum at an early stage (Venugopal and Narendran 1992a). The various parameters of the algorithm were finalized for specific problems after running the program at different values of the parameters. This section presents an implementation of the simulated annealing for cell formation. The main steps of SAA are: initial solution, generation of neighbourhood solution, acceptance/rejection of generated solution, and termination.

Initial solution

Initially machines are allotted randomly to each cell. For this machine assignment, an initial part allocation is obtained. Thus, an initial solution and objective function are obtained.

Generation of a neighbourhood solution

To generate subsequent neighbourhood solutions, two actions can be adopted – move and/or swap. A move is performed by randomly selecting two cells, then choosing randomly a machine inside one of the cells and moving it to the other one. Repeat this process if the stated any stated constraint is violated. A swap is to exchange two randomly selected machines inside two randomly chosen cells.

Acceptance/rejection of the generated solution

The generated solution is accepted if the objective function value improves. If the objective function value does not improve, the solution is accepted with a probability depending on the temperature, which is set to allow the acceptance of a large proportion of generated solution at the beginning. Then the temperature is lowered to reduce the probability of acceptance. At each temperature many moves are attempted and the algorithm stops when predefined conditions are met.

Termination

The algorithm can be terminated in three ways: when the specified maximum iterations are reached or the acceptance ratio is below a predetermined value or if the objective function does not change for a specified number of iterations. The values of the stopping criteria are a compromise between the solution quality and computational time.

5.4.1 Development of SA model (Model 2) using binary part-machine incidence matrix for cell formation

In this section a SA model developed for cell formation is presented. The input to the algorithm is the binary part-machine incidence matrix. The objective is to minimize the weighted sum of exceptional elements and voids. This model solves the cell formation problem in presence of alternate process plans for parts. The basic flowchart of the SA is shown in figure 5.5.

5.4.1.1 Mathematical formulation

Notations:

i, j : variables for machines $(i \neq j)$

n : total number of machines

k : variable for parts

P : total number of parts

x, y : variables for cells $(x \neq y)$

C : total number of cells

F_{ij}^{k} : flow/interaction between machine i and j for part k

n'_k : number of process plans for part k

The objective (minimization of weighted sum of exceptional elements and voids) is computed as:

$$\text{Minimize} \quad z = \sum_{x=1}^{C}\sum_{i=1}^{n}\sum_{k=1}^{P}\sum_{r=1}^{n'_k} w_{ki} a_{ki}^{r} x_{kx}^{r} (1 - a_{ix}) + \sum_{x=1}^{C}\sum_{i=1}^{n}\sum_{k=1}^{P}\sum_{r=1}^{n'_k} (1 - w_{ki})(1 - a_{ki}^{r}) a_{ix} x_{kx}^{r}$$

subject to

$x_{kx}^{r} = 1 \qquad \forall k$

This constraint gurantees that each part is allocated to one cell and only one process plan is selected for the part

$$a_{ix} = \begin{cases} 1, & \text{if machine } i \text{ is in cell } x \\ 0, & \text{otherwise} \end{cases}$$

$$a_{ki}^{r} = \begin{cases} 1, & \text{if part } k \text{ requires processing on machine } i \text{ in process plan } r \\ 0, & \text{otherwise} \end{cases}$$

$$x_{kx}^{r} = \begin{cases} 1, & \text{if part } k \text{ is in cell } x \text{ and process plan } r \text{ is selected} \\ 0, & \text{otherwise} \end{cases}$$

w_{ki} = weight of exceptional element corresponding to part k and machine i

$1 - w_{ki}$ = weight of void corresponding to part k and machine i

$0 \le w_{ki} \le 1$

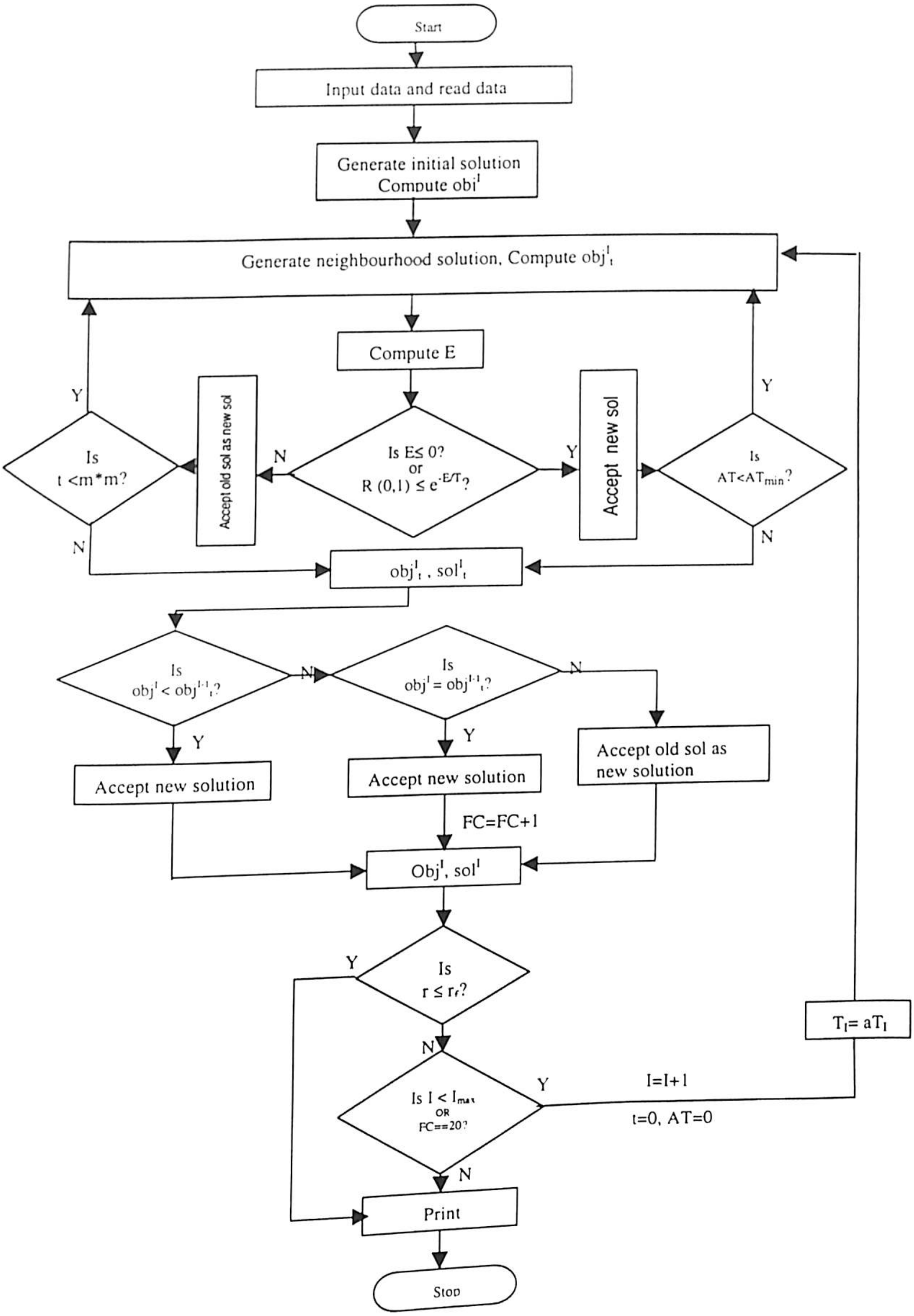

Figure 5.5: Basic flow chart of the SA

5.4.1.2 Algorithm

```
Step 1   Input P, n, $n_k^r$, $AT_{min}$, $r_f$, a, $T_I$
Step 2   Read part-machine incidence matrix
Step 3   Generate an initial solution, compute objective value (obj)
Step 4   Initialize I = 0 and set $obj^I = obj$ and $sol^I = sol$
Step 5   Initialize t = 0, AT = 0 and set $obj_t = obj^0$ and $sol_t = sol^0$
Step 6   Generate a neighbourhood solution and compute $obj_t$
Step 7   Compute $E = obj_t - obj_{t-1}$
Step 8   If E <= 0 or random no. R between (0,1) <= $e^{-E/T}$
             Accept $obj_t$ and $sol_t$ and update AT = AT + 1
         else accept $obj_t = obj_{t-1}$ and $sol_t = sol_{t-1}$ and update t = t + 1
Step 9   If $AT < AT_{min}$ or t < n*n, set $obj^I = obj_t$, $sol^I = sol_t$ and go to step 6
         else go to step 10
Step10   If $obj^I < obj^{I-1}$ accept $obj^I$ and $sol^I$
         else if $obj^I = obj^{I-1}$ accept $obj^I$ and $sol^I$ and set FC=FC+1
              else accept $obj^I = obj^{I-1}$ and $sol^I = sol^{I-1}$
Step11   Compute r = AT/t, if $r <= r_f$ go to step 13
                   else go to step 12
Step12   If $I < I_{max}$ or FC= =20, I = I + 1, T = a T and go to step 5
              else go to step 13
Step13   Print $sol^I$, $obj^I$, no. of cells
Step14   Stop
```

5.4.1.3 Validation

This model is validated by solving three examples two of which are from literature and one generated hypothetically.

Example 1: This example is same as example 1 in section 5.3.1.2. Only the part-machine incidence matrix is considered here. The solution is shown below in table 5.15.

Table 5.15: Rearranged part-machine matrix for example 1

	Machines					
Parts	1	3	6	2	4	5
1	1	1	1			
2	1	1	1			
5	1	1	*			
6	*	1	1	1		
8	1	1	*		1	
3		1		1	*	1
4				1	1	1
7				1	1	1

Example 2: This example is same as example 2 in section 5.3.1.2. Only the part-machine incidence matrix is considered here. The solution is shown below in table 5.16.

Table 5.16: Rearranged part-machine matrix for example 2

Machines ▶ Parts ▼	1	7	9	2	6	8	3	5	4	10
1	1	1	1					1		
2	1	1								
8	1	1	1							
13	1	1								
16	1	1								
18			1	1				1		
21	1		1							
22	1	1	1				1			
24		1	1							
5				1	1	1			1	
7					1	1				
15				1	1	1				
17				1	1	1				
19				1	1					
20				1	1	1				
4							1	1		
6							1	1		1
11							1			
25		1					1	1		
3									1	1
9						1			1	
10						1			1	
12										1
14				1					1	1
23									1	1

Example 3: This example generated hypothetically to validate the model for alternate process plans is shown in table 5.17. The solution is shown in table 5.18.

Table 5.17: Incident matrix for example 3

Part	Process Plan	1	2	3	4	5	6	7	8	9	10
1	1	1	1		1						
	2				1		1				
	3			1	1						1
2	1							1	1		1
	2	1				1				1	1
3	1			1				1	1		
	2	1				1		1			
	3	1	1								1
4	1			1				1		1	
	2			1				1	1		
5	1	1				1					1
	2		1			1				1	1
6	1	1	1	1							
	2			1				1	1		
	3					1	1	1			
7	1		1		1		1				
	2	1	1		1						
	3				1			1	1		
						1		1		1	1
8	1	1								1	1
	2	1						1	1		1
9	1			1				1		1	
	2			1					1		
10	1	1		1				1	1		
	2			1							

Table 5.18: Rearranged part-machine matrix for example 3

Part	Process Plan	2	4	6	1	5	9	10	3	7	8
1	2		1	1							
7	1	1	1	1							
2	2				1	1	1	1			
5	2					1	1	1			
		1			1		1	1			
8	2								1	1	1
3	1								1	1	1
4	2								1	1	1
6	2							1	1	1	1
9	1								1	1	1
10	2										

5.4.1.4 Comparison of results of model 1 and model 2

Comparison of table 5.3 and table 5.15 which are the solutions of the same example by model 1 and model 2 respectively shows that both the models has given the same output (equal exceptional elements and voids). However, comparison of tables 5.10 and table 5.16 shows the output of two models is different. This is on two accounts; one because the final objective function for model 1 is different although the initial grouping of parts is done with the objective of minimizing the weighted sum of exceptional elements and voids, second the solution of ART1 algorithm is dependent upon the ordering of the input vectors (incident part-machine matrix). The total cost calculated for the solution of model 2 comes out to be 466500$, which is less than the cost computed for model 1 solution (607500$).

5.4.2 Development of SA model (Model 3) using operation sequence of parts for cell formation

In this section also a model developed based on the SA is presented. However, unlike model 2, this model uses operation sequence of parts and the objective is to minimize the number of intercell moves. This model also solves the cell formation problem in presence of alternate process plans for parts. Demand and batch size for parts is also considered in this model.

5.4.2.1 Mathematical formulation

Notations:

i, j : variables for machines ($i \neq j$)

n : total number of machines

k : variable for parts

P : total number of parts

D_k : production volume of part k for a given planning horizon

B_k : transfer batch size of part k

x, y : variables for cells ($x \neq y$)

C : total number of cells

F_{ij}^k : flow/interaction between machine i and j for part k

S_{ki}^r : operation number for the operation done on part k using machine i in process plan r

n_k' : number of process plans for part k

The objective (minimization of intercell moves) is computed as:

$$\text{Minimize} \qquad z = \sum_{x=1}^{C}\sum_{y=1}^{C}\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{P}\sum_{r=1}^{n_k'} F_{ij}^k a_{ix} a_{jy} a_{ki}^r a_{kj}^r x_{kx}^r x_{ky}^r$$

$$\text{where } F_{ij}^k = \begin{cases} D_k \big/ B_k, \ if \left|S_{ki}^r - S_{kj}^r\right| = 1 \ \& \ S_{ki}^r, S_{kj}^r > 0 \\ 0, \text{ otherwise} \end{cases}$$

$$a_{ix} = \begin{cases} 1, \text{ machine } i \text{ is in cell } x \\ 0, \text{ otherwise} \end{cases}$$

$$a_{jy} = \begin{cases} 1, \text{ machine } j \text{ is in cell } y \\ 0, \text{ otherwise} \end{cases}$$

$$a_{ki}^r = \begin{cases} 1, \text{ if part } k \text{ uses machine } i \text{ in route } r \\ 0, \text{ otherwise} \end{cases}$$

Subject to:

$$\sum_{r=1}^{n_k'} x_{kx}^r, x_{ky}^r = 1 \quad \forall k, x \neq y \qquad (1)$$

$$C = C_{\max} \qquad (2)$$

The first constraint guarantees that each part is allocated to one cell and only one process plan is selected for the part. The second constraint guarantees that the number of cells formed are equal to the required number of cells.

5.4.2.2 Algorithm

```
Step 1    Input P, n, $C_{max}$, $n_k^r$, $AT_{min}$, $r_f$, a, $T_I$
Step 2    Read operation sequence, $D_k$ and $B_k$
Step 3    Generate an initial solution, compute objective value (obj)
Step 4    Initialize I = 0 and set $obj^I$ = obj and $sol^I$ = sol
Step 5    Initialize t = 0, AT = 0 and set $obj_t = obj^0$ and $sol_t = sol^0$
Step 6    Generate a neighbourhood solution and compute $obj_t$
Step 7    Compute $E = obj_t - obj_{t-1}$
Step 8    If E <= 0 or random no. R between (0,1) <= $e^{-E/T}$
          Accept $obj_t$ and $sol_t$ and update AT = AT + 1
          else accept $obj_t = obj_{t-1}$ and $sol_t = sol_{t-1}$ and update t = t + 1
Step 9    If AT < $AT_{min}$ or t < n*n, set $obj^I = obj_t$, $sol^I=sol_t$ and go to step 6
          else go to step 10
Step10    If $obj^I$ <$obj^{I-1}$ accept $obj^I$ and $sol^I$
          else if $obj^I$ =$obj^{I-1}$ accept $obj^I$ and $sol^I$ and set FC=FC+1
                else accept $obj^I = obj^{I-1}$ and $sol^I = sol^{I-1}$
Step11    Compute r = AT/t, if r<=$r_f$ go to step 13
                         else go to step 12
Step12    If I < $I_{max}$ or FC= =20, I = I + 1, T = a * T and go to step 5
                else go to step 13
Step13    Print $sol^I$, $obj^I$, no. of cells, $r_f$, and I
Step14    Stop
```

5.4.2.3 Validation

This model is validated by solving four examples extracted from literature. Each example is further divided into two sub-examples - one without considering the demand and other by considering the demand and batch size.

Example 1: The 12 machines and 12 parts example (table 5.19) with alternate process plans was extracted from Lozano *et al.* (1999). Lozano *et al.* (1999) has considered four planning horizon but in this example only one planning horizon is considered and accordingly the demand for one planning horizon is considered here. The solutions are shown in tables 5.20 and 5.21.

Table 5.19: Input data for example 1

Part no.	Process plan	Operation No. (machine no.)	Demand	Batch size
1	1	1(6), 2(5), 3(3), 4(12), 5(8), 6(11)	12	1
	2	1(10), 2(11), 3(6), 4(5), 5(7)		
2	1	1(10), 2(2), 3(4), 4(1), 5(5)	21	1
	2	1(4), 2(1), 3(10), 4(3), 5(5)		
	3	1(12), 2(2), 3(6)		
3	1	1(8), 2(5), 3(2), 4(12)	20	1
	2	1(12), 2(8)		
4	1	1(9), 2(2), 3(4)	18	1
	2	1(2), 2(7), 3(3), 4(11), 5(12)		
5	1	1(1), 2(7), 3(4), 4(2), 5(9)	28	1
6	1	1(12), 2(3), 3(2), 4(11), 5(8), 6(5)	10	1
	2	1(11), 2(10), 3(5), 4(8)		
7	1	1(10), 2(7), 3(11), 4(5)	12	1
	2	1(3), 2(4), 3(10), 4(7)		
8	1	1(5), 2(2), 3(4)	16	1
9	1	1(6), 2(7), 3(11), 4(3), 5(2)	23	1
	2	1(2), 2(3), 3(11), 4(6)		
10	1	1(4), 2(8), 3(5)	29	1
11	1	1(3), 2(2), 3(10), 4(9), 5(12)	21	1
12	1	1(6), 2(7), 3(2)	20	1

Table 5.20: Solutions for example 1 without demand and intercell moves as objective

C	Parts (process plan)	Machines	Objective value
2	1(2), 6(2), 7(1), 9(2), 12(1)	1,5,6,7,10,11	9
	2(3), 3(2), 4(1), 5(1), 8(1), 10(1), 11(1)	2,3,4,8,9,12	
3	1(2), 6(2), 7(1), 9(2), 12(1)	1,6,7,10,11	13
	3(2), 10(1)	5,8	
	2(3), 4(1), 5(1), 8(1), 11(1)	2,3,4,9,12	

Table 5.21: solutions for example 1 with demand and intercell moves as objective

C	Parts (process plan)	Machines	Objective value
2	Same as above	Same as above	189
3	Same as above	Same as above	245

Example 2: The 20 machines and 20 parts example (table 5.22) with alternate process plans was taken from Nagi *et al.* (1990). Solutions are shown in tables 5.23 and 5.24.

Table 5.22: Input data for example 2

Part no.	Process plan	Operation No. (machine no.)	Demand	Batch size
1	1	1(12), 2(9), 3(6)	2	1
	2	1(12), 2(9), 3(7)		
2	1	1(6), 2(12), 3(1)	2	1
	2	1(7), 2(12), 3(1)		
3	1	1(1), 2(9), 3(12), 4(7)	2	1
	2	1(1), 2(9), 3(12), 4(7)		
4	1	1(1), 2(12), 3(6)	2	1
	2	1(1), 2(12), 3(7)		
5	1	1(9), 2(1), 3(12), 4(19)	2	1
	2	1(9), 2(1), 3(12), 4(18)		
	3	1(9), 2(1), 3(12), 4(20)		
6	1	1(6), 2(5), 3(2)	2	1
	2	1(7), 2(5), 3(2)		
7	1	1(5), 2(16), 3(19), 4(7)	2	1
	2	1(5), 2(16), 3(18), 4(7)		
	3	1(5), 2(16), 3(20), 4(7)		
	4	1(5), 2(16), 3(19), 4(6)		
	5	1(5), 2(16), 3(18), 4(6)		
	6	1(5), 2(16), 3(20), 4(6)		
8	1	1(16), 2(7), 3(2)	2	1
	2	1(16), 2(6), 3(2)		
9	1	1(16), 2(2), 3(19), 4(7)	1	1
	2	1(16), 2(2), 3(19), 4(6)		
	3	1(16), 2(2), 3(18), 4(7)		
	4	1(16), 2(2), 3(18), 4(6)		
	5	1(16), 2(2), 3(20), 4(7)		
	6	1(16), 2(2), 3(20), 4(6)		
10	1	1(1), 2(16), 3(5), 4(6)	3	1
	2	1(1), 2(16), 3(5), 4(7)		
11	1	1(8), 2(3), 3(11), 4(18)	3	1
	2	1(8), 2(3), 3(11), 4(19)		
	3	1(8), 2(3), 3(11), 4(20)		
12	1	1(3), 2(8), 3(18)	3	1
	2	1(3), 2(8), 3(19)		
	3	1(3), 2(8), 3(20)		
13	1	1(11), 2(8), 3(3), 4(18)	4	1
	2	1(11), 2(8), 3(3), 4(19)		
	3	1(11), 2(8), 3(3), 4(20)		
14	1	1(10), 2(18), 3(14), 4(17)	2	1
	2	1(10), 2(19), 3(14), 4(17)		
	3	1(10), 2(20), 3(14), 4(17)		
15	1	1(18), 2(17), 3(10)	2	1
	2	1(19), 2(17), 3(10)		
	3	1(20), 2(17), 3(10)		
16	1	1(18), 2(10), 3(14)	2	1
	2	1(19), 2(10), 3(14)		
	3	1(20), 2(10), 3(14)		
17	1	1(17), 2(14), 3(10)	2	1
18	1	1(13), 2(4), 3(15)	3	1
19	1	1(4), 2(13), 3(15)	3	1
20	1	1(15), 2(4)	3	1

Table 5.23: Solutions for example 2 without demand and intercell moves as objective

C	Parts	Machines	Objective value
5	1(2), 2(2), 3(2), 4(2), 5(1)	1,7,9,12	2
	6(1), 7(6), 8(2), 9(6), 10(1)	2,5,6,16,20	
	11(1), 12(1), 13(1)	3,8,11,18	
	14(2), 15(2), 16(2), 17(1)	10,14,17,19	
	18(1), 19(1), 20(1)	4,13,15	
4	1(2), 2(2), 3(2), 4(2), 5(1), 14(2), 15(2), 16(2), 17(1)	1,7,9,10,12,14,17,19	0
	6(1), 7(6), 8(2), 9(6), 10(1)	2,5,6,16,20	
	11(1), 12(1), 13(1)	3,8,11,18	
	18(1), 19(1), 20(1)	4,13,15	

Table 5.24: Solutions for example 2 with demand and intercell moves as objective

C	Parts	Machines	Objective value
5	1(2), 2(2), 3(2), 4(2), 5(1)	1,7,9,12	5
	6(1), 7(6), 8(2), 9(6), 10(1)	2,5,6,16,20	
	11(1), 12(1), 13(1)	3,8,11,18	
	14(2), 15(2), 16(2), 17(1)	10,14,17,19	
	18(1), 19(1), 20(1)	4,13,15	
4	1(2), 2(2), 3(2), 4(2), 5(1), 14(2), 15(2), 16(2), 17(1)	1,7,9,10,12,14,17,19	0
	6(1), 7(6), 8(2), 9(6), 10(1)	2,5,6,16,20	
	11(1), 12(1), 13(1)	3,8,11,18	
	18(1), 19(1), 20(1)	4,13,15	

Example 3: The 20 machines and 20 parts example extracted from Harhalakis *et al.* (1990a) is shown in table 5.25. The demand and batch size have been assumed as this was not considered by the Harhalakis *et al.* (1990a). This example is solved for 3-cell, 4-cell and 5-cell solutions. The solutions obtained without considering demand and with demand are given in tables 5.26 and 5.27 respectively. The 3-cell solution without demand is better than the 3-cell solution obtained by Adil and Rajamani (2000). The 4-cell solution and 5-cell solution are similar to the solutions obtained by Harhalakis *et al.* (1990a) and Reddy and Wadhwa (1999) respectively.

Table 5.25: Input data for example 3

Parts	Operation number (machine no.)	Demand	Batch size
1	1(12), 2(1), 3(9), 4(18), 5(20)	20	20
2	1(11), 2(3), 3(2)	80	40
3	1(8), 2(20), 3(19)	200	50
4	1(3), 2(11), 3(2), 4(10)	50	25
5	1(4), 2(15), 3(6), 4(7)	100	25
6	1(11), 2(14), 3(16), 4(17), 5(5)	150	25
7	1(5), 2(16), 3(17)	40	20
8	1(15), 2(13), 3(7), 4(9), 5(4)	80	40
9	1(18), 2(9), 3(11), 4(1), 5(12)	30	15
10	1(19), 2(20), 3(8)	20	5
11	1(11), 2(14), 3(3)	20	10
12	1(9), 2(18), 3(5), 4(12), 5(1)	50	25
13	1(6), 2(7), 3(15), 4(17)	80	20
14	1(8), 2(10), 3(1), 4(2)	50	10
15	1(13), 2(14), 3(16), 4(17)	150	25
16	1(15), 2(7), 3(6), 4(19)	80	20
17	1(9), 2(1), 3(12)	100	20
18	1(8), 2(19), 3(20), 4(10)	50	25
19	1(3), 2(2), 3(11), 4(5)	150	25
20	1(18), 2(10), 3(1), 4(12)	40	20

Table 5.26: Solutions for example 3 without demand and intercell moves as objective

C	Cells	Parts	Machines	Objective value
3	1	2,4,6,7,11,15,19	2,3,5,11,14,16,17	11
	2	5,8,13,16	4,6,7,13,15	
	3	1,3,9,10,12,14,17,18,20	1,8,9,10,12,18,19,20	
4	1	2,4,6,7,11,15,19	2,3,5,11,14,16,17	14
	2	1,9,12,14,17,20	1,9,10,12,18	
	3	3,10,18	8,19,20	
	4	5,8,13,16	4,6,7,13,15	
5	1	1,9,12,14,17,20	1,9,10,12,18	17
	2	2,4,11,19	2,3,11,14	
	3	5,8,13,16	4,6,7,13,15	
	4	3,10,18	8,19,20	
	5	6,7,15	5,16,17	

Table 5.27: Solutions for example 3 with demand and intercell moves as objective

C	Cells	Parts	Machines	Objective value
3	1	2,4,6,7,11,15,19	2,3,5,11,14,16,17	33
	2	5,8,13,16	4,6,7,13,15	
	3	1,3,9,10,12,14,17,18,20	1,8,9,10,12,18,19,20	
4	1	5,8,13,16	4,6,7,15	39
	2	1,9,12,14,17,20	1,9,10,12,18	
	3	2,4,6,7,11,15,19	2,3,5,11,13,14,16,17	
	4	3,10,18	8,19,20	
5	1	6,7,11,15,19	5,11,13,14,16,17	53
	2	3,10,18	8,19,20	
	3	5,8,13,16	4,6,7,15	
	4	1,9,12,14,17,20	1,9,10,12,18	
	5	2,4	2,3	

Example 4: The 30 machines and 41 parts example taken from Seifoddini and Djassemi (1995) is shown in table 5.28. The batch size of unity has been considered for all parts. This example is solved for 5-cell, 6-cell and 7-cell solutions. The solutions obtained without considering demand and with demand are given in tables 5.29 and 5.30 respectively.

Table 5.28: Input data for example 4

Parts	Operation number (machine no.)	Demand	Batch size
1	1(20), 2 (30), 3(19), 4(29), 5 (8)	115	1
2	1(10), 2 (23)	16	1
3	1(20), 2(30), 3(19), 4(29), 5 (9)	120	1
4	1(14), 2 (25)	78	1
5	1(14)	91	1
6	1(6), 2(16)	71	1
7	1(17), 2(4)	67	1
8	1(8), 2(28), 3(27)	82	1
9	1(29), 2(8)	61	1
10	1(22), 2(1), 3(11), 4(21)	8	1
11	1(2), 2(12)	63	1
12	1(3), 2(22), 3(2), 4(21), 5 (10), 6(23), 7 (11)	144	1
13	1(29), 2(9)	127	1
14	1(18), 2(8)	76	1
15	1(27), 2(4)	75	1
16	1(7), 2(26), 3(17), 4(18)	87	1
17	1(5), 2(15)	31	1
18	1(2), 2(14)	96	1
19	1(12), 2(13)	110	1
20	1(12)	136	1
21	1(30), 2 (19), 3(29), 4 (9)	84	1
22	1(29)	120	1
23	1(3), 2(22), 3(10), 4(12)	78	1
24	1(12), 2(4)	91	1
25	1(4), 2(13)	76	1
26	1(4), 2(16), 3 (14)	139	1
27	1(7), 2(26), 3(17), 4(18)	97	1
28	1(4)	69	1
29	1(19), 2(8), 3(28)	61	1
30	1(29)	55	1
31	1(3), 2(22), 3(1), 4(21), 5(23)	87	1
32	1(4), 2(22), 3(1), 4(2), 5(21)	31	1
33	1(1), 2(11), 3(2), 4(21)	93	1
34	1(7), 2(26), 3(18), 4(5)	60	1
35	1(28), 2(4)	128	1
36	1(7), 2(26), 3(17), 4(5)	49	1
37	1(15), 2(26)	81	1
38	1(13), 2(24)	120	1
39	1(3), 2(22), 3 (1), 4(11), 5(2), 6(10), 7(23), 8(12)	84	1
40	1(3), 2(22), 3(21), 4(12)	110	1
41	1(1), 2(11), 3(2)	31	1

Table 5.29: Solutions for example 4 without demand and intercell moves as objective

C	Parts	Machines	Objective value
5	2,10,11,12,20,23,31,32,33,39,40,41	1,2,3,10,11,12,21,22,23	9
	15,19,24,25,28,35,38	4,13,24,27	
	7,14,16,17,27,34,36,37	5,7,15,17,18,26	
	1,3,8,9,13,21,22,29,30	8,9,19,20,28,29,30	
	4,5,6,18,26	6,14,16,25	
6	1,3,9,13,14,21,22,29,31	8,9,19,20,29,30	16
	7,16,17,27,34,36,37	5,7,15,17,18,26	
	2,11,19,20,23,24,25,38	10,12,13,23,24	
	4,5,6,18,26	6,14,16,25	
	8,15,28,35	4,27,28	
	10,12,31,32,33,39,40,41	1,2,3,11,21,22	
7	10,23,31,32,40	1,3,22	20
	2,11,12,20,33,39,41	2,10,11,12,21,23	
	4,5,18	14,25	
	6,8,15,24,26,28,29,35	4,6,8,16,27,28	
	7,14,16,17,27,34,36,37	5,7,15,17,18,26	
	1,3,9,13,21,22,30	9,19,20,29,30	
	19,25,38	13,24	

Table 5.30: Solutions for example 4 with demand and intercell moves as objective

C	Parts	Machines	Objective value
5	2,10,11,12,20,23,31,32,33,39,40,41	1,2,3,10,11,12,21,22,23	820
	15,19,24,25,28,35,38	4,13,24,27	
	7,14,16,17,27,34,36,37	5,7,15,17,18,26	
	1,3,8,9,13,21,22,29,30	8,9,19,20,28,29,30	
	4,5,6,18,26	6,14,16,25	
6	1,3,9,13,21,22,29,30	8,9,19,20,29,30	1232
	4,5,6,8,15,18,24,25,26,28,35	4,6,14,16,25,27,28	
	7,14,16,17,27,34,36,37	5,7,15,17,18,26	
	23,40	3,22	
	19,38	13,24	
	2,10,11,12,20,31,32,33,39,41	1,2,10,11,12,21,23	
7	10,23,31,32,40	1,3,22	1589
	2,11,12,20,33,39,41	2,10,11,12,21,23	
	4,5,18	14,25	
	6,8,15,24,26,28,29,35	4,6,8,16,27,28	
	7,14,16,17,27,34,36,37	5,7,15,17,18,26	
	1,3,9,13,21,22,30	9,19,20,29,30	
	19,25,38	13,24	

5.5 Conclusions

This chapter presents an extensive review of literature on cell formation approaches and the three models developed for the cell formation. The literature review indicates the need of cell formation methods that consider the factors like operation sequence, production volume of parts, number of cells, cell size, capacity of machines, workload on machines, processing time on parts, machine utilization, size of the problem, product mix, cost, *etc.* There is a growing need to develop methods based on the artificial intelligence techniques like neural networks, simulated annealing, and genetic algorithms.

Model 1 presents a ART1 network based algorithm for solving the cell formation problem with a view to generating feasible solutions that satisfy real-world constraints of production volume, processing time, number of cells, minimum acceptable utilization levels for individual machines, machine downtime, desirable machine utilization, maximum permissible workload on machines and other management constraints like number of shifts, working days and maintenance philosophy. The model also introduces the cost of inter-cell material handling and voids in a practical way by accounting for the production volumes of the parts making inter-cell moves and the total workload of the machines in the cells. The neural network can be structured on the basis of the number of machines as well as the upper bound specified on the number of cells. The network is also capable of handling the problem of product flexibility in a CMS. Other cell design constraints like machine duplication and alternate process plans are not included in the algorithm but these can be accounted for by looking at the feasible solutions and individual machine utilization as the algorithm is user interactive. The objective of model 1 is to form feasible cells with minimization of weighted sum of costs associated with exceptional elements and voids. Model 2 is a simulated annealing model for cell formation with an objective to minimize the weighted sum of exceptional elements and voids. This model considers the alternate process plans for the parts and the binary part-machine incidence matrix as input. The model is versatile as any value of weights for individual exceptional elements and voids can be given. Model 3 is also a simulated annealing model, which considers the alternate process plans, operation sequence, demand, and batch size of parts. The objective of this model is to minimize the intercellular moves. In this model the number of cells are specified *a prior*. The limit on the cells may arise due to many causes such as better utilization of employees, manufacturing equipments, and space; and safety and technological considerations.

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Chapter 6

Design of Layout for Cellular Manufacturing Systems

6.1 Introduction

Recent studies have questioned the predominance of cellular layouts over functional layouts (Flynn and Jacobs 1987, Morris and Tersine 1990) largely because the design of layout for cellular manufacturing systems (CMS) has not get the researcher's attention as much as cell formation in cellular manufacturing (Wang *et al.* 1998). Most of the techniques for the design of CMS consider only cell formation phase. For this lack of information on layout, the benefits of CMS cannot be validated (Salum 2000). Many of the existing cell formation techniques mainly perform this task by minimizing the number of exceptional parts (the parts which require further processing outside the designated cells), which tend to generate smaller number of cells. Some researchers in cellular manufacturing field had tried to minimize the number of inter-cell moves and/or intra-cell moves, without considering the actual layout of the machines and cells (Adil and Rajamani 2000, Logendran 1990, Ballakur and Steudel 1987). The exceptional elements and voids have been used as surrogate measures for inter-cell and intra-cell moves cost. These measures do not reflect the actual moves cost. The actual moves cost is proportional to the distance traveled and the number of moves. The number of moves depends on the operation sequence, multiple nonconsecutive visits to the same machine, production volume, and the transfer batch size; the distance traveled depends on the layout of machines within the cells and the layout of cells on the shop floor

(Mukherjee *et al.* 1999, Logendran 1991). It is natural that the parts with higher production volume and lower batch size shall contribute more to the intra-cell and inter-cell moves. Also, an intermediate operation outside cell contribute two moves meanwhile the first and last operation contribute only one move. The layout data can be quantitative and/or qualitative. Qualitative factors such as noise, heat, flexibility, employee satisfaction, safety, *etc.* are non-quantifiable and must be considered in making transition from pure model to practicable solution (Shang 1993). Some of the qualitative factors are positive which require the proximity of facilities, while others are negative factors that require the facilities to be farthest apart. It is also important that quantitative approach should not be dismissed in favour of totally qualitative approach as the quantitative aspect of the facility problem can not be reckoned with accuracy through intuition alone (Francis and White 1974).

In this chapter, a multi-criteria mathematical formulation is presented as quadratic assignment problem for the design of layout for CMS considering both qualitative as well as quantitative factors. Two models developed for solving the mathematical model are presented. One model called **MUCH** uses pairwise exchange heuristic and the other called **FUGEN** uses a genetic algorithm with embedded fuzzy logic and AHP models. A comparison of results of two models is also presented.

6.2 Literature Review

Kusiak and Park (1994) developed heuristics for machine layout in cellular manufacturing systems. They considered two patterns of layout: single row layout (all machines arranged along one side of a line) and double row layout (machines are located on both sides of a line). Sarker and Yu (1994) presented a successive approach to solve the bottleneck machine problem in CMS. The first phase configures the cell layout that minimizes the total inter-cell material handling cost of all bottleneck parts. The second phase of the procedure finds the bottleneck machines that need to be duplicated, by a binary linear programming model, in order to minimize the total cost. The total cost includes the cost of duplicating bottleneck machines and the cost of inter-cell material moves if the machines are not duplicated. Ho and Moodie (2000) addressed the cell layout problem combining search algorithm and Linear Programming models to layout the cells and their flow paths in tree configuration. The search algorithm has a backtracking procedure that allows one to explore alternative layouts, while the mathematical programming model helps to obtain accurate layouts and their flowpaths. The proposed layout procedure interacts with designer and allows designer to include qualitative considerations into layout design. This procedure avoids awkward layouts, irregular shapes of cells and flow paths. This paper does not consider the layout of machines in the cells. Elwany *et al.* (1997) used a multigoal model developed by Harmonsky and Tothero (1992) to incorporate the quantitative and/or qualitative criteria in the intercell layout combining a knowledge-based system and simulated annealing algorithm. The knowledge-based system generates a layout based on a set of rules, this layout is seeded optionally to an improvement simulated annealing global optimisation algorithm to find better configuration for the situation. This paper does not consider the layout of machines in the cells and also it requires the flow and distance as user input. Salum (2000) proposed a two-phase model to layout machines on the shop floor that reduces the total manufacturing lead time. In the first phase the system is simulated to obtain the data, which is used to find similarity measures between machines in the second phase. The second phase then exploits an algorithm, which creates and uses these similarity measures to construct a layout by locating machines with higher similarity next to each other to minimize total material handling time and mean manufacturing lead time.

This method results into a logical layout of all machines on the shop floor rather than physical layout and shapes of resulting layouts are unrealistic (irregular shapes). Other drawback of this model is that layout of cells is not considered. Urban *et al.* (2000) proposed a model that does not require the machines to be placed in a functional layout or in a cellular arrangement, but allows the material flow requirements to dictate the machine placement. This model is formulated as an aggregation of the quadratic assignment problem and several network flow problems coupled with linear side constraints. A mixed integer program is presented to find the optimal solution for small problems, and heuristics are developed to solve larger problems. But their method also results in a logical layout rather than a physical layout which some authors call 'virtual cellular manufacturing' (Kannan and Ghosh 1996). Irani *et al.* (2000) introduced PFAST (Production Flow Analysis and Simplification Toolkit) to evaluate and simplify the material flow network prior to the design of the layout. Depending on the type of input data and desired results, PFSAT offers a variety of algorithms to the facility planner. The basic idea of the PFAST is to apply the cell formation algorithms to layout design. Bazargan-Lari *et al.* (2000) and Bazargan-Lari (1999) proposed machine layout and intercell layout designs for CMS. In the proposed methodology nondominated intracell layouts are generated for each cell based on two criteria, namely the area allocated to the cell and the travelling cost. A filtering process is used to select the most different layout designs in an effort to handle information overload and to reduce the number of nondominated solutions. Finally, these nondominated intracell layout designs are integrated to produce multiple efficient intercell layouts. A goal programming approach is used. Bazargan-Lari and Kaebernick (1996) developed a model for intra-cell and inter-cell layout. Bazargan-Lari and Kaebernick (1997) also developed a model to layout machines in CM environment. Wang and Sarker (2002) developed a QAP model to assign cells to linear locations in order to minimize the intercell material handling cost incurred due to bottleneck machines in CMS. They developed heuristics to solve the problem. The binary part-machine matrix is considered to calculate the number of bottleneck machines. The location-to-location distance and the inter-cell material flow matrix are input to the model. Moreover, the machine layout is not considered and the authors have admitted that their inter-cell material flow matrix is not a good representation in CMS.

The facility layout problem was formulated as QAP for the first time by Koopmans and Beckmann (1957). Since then other types of modelling like quadratic set covering problem (Bazaraa 1975), linear integer programming problem (Lawler 1963), mixed integer programming problem (Kaufman and Broeckx 1978), graph theoretic problem (Foulds and Robinson 1976), *etc.* have been tried. Kusiak and Heregu (1987) gives a comprehensive literature survey of the existing methods for facility layout. The QAP formulation of the problem belongs to the class of NP-complete (Sahni and Gonzalez 1976) and the size of the problems that can be solved by the existing optimal methods is limited (≤15). Consequently, many heuristics have been developed for solving the QAP.

6.3 Development of Multi-criteria Mathematical Formulation for Layout of CMS

The multi-criteria mathematical formulation given in this section deals with the minimization of the integrated (intra-cell and inter-cell) cost function. Machine layout problem inside the cells and cell layout problem on the shop floor are modelled as Quadratic Assignment Problems (QAP) to assign *n* facilities (machines/cells) to *n* locations with a view to minimize the material handling (quantitative) and to maximize the closeness (qualitative) between the facilities (machines/cells).

Notations:

i and j : variables for machines ($i \neq j$)

n : total number of machines

k : variable for parts

P : total number of parts

D_k : production volume of part k for a given planning horizon

B_k : transfer batch size of part k

x, y : variables for cells ($x \neq y$)

C : total number of cells

p, q : variables for locations ($p \neq q$)

d_{pq} : distance from location p to location q (rectilinear distance)

F_{ij}^{k} : flow/interaction between machine i and j for part k

f_{ij} : flow/interaction between machines i and j for all parts

im_{ij}^{x} : flow/interaction between machines i and j in cell x

ic_{xy} : flow/interaction between cells x and y

S_{ki} : operation number for the operation done on part k using machine i

w_1 : weight for qualitative factors

w_2 : weight for quantitative factors

α_1 : weight for intra cell objective function

α_2 : weight for inter cell objective function

The objective of the model is to minimize z, where (1)

$$z = \alpha_1 IM + \alpha_2 IC$$

Where IM and IC are the intra-cell layout and inter-cell layout objective functions respectively as given below:

$$IM = \sum_{x=1}^{C} IM^{x} \tag{2}$$

$$IM^{x} = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{p=1}^{n}\sum_{q=1}^{n} c_{ijpq}.x_{ip}.x_{jq} \tag{2.1}$$

$$c_{ijpq} = w_2 a_{ijpq} - w_1 b_{ijpq}$$

$$a_{ijpq} = im_{ij}^{x} d_{pq}, i \neq j \text{ or } p \neq q$$

$$im_{ij}^{x} = \sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij} a_{ix} a_{jx} \tag{2.2}$$

$$f_{ij} = \sum_{k=1}^{P} F_{ij}^{k}$$

$$F_{ij}^{k} = \begin{cases} D_k / B_k, \text{ if } \left| S_{ki} - S_{kj} \right| = 1 \\ 0, \text{ otherwise} \end{cases}$$

$$a_{ix} = \begin{cases} 1, \text{ if machine } i \text{ in cell } x \\ 0, \text{ otherwise} \end{cases}$$

$$a_{jx} = \begin{cases} 1, \text{ if machine } j \text{ in cell } x \\ 0, \text{ otherwise} \end{cases}$$

$$b_{ijpq} = \begin{cases} r_{ij}, \text{ if location } p \text{ and } q \text{ are neighbours} \\ 0, \text{ otherwise} \end{cases}$$

r_{ij} = closeness ranking value when machines i and j are neighbours with common boundary

$$x_{ip} = \begin{cases} 1, \text{ if machine } i \text{ is assigned to location } p \\ 0, \text{ otherwise} \end{cases}$$

$$\text{IC} = \sum_{x=1}^{C}\sum_{y=1}^{C}\sum_{p=1}^{C}\sum_{q=1}^{C} c_{xypq}.x_{xp}.x_{yq} \tag{3}$$

where,

$$c_{xypq} = w_2 a_{xypq} - w_1 b_{xypq}$$

$$a_{xypq} = ic_{xy}\, d_{pq}, x \neq y \text{ or } p \neq q$$

$$ic_{xy} = \sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij} a_{ix} a_{jy} \tag{3.1}$$

$$a_{ix} = \begin{cases} 1, \text{ if machine } i \text{ in cell } x \\ 0, \text{ otherwise} \end{cases}$$

$$a_{jy} = \begin{cases} 1, \text{ if machine } j \text{ in cell } y \\ 0, \text{ otherwise} \end{cases}$$

$$b_{xypq} = \begin{cases} r_{xy}, \text{ if location } p \text{ and } q \text{ are neighbours} \\ 0, \text{ otherwise} \end{cases}$$

r_{xy} = closeness ranking value when cells x and y are neighbours with common boundary

$$x_{xp} = \begin{cases} 1, \text{ if machine } x \text{ is assigned to location } p \\ 0, \text{ otherwise} \end{cases}$$

Subject to:

$$\sum_{i=1}^{n} x_{ip} = 1 \quad \forall p \tag{4}$$

$$\sum_{p=1}^{n} x_{ip} = 1 \quad \forall i \tag{5}$$

$$\sum_{x=1}^{C} x_{xp} = 1 \quad \forall p \tag{6}$$

$$\sum_{p=1}^{C} x_{xp} = 1 \quad \forall x \tag{7}$$

$$w_1 + w_2 = 1$$
$$w_1, w_2 \geq 0$$

Constraints (4) and (5) assure that each location and machine can be assigned to one machine and one location only. Constraints (6) and (7) assure that each location and each cell can be assigned to one cell and one location only.

6.4 Development of Multi-criteria Heuristic Model (MUCH) for Layout of CMS

Multi-criteria heuristic model (MUCH) for layout of CMS is developed based on the multi-criteria mathematical formulation. Pairwise exchange of facilities (machines/cells) is used for design of layout of CMS. The algorithm of MUCH model is given below and the flow chart is shown in figure 6.1.

6.4.1 Algorithm

```
Step 0    Input number of cells, parts and machines therein, $w_1$, $\alpha_1$
Step 1    Read demand, transfer batch size and operation sequence of parts
Step 2    Set $x=0$
Step 3    Generate initial machine layout, compute $c_{ijpq}$
Step 4    Set $i=0$
Step 5    Set $j=j+1$
Step 6    Exchange i and j, compute $c_{ijpq}^{new}$
Step 7    If $c_{ijpq}^{new} \leq c_{ijpq}^{old}$, update $c_{ijpq}^{new} = c_{ijpq}^{new}$, $layout^{new} = layout^{new}$
          else $c_{ijpq}^{new} = c_{ijpq}^{old}$, $layout^{new} = layout^{old}$
Step 8    If $j < n$, $j = j+1$ and go to Step 6
              else    if $i< n-1$, $i=i+1$ and go to Step 5
                      else go to Step 9
Step 9    Compute $IM^x$
Step 10   Print layout and $IM^x$
Step 11   If $x < C$, $x = x+1$ and go to Step 3, else go to Step 12
Step 12   Compute IM
Step 13   Generate initial cell layout, and compute $c_{xypq}$
Step 14   Set $x=0$
```

```
Step 15   Set y=y+1
Step 16   Exchange x and y and compute $c_{xypq}^{new}$
Step 17   If $c_{xypq}^{new} \leq c_{xypq}^{old}$, update $c_{xypq}^{new} = c_{xypq}^{new}$, $layout^{new} = layout^{new}$
              else $c_{xypq}^{new} = c_{xypq}^{old}$, $layout^{new} = layout^{old}$
Step 18   If $y < C$, $y = y+1$ and go to Step 16
              else    if $x < C-1$, $x=x+1$ and go to Step 15
                      else go to Step 19
Step 19   Compute IC
Step 20   Print layout and IC
Step 21   Compute and print TC
Step 22   Stop
```

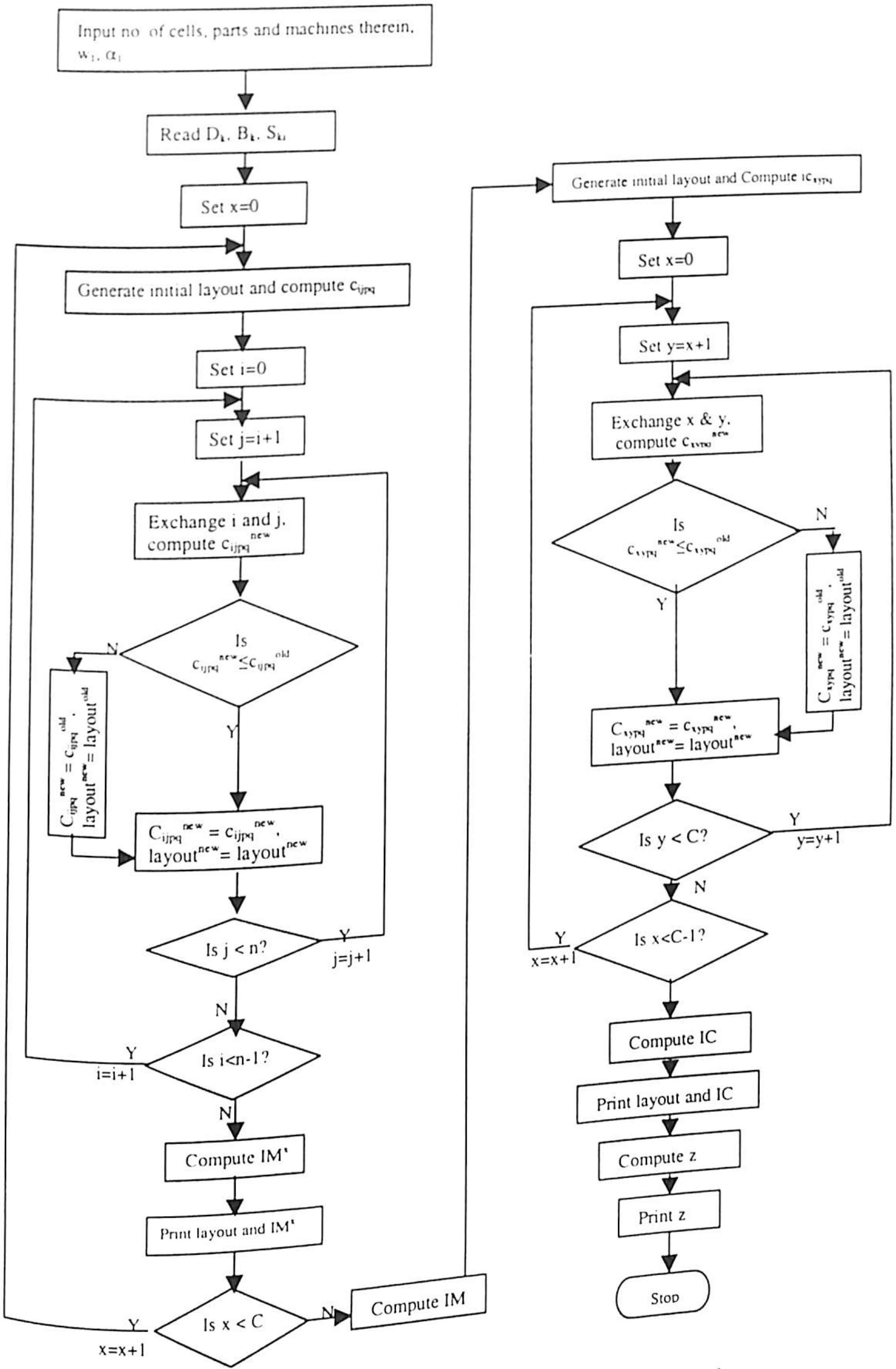


Figure 6.1: Flowchart of the MUCH model

6.4.2 Validation

The model is validated by designing the layout for two examples (example 3, table 5.25; and example 4, table 5.28) for which the cells are formed in chapter 5. For example 3 (table 5.25), the solutions without demand and with demand are considered. Further the layout designs are carried out for different values of qualitative factors (w_1) as shown in tables 6.1 and 6.2. For example 4 (table 5.28), solutions with demand are considered for the layout design and the layout is done for $w_1 = 0$ as shown in table 6.3. In total nine problems (solutions given in tables 5.26, 5.27, and 5.30) are taken for layout design.

The assumptions made in the proposed method are that the machines (cells) are of equal size, the distances between the adjacent machines (cells) are one unit each, and the cost is proportional to the total material handling and linear in nature. It has also been assumed that the cells as well as the shop floor areas are rectangular in shape. This assumption is realistic and practical as pointed out by Black (1983). Values of α_1 and α_2 are taken as 0.7 and 1.0 (Seifoddini and Djassemi 1995). The initial layout for machine layout and cell layout is given in ascending order (machine number or cell number). Scoring is done using Dutta and Sahu (1982) pattern given below:

A=6, E=5, I=4, O=3, U=2, X=1

The layout designs (tables 6.1, 6.2, and 6.3) show that the best solutions (cells formed) in chapter 5 need not to be the best if layout is considered. As shown in figure 6.2a, the best solution without considering layout is 3-cell solution and worst solution is 5-cell solution but 4-cell solution is worst when the layout is considered ($w_1 = 0$). For example 4 (table 5.28), as shown in figure 6.2c, the best solution without considering layout is 5-cell solution but 6-cell solution is best when the layout is considered ($w_1 = 0$). However, for example 3 (table 5,25), the best and worst solutions without considering layout and with layout are same.

Table 6.1a: Layout for 3-cell solution of table 5.26 using **MUCH**

	Cell 1		Cell2		Cell 3		Inter cell		Objective value
Machines	2,3,5,11,14,16,17		4,6,7,13,15		1,8,9,10,12,18,19,20				
Parts	2,4,6,7,11,15,19		5,8,13,16		1,3,9,10,12,14,17,18,20				
W_1	Layout	IM^1	Layout	IM^2	Layout	IM^3	Layout	IC	z
0.0	2 11 14 16 5 3 17	28.0	13 15 4 7 6	11.0	8 10 18 20 1 9 19 12	26.0	3 2 1	13	58.5
0.1	2 11 17 3 14 16 5	22.2	6 7 4 13 15	9.7	18 10 9 20 12 1 19 8	26.3	3 2 1	12.2	52.24
0.2	2 11 17 3 14 16 5	18.4	7 15 13 6 4	7.0	18 10 9 20 12 1 19 8	21.6	3 2 1	9.4	42.3
0.3	2 11 17 3 14 16 5	14.6	7 15 13 6 4	5.0	18 10 9 20 12 1 19 8	16.9	3 2 1	7.6	33.15
0.4	2 11 17 3 14 16 5	10.8	7 6 13 15 4	3.0	18 10 9 20 12 1 19 8	12.2	3 2 1	5.8	24.0
0.5	2 11 14 3 17 16 5	7.0	7 6 13 15 4	0.5	10 18 9 20 12 1 19 8	7.5	3 2 1	4.0	14.5
0.6	2 17 16 11 14 5 3	0.6	13 7 6 4 15	-2.2	10 9 18 20 12 1 19 8	2.6	3 2 1	2.2	2.9
0.7	2 17 16 11 14 5 3	-3.3	13 7 6 4 15	-4.4	10 9 18 20 12 1 19 8	-2.8	3 2 1	0.4	-6.95
0.8	2 16 17 14 5 11 3	-7.2	6 15 7 13 4	-7.4	10 18 9 12 20 1 8 19	-8.2	3 2 1	-1.4	-17.36
0.9	2 16 17 14 5 11 3	-12.1	6 15 7 13 4	-10.2	10 9 18 20 12 8 19 1	-13.4	3 2 1	-3.2	-28.19
1.0	16 5 14 11 2 17 3	-16.0	13 15 7 6 4	-13.0	20 12 10 18 19 9 8 1	-19.0	3 2 1	-5.0	-38.6

Table 6.1b: Layout for 4- cell solution of table 5.26 using **MUCH**

	Cell 1		Cell2		Cell 3		Cell 4		Inter cell		Objective value
Machines	2,3,5,11,14,16,17		1,9,10,12,18		8,19,20		4,6,7,13,15				
Parts	2,4,6,7,11,15,19		1,9,12,14,17,20		3,10,18		5,8,13,16				
W_1	Layout	IM^1	Layout	IM^2	Layout	IM^3	Layout	IM^4	Layout	IC	Z
0.0	2 11 14 16 5 3 17	28.0	18 12 10 9 1	16.0	20 19 8	7.0	13 15 4 7 6	11.0	4 3 1 2	16	59.4
0.1	2 11 17 3 14 16 5	22.2	1 12 10 9 18	13.0	20 19 8	5.8	6 7 4 13 15	9.7	4 3 1 2	13.6	49.09
0.2	2 11 17 3 14 16 5	18.2	1 12 10 9 18	10.0	20 19 8	4.6	7 15 13 6 4	7.0	4 3 1 2	11.4	39.26
0.3	5 14 11 16 3 2 17	10.7	1 12 10 9 18	7.0	20 19 8	3.4	7 15 13 6 4	5.0	4 3 1 2	9.4	27.46
0.4	5 14 11 16 3 2 17	6.6	1 12 10 9 18	4.0	20 19 8	2.2	7 6 13 15 4	3.0	4 3 1 2	6.8	17.86
0.5	5 14 11 16 3 2 17	2.5	1 12 10 18 9	1.0	20 19 8	1.0	7 6 13 15 4	0.5	4 3 1 2	4.5	8.0
0.6	5 14 11 16 3 2 17	-1.6	1 12 10 18 9	-2.6	20 19 8	-0.2	13 7 6 4 15	-2.2	4 3 1 2	2.2	-2.42
0.7	5 14 11 16 3 2 17	-5.7	12 1 10 9 18	-5.0	8 20 19	-1.5	13 7 6 4 15	-4.4	4 3 1 2	-0.1	-11.72
0.8	5 14 11 16 3 2 17	-9.8	12 1 18 9 10	-8.4	8 20 19	-3.0	6 15 7 18 4	-7.4	4 3 1 2	-2.4	-22.42
0.9	5 14 11 16 3 2 17	-13.9	12 1 18 9 10	-12.2	8 20 19	-4.5	6 15 7 18 4	-10.2	2 4 3 1	-5.1	-33.66
1.0	5 16 14 2 3 17 11	-20.0	18 10 12 9 1	-18.0	8 20 19	-6.0	13 15 7 6 4	-13.0	2 4 3 1	-8.0	-47.9

Table 6.1c: Layout for 5-cell solution of table 5.26 using MUCH

	Cell 1		Cell2		Cell 3		Cell 4		Cell 5		Inter cell		Objective value
Machines	1,9,10,12,18		2,3,11,14		4,6,7,13,15		8,19,20		5,16,17				
Parts	1,9,12,14,17,20		2,4,11,19		5,8,13,16		3,10,18		6,7,15				
W_1	Layout	IM^1	Layout	IM^2	Layout	IM^3	Layout	IM^4	Layout	IM^5	Layout	IC	z
0.0	18 12 10 9 1	16.0	14 11 3 2	11.0	13 15 4 7 6	11.0	20 19 8	7.0	17 16 5	6.0	5 3 4 2 1	23	58.7
0.1	18 9 10 12 1	13.0	2 3 11 14	8.9	15 6 4 13 7	9.5	20 8 19	5.7	17 16 5	5.0	5 3 4 2 1	19.9	49.37
0.2	18 9 10 12 1	10.0	2 3 11 14	6.8	15 6 4 13 7	7.0	20 8 19	4.4	17 16 5	4.0	5 3 4 2 1	16.8	39.34
0.3	18 9 10 12 1	7.0	2 3 11 14	4.7	15 6 4 13 7	4.5	20 8 19	3.1	17 16 5	3.0	5 3 4 2 1	13.7	29.31
0.4	18 10 9 12 1	4.0	2 3 11 14	2.6	15 6 4 13 7	2.0	20 8 19	1.8	17 16 5	2.0	5 3 4 2 1	10.6	19.28
0.5	18 10 9 12 1	0.5	2 3 11 14	0.5	15 6 4 13 7	-0.5	20 8 19	0.5	17 16 5	1.0	5 3 4 2 1	7.5	8.9
0.6	18 10 9 12 1	-3.0	2 3 11 14	-1.6	15 6 4 13 7	-3.0	20 8 19	-0.8	17 16 5	0	5 3 4 2 1	4.2	-1.68
0.7	18 10 9 12 1	-6.5	2 3 11 14	-3.7	15 6 4 13 7	-5.5	20 8 19	-2.1	17 16 5	-1.0	2 4 3 5 1	0.8	-12.36
0.8	18 10 9 12 1	-10	2 3 11 14	-5.8	15 6 4 13 7	-8.0	20 8 19	-3.4	17 16 5	-2.0	4 2 5 1 3	-3.4	-23.84
0.9	18 10 9 12 1	-13.5	2 3 11 14	-7.9	15 6 4 13 7	-10.5	20 8 19	-4.7	17 16 5	-3.0	4 2 5 1 3	-7.2	-34.92
1.0	18 10 9 12 1	-17.0	2 3 11 14	-10	15 6 4 13 7	-13	20 8 19	-6.0	17 16 5	-4.0	4 2 5 1 3	-11.0	-46.0

Table 6.2a: Layout for 3-cell solution of table 5.27 using **MUCH**

	Cell 1		Cell2		Cell 3		Inter cell		Objective value
Machines	2,3,5,11,14,16,17		4,6,7,13,15		1,8,9,10,12,18,19,20				
Parts	2,4,6,7,11,15,19		5,8,13,16		1,3,9,10,12,14,17,18,19,20				
W_1	Layout	IM^1	Layout	IM^2	Layout	IM^3	Layout	IC	z
0.0	11 5 17 3 14 16 2	88.0	7 15 13 6 4	38.0	8 10 18 20 1 9 19 12	66.0	1 3 2	41.0	175.4
0.1	11 5 17 3 14 16 2	78.3	7 15 13 6 4	33.3	8 10 18 20 1 9 19 12	58.3	1 3 2	36.6	155.53
0.2	11 5 17 3 14 16 2	68.6	7 15 13 6 4	28.6	8 10 18 20 1 9 19 12	50.6	1 3 2	32.2	135.66
0.3	11 5 17 3 14 16 2	58.9	7 15 13 6 4	23.9	8 10 18 20 1 9 19 12	42.9	1 3 2	27.8	115.79
0.4	11 5 17 3 14 16 2	49.2	7 15 13 6 4	19.2	8 10 18 20 1 9 19 12	35.2	1 3 2	23.4	95.92
0.5	11 5 17 3 14 16 2	39.5	7 15 13 6 4	14.5	19 9 12 20 1 18 8 10	35.0	3 2 1	19.0	81.3
0.6	11 5 17 3 14 16 2	29.8	7 6 13 15 4	9.6	10 18 9 8 12 1 20 19	23.6	3 2 1	14.2	58.3
0.7	11 5 17 3 14 16 2	20.1	13 7 6 4 15	3.7	10 18 9 8 12 1 20 19	14.2	3 2 1	9.4	36.0
0.8	11 5 17 3 14 16 2	10.4	13 7 6 4 15	-1.2	19 9 18 10 12 1 20 8	4.6	3 2 1	4.6	14.26
0.9	5 11 14 16 2 3 17	-4.0	13 7 6 4 15	-6.1	12 18 9 10 20 1 8 19	-7.0	3 2 1	-0.2	-12.17
1.0	16 5 14 3	-16.0	13 15 7 6 4	-13.0	20 12 10 18 19 9 8 1	-19.0	3 2 1	-5.0	-38.6

Table 6.2b: Layout for 4-cell solution of table 5.27 using **MUCH**

	Cell 1		Cell2		Cell 3		Cell 4		Inter cell		Objective value
Machines	2,3,5,11,14,16,17		1,9,10,12,18		8,19,20		4,6,7,13,15				
Parts	2,4,6,7,11,15,19		1,9,12,14,17,20		3,10,18		5,8,13,16				
W$_1$	Layout	IM^1	Layout	IM^2	Layout	IM^3	Layout	IM^4	Layout	IC	Z
0.0	11 5 17 3 14 16 2	88	18 12 10 9 1	41.0	10 19 8	22	7 15 13 6 4	38	4 3 1 2	45	177.3
0.1	11 5 17 3 14 16 2	78.2	1 12 10 9 18	35.5	10 19 8	19.3	7 15 13 6 4	33.3	4 3 1 2	39.8	156.21
0.2	11 5 17 3 14 16 2	68.4	1 12 10 9 18	30	10 19 8	16.6	7 15 13 6 4	28.6	4 3 1 2	34.6	135.12
0.3	11 5 17 3 14 16 2	58.6	1 12 10 9 18	20.5	10 19 8	13.9	7 15 13 6 4	23.9	4 3 1 2	29.4	114.03
0.4	11 5 17 3 14 16 2	48.8	1 12 10 9 18	19	10 19 8	11.2	7 15 13 6 4	19.2	4 3 1 2	24.2	92.94
0.5	11 5 17 3 14 16 2	39.0	1 12 10 9 18	13.5	10 19 8	8.5	7 15 13 6 4	14.5	4 3 1 2	19.0	71.85
0.6	11 5 17 3 14 16 2	29.2	1 12 10 9 18	8.0	10 19 8	5.8	7 6 13 15 4	9.6	4 3 1 2	13.8	50.62
0.7	11 5 17 3 14 16 2	19.4	1 12 10 9 18	2.5	10 19 8	3.1	13 7 6 4 15	3.7	4 3 1 2	8.6	28.69
0.8	11 5 17 3 14 16 2	9.6	12 1 10 9 18	-3.2	10 19 8	0.4	13 7 6 4 15	-1.2	4 3 1 2	3.4	7.32
0.9	16 11 14 5 2 3 17	-5.6	12 1 18 9 10	-9.4	8 20 19	-2.4	13 7 6 4 15	-6.1	4 3 1 2	-1.8	-18.25
1.0	5 16 14 2 3 17 11	-20.0	18 10 12 9 1	-18.0	8 20 19	-6.0	13 15 7 6 4	-13.0	2 4 3 1	-8.0	-47.9

Table 6.2c: Layout for 5-cell solution of table 5.27 using **MUCH**

	Cell 1		Cell2		Cell 3		Cell 4		Cell 5		Inter cell		Objective value
Machines	5,11,13,14,16,17		8,19,20		4,6,7,15		1,9,10,12,18		2,3				
Parts	6,7,11,15,19		3,10,18		5,8,13,16		1,9,12,14,17,20		2,4				
W_1	Layout	IM^1	Layout	IM^2	Layout	IM^3	Layout	IM^4	Layout	IM^5	Layout	IC	z
0.0	16 17 5 14 13 11	64.0	20 19 8	22	15 7 4 6	32.0	18 12 10 9 1	41.0	3 2	8.0	4 1 5 2 3	64	180.9
0.1	16 17 5 14 13 11	56.0	20 8 19	19.2	6 7 4 15	28.1	18 9 10 12 1	35.5	3 2	7.0	4 1 5 2 3	56.6	158.66
0.2	16 17 5 14 13 11	48.0	20 8 19	16.4	6 7 4 15	24.2	18 9 10 12 1	30.0	3 2	6.0	4 1 5 2 3	49.2	136.42
0.3	16 17 5 14 13 11	40.0	20 8 19	13.6	6 7 4 15	20.3	18 9 10 12 1	24.5	3 2	5.0	4 1 5 2 3	41.8	114.18
0.4	16 17 5 14 13 11	32.0	20 8 19	10.8	6 7 4 15	16.4	18 9 10 12 1	19.0	3 2	4.0	4 1 5 2 3	34.4	91.94
0.5	16 17 5 14 13 11	24.0	20 19 8	8	6 7 4 15	12.5	18 9 10 12 1	13.0	3 2	3.0	4 1 5 2 3	27.0	69.35
0.6	11 14 5 13 16 17	16.4	20 19 8	5.2	6 7 4 15	8.6	18 9 10 12 1	7.0	3 2	2.0	4 1 5 2 3	19.6	47.04
0.7	11 14 5 13 16 17	7.8	20 8 19	2.4	6 7 4 15	4.7	18 9 10 12 1	1.0	3 2	1.0	4 1 5 2 3	12.2	24.03
0.8	11 14 15 5 13 17	-1.6	20 8 19	-0.4	6 7 4 15	0.8	18 9 10 12 1	-5.0	3 2	0.0	2 4 3 5 1	6.0	1.94
0.9	11 5 17 14 16 13	-10.6	20 8 19	-3.2	6 7 4 15	-3.1	18 9 10 12 1	-11.0	3 2	-1.0	2 3 5 4 1	-0.5	-20.73
1.0	11 5 17 14 16 13	-20.0	20 8 19	-6.0	6 7 4 15	-7.0	18 9 10 12 1	-17.6	3 2	-2.0	4 2 5 1 3	-11.0	-47.4

Table 6.3a: Layout for 5-cell solution of table 5.30 using **MUCH**

	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Inter cell
Machines	1,2,3,10,11,12,21,22,23	4,13,24,27	5,7,15,17,18,26	8,9,19,20,28,29,30	6,14,16,25	
Parts	2,10,11,12,20,23,31,32,33,39,40,41	15,19,24,25,28,35,38	7,14,16,17,27,34,36,37	1,3,8,9,13,21,22,29,30	4,5,6,18,26	
Layout	23 21 12 10 22 3 11 1 2	27 24 4 13	26 17 18 7 15 5	19 29 28 30 9 8 20	25 14 6 16	4 2 1 3 5
IM/IC	4651	271	1181	1882	288	983
Z	6774.1					

Table 6.3b: Layout for 6-cell solution of table 5.30 using **MUCH**

	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Inter cell
Machines	8,9,19,20,29,30	4,6,14,16,25,27,28	5,7,15,17,18,26	3,22	13,24	1,2,10,11,12,21,23	
Parts	1,3,9,13,21,22,29,30	4,5,6,8,15,18,24,25,26,28,35	7,14,16,17,27,34,36,37	23,40	19,38	2,10,11,12,20,31,32,33,39,41	
Layout	29 19 30 9 8 20	16 14 25 4 28 27 6	26 17 18 7 15 5	3 22	13 24	11 12 23 2 21 10 1	3 6 4 1 2 5
IM/IC	1617	858	1181	503	120	2623	1440
Z	6271.4						

Table 6.3c: Layout for 7-cell solution of table 5.30 using **MUCH**

	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Inter cell
Machines	1,3,22	2,10,11,12,21,23	14,25	4,6,8,16,27,28	5,7,15,17,18,26	9,19,20,29,30	13,24	
Parts	10,23,31, 32,40	2,11,12,20,33, 39,41	4,5,18	6,8,15,24,26, 28,29,35	7,14,16,17,27, 34,36,37	1,3,9,13,21, 22,30	19,25,38	
Layout	22 3 1	23 10 11 12 21 2	14 25	6 28 8 16 4 27	26 17 18 7 15 5	29 19 30 9 20	13 24	5 4 6 1 2 3 7
IM/IC	713	1986	78	720	1181	1439	120	2021
Z	6386.9							

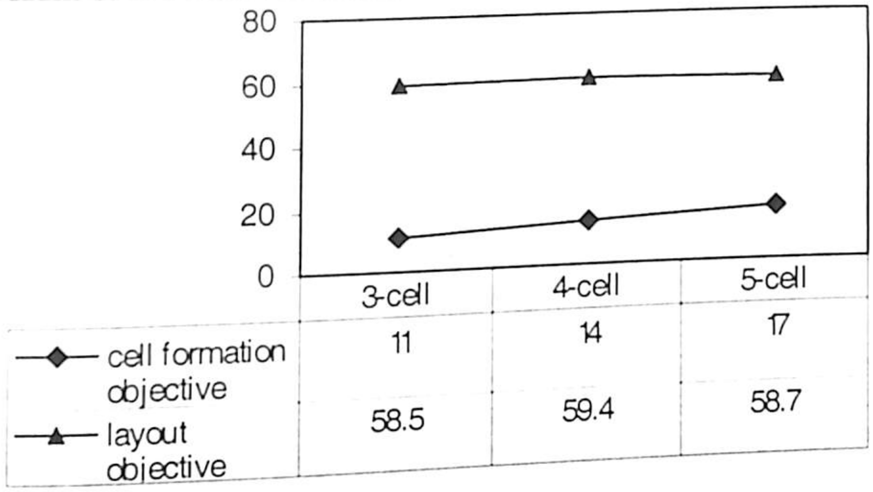


Figure 6.2a

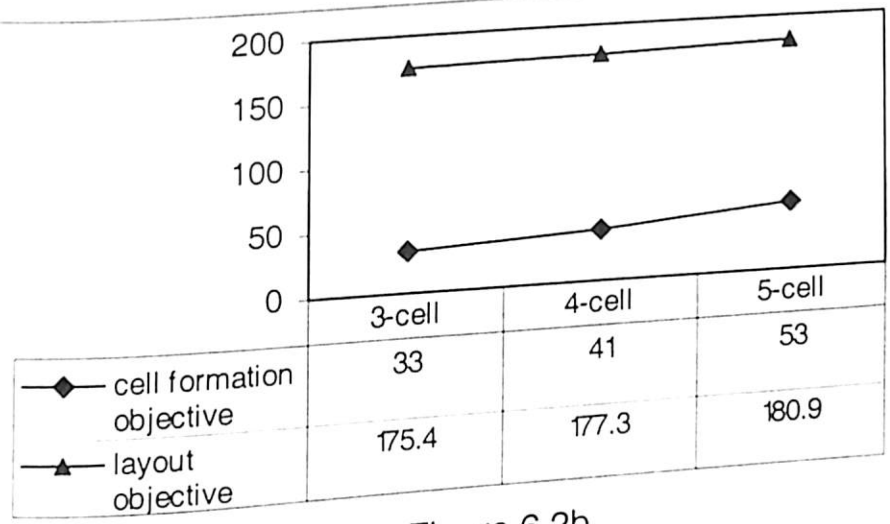


Figure 6.2b

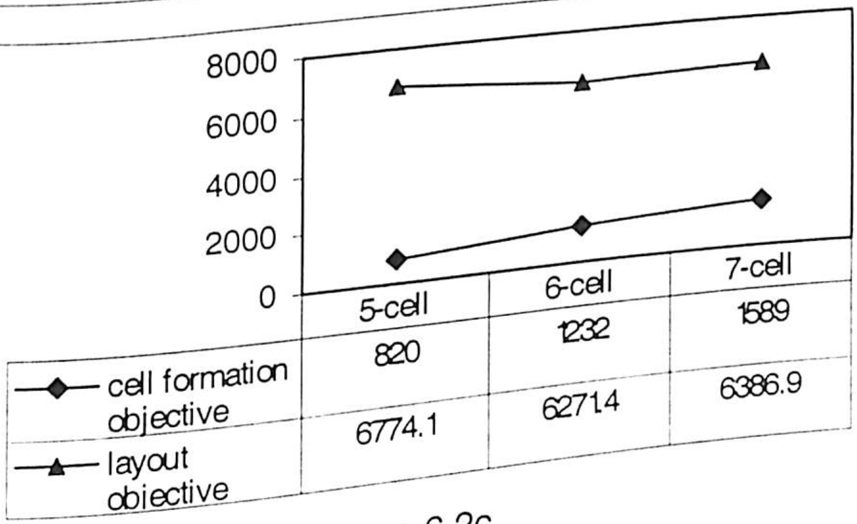


Figure 6.2c

Figure 6.2: Comparison of cell formation objective (chapter 5) and layout objective using MUCH

6.5 Development of GA based Multi-criteria Model (FUGEN) for Layout of CMS

One of the real difficulties in using qualitative factors for layout design is the natural vagueness associated with these factors (Evans *et al.* 1987, Dweiri and Meier 1996) as these factors are based on the judgments of experts who decide the relationship between each pair of facilities. The decision is usually based on many qualitative considerations and is vague in nature. The use of fuzzy methodologies is one approach for handling inexact and vague data and yet to work in mathematically strict and rigorous way (Kickert 1978, Karwowski and Mital 1986). In this, fuzzy set theory is used which provides a framework for modeling vague systems and allows for the treatment of uncertainty to derive closeness rating. Further, practically, all qualitative factors shall not have equal importance. Therefore, Analytic Hierarchy Process (AHP) in combination with fuzzy logics will be used to assign the different weightage to the qualitative factors between each pair of facilities (activities) to make the layouts more practical as well as to check the consistency of the designer.

Sirinaovakul and Thajchayapong (1994) emphasized that the conventional heuristic techniques do not consider enough possible outcomes in the solution process to arrive at the optimal point, and are very sensitive to the initial solution. In this context random search techniques of simulated annealing (Kirkpatrick *et al.* 1983) and genetic algorithms (Goldberg 1989, Holland 1975) are promising candidates for facility layout design. The basic difference between simulated annealing (SA) and genetic algorithms (GA) is that GA always works with the population of solutions while SA works on one solution at a time. This inherent parallelism allows it to exploit information over a large area of the search space with relatively less computational effort. Tate and Smith (1995), Suresh *et al.* (1995), Islier (1998), Hamamoto and Salvendy (1999), Rajasekharan *et al.* (1998), Kochhar and Heragu (1998), and Al-Hakim (2000) have used genetic algorithms to solve traditional facility layout problem.

6.5.1 Introduction to genetic algorithms

Genetic algorithms are random probabilistic search techniques. They emulate the natural process of evolution and hereditary by processing towards the optimum (A-Sultan *et al.* 1996). The process of evolution and adaptation of individuals in nature is based on the Darwin's 'survival of fittest' principle wherein the *stronger (fitter)* individuals are more likely to survive in their environment than the *weaker* individuals. As a result, they can live longer and reproduce more often, generating new generations even stronger than themselves. Holland (1975) showed that a computer simulation of this process of natural adaptation could be employed for solving optimisation problems. Goldberg (1989), and Liepins and Hilliard (1989) give detailed insight into different aspects of the genetic algorithms. In genetic algorithms the population, selection policy, genetic operators, and termination criteria play important role in providing efficient solutions to large combinatorial optimization problems at a very low computational cost.

Population

The search technique consists of generating an initial population at random. The population is a subset of the total solution space at any instant of the solution process. Any feasible solution of the problem called chromosome is an element of the population. Chromosomes (strings) are combinations of symbols, known as genes, which represent the individual characteristics of the chromosome. The successive generations (children) of the population are generated from the current population (parents) by a process known as *selection*.

Selection for reproduction

The selection criteria most commonly implemented in GA is based on the roulette wheel method, which chooses an individual based on the magnitude of its fitness value relative to the rest of the population and good parents gets higher probability of being selected for reproduction than poor parent. Fitness value of a chromosome (solution) is its objective value determined using a mathematical function that maps a particular solution onto a single positive number that is a measure of the solution's worth. The probability of an individual *i* being selected to be reproduced can be expressed as follow:

$$P^i = \frac{F_i}{\sum_{j=1}^{N} F_j}$$

where, F_i is fitness value of individual *i* and N is the number of individuals in the population. Based on the probability, the genetic operators are applied to create a new population.

Genetic operators

Two classical operators most commonly used are crossover and mutation operators. The exploration of search space is critically dependent on the genetic operators (Suresh *et al.* 1995). The crossover operator operates on two chromosomes and generates the offspring. Crossover is the exchange of sub-strings between selected parents. Since it is an inheritance mechanism, the offspring inherits some characteristics of the parents (Islier 1998). The standard crossover operators usually applied are the simple crossover (figure 6.3a), the partially matched crossover (PMX), the order crossover (OX), and the cyclic crossover (CX) (Goldberg 1989). Other types of crossover can be used depending on the specific applications as in Tate and Smith (1995) and Al-Hakim (2000). Mutation operator (figure 6.3b) makes random changes to one or more elements in a solution string. According to Goldberg (1989), when sparingly used with reproduction and crossover, it is an insurance against premature loss of important notions. Austin (1989) suggested some advanced strategies to increase the efficiency of genetic algorithms. One of these strategies - elitism is employed to prevent destruction of the good solutions by genetic operators. The best solution of each population is copied to the following generation.

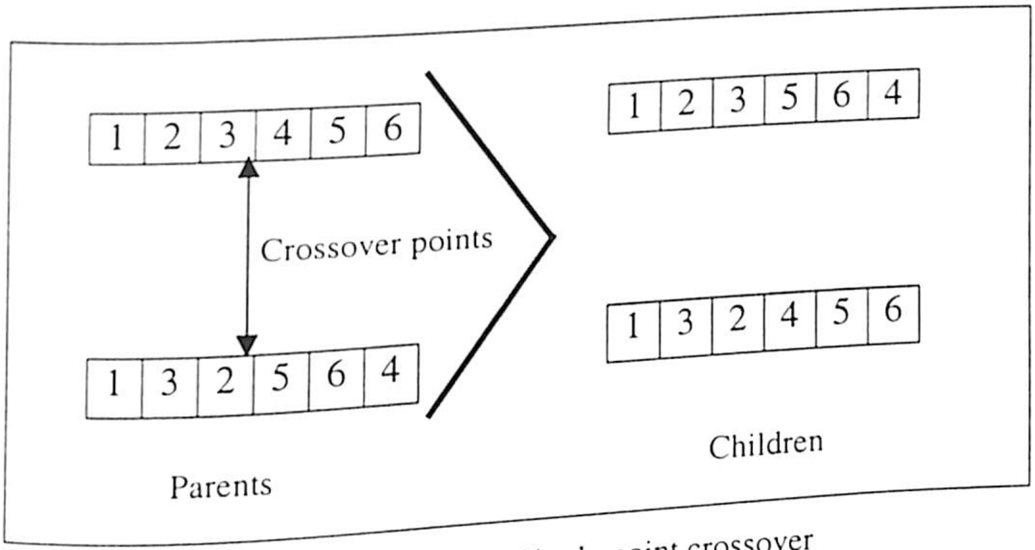


Figure 6.3a: Single point crossover

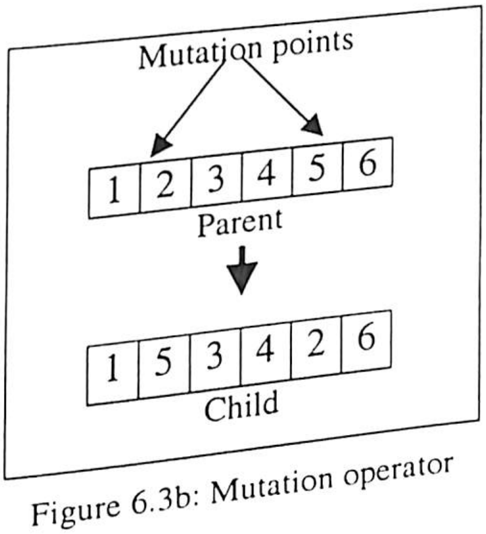


Figure 6.3b: Mutation operator

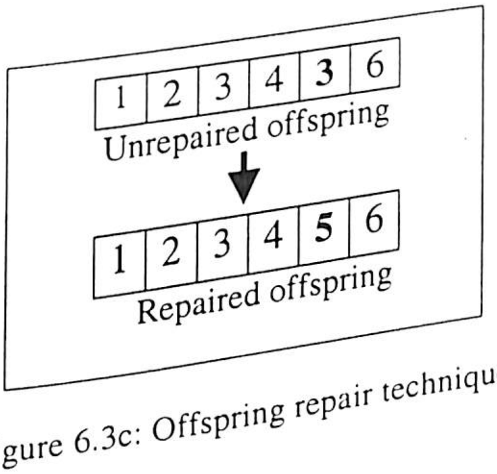


Figure 6.3c: Offspring repair technique

Palmer and Kershenbaum (1995) and Islier (1998) pointed to the fact that classical crossover and mutation operators may produce infeasible solutions. The central problem in the application of genetic algorithms is constraint handling (Michalewicz 1994, Glover and Greenberg 1989). Some constraints and operators, to maintain the structure and feasibility of solutions, are needed to check infeasible solutions (Al-Hakim 2000). Four basic constraint-handling techniques are (Michalewicz *et al.* 1996, Eiben *et al.* 1995):

i) Filtering/Rejecting: check the feasibility of each generated offspring and eliminate those that are not allowed. Used by Tam and Chan (1998).

ii) Penalizing: Homaifar *et al.* (1994) proposed a method based on multi-level assignment of penalty factors. Here, a stepwise increasing penalty function depending on severity of violation is employed. Coit and Smith (1996) suggested a technique where an adaptive penalty function learns to adapt itself based on the severity of the constraints of a particular problem.

iii) Repairing: modify the candidates that are not feasible. Islier (1998) provided repairing procedure based on the concept of 'replace the foremost reoccurrence with the foremost vacancy' (figure 6.3c).

iv) Preserving: use the specific operators that produce feasible offspring from feasible parents. An inversion operator was presented by Islier (1998) to be used with classic crossover and mutation operators to produce feasible offspring.

Termination criteria

There are two commonly used termination criteria to stop the search. The first one takes into account the fitness of all the individual chromosomes of the population to determine if the GA has converged to certain value. The second one stops the search when a user specified number of generations are reached.

6.5.1 Determination of closeness rating using fuzzy logic and AHP

The methodology of determining closeness rating using fuzzy logic and AHP is given below:

Step 1: The first step is the variable (qualitative factors and weight factors) fuzzification.

a) Define all the qualitative variables that can influence the closeness rating. Determine the value of qualitative variables for each pair of facilities; define the membership functions and the linguistic variables (see figure 6.4). The membership functions are developed using expert's knowledge, interviews of involved people and/or past history of facilities layout. However in this model the values of the qualitative variables are chosen arbitrarily on a scale of 0 to 100. In the actual design process, the designer has to collect the data and define the proper membership functions for various variables.

b) Determine weight factors for each pair of facilities (activity) using AHP. The AHP precedure is given in chapter 3. Next, define the membership function and linguistic variables for the weight factors (see figure 6.5). At this point, the fuzzification is complete.

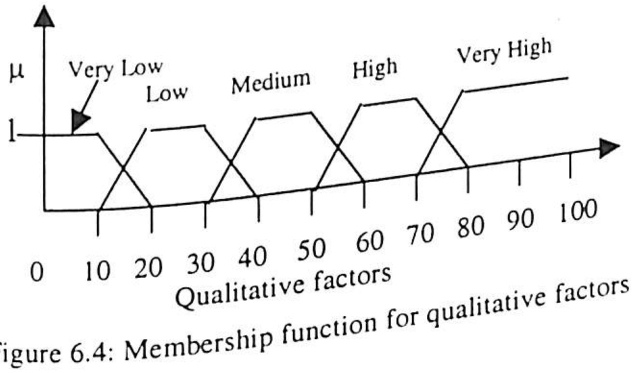


Figure 6.4: Membership function for qualitative factors

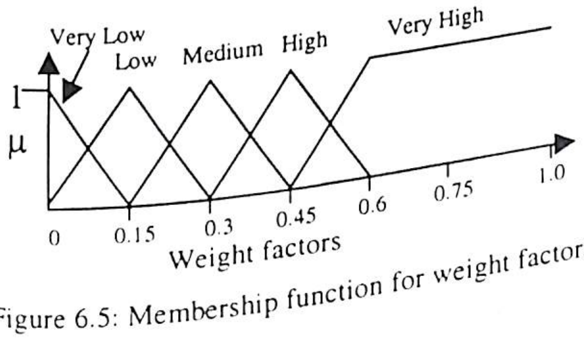


Figure 6.5: Membership function for weight factors

Step 2: Establish the decision making logic or decision rules. These rules usually take the form of IF-THEN rules. These rules imitate the designer's decision and are conveniently tabulated in look-up tables (see table 6.4a, 6.4b, and 6.4c). The Minimum operator (Mamdani and Assilian 1975, Mamdani 1976), i.e., the membership function of the closeness rating for each decision is the minimum value of the input variable's membership function, will be used as shown below:

$$\mu^{label}_{closeness\ rating} = Minimum\{\mu^{label}_{input_1 value} \ldots\ldots \mu^{label}_{input_2 value}\}$$

Table 6.4a: Decision rules for QF_1

QF/WF	VL	L	M	H	VH
VL	U	U	O	O	I
L	U	O	O	I	E
M	O	O	I	E	E
H	O	I	E	E	A
VH	I	E	E	A	A

Table 6.4b:Decision rules for QF_2

QF/WF	VL	L	M	H	VH
VL	U	U	U	O	O
L	U	U	O	O	I
M	U	O	O	I	E
H	O	O	I	E	A
VH	O	I	E	A	A

Table6.4c: Decision rules for QF_3

EF/WF	VL	L	M	H	VH
VL	U	U	O	I	I
L	U	O	I	I	E
M	O	I	I	E	E
H	I	I	E	E	A
VH	I	E	E	A	A

Step 3: Next, find the crisp (exact) values of the closeness rating (defuzzification) by centre of area method (Lee 1990) as shown below:

$$R_0 = \frac{\sum_i \mu_R^g \times R}{\sum_i \mu_R^g}$$

Where : R_o = the final crisp rating of the activity.

i = the rules used in the activity.

R = the numerical rating of the activity of the rule.

μ_R^g = membership value of the activity for rule.

These values of closeness rating can be used to develop a more efficient layout. An illustrative calculation of closeness rating, for the layout of six machines in a cell, using fuzzy logic and AHP is given below:

Step1: Consider an example of assigning six facilities to six locations. The qualitative data and the desired relative importance for each pair of facilities are given in table 6.5.

Table 6.5: The qualitative data and the desired relative importance

Activity	Qualitative factor 1 (QF1)	Qualitative factor 2 (QF2)	Qualitative factor3 (QF3)	Intensity Importance of factors		
				1over2	1over3	2over3
1-2	75.00	0.00	15.00	1/4	1	4
1-3	50.00	0.00	25.00	1/4	1	3
1-4	83.00	0.00	35.00	1/4	1	4
1-5	92.00	0.00	65.00	1/3	1	4
1-6	24.00	0.00	0.00	1	1	1
2-3	20.00	25.00	20.00	1/2	1	3
2-4	87.00	50.00	75.00	2	5	2
2-5	60.00	90.00	95.00	2	3	1
2-6	75.00	0.00	0.00	1	1	1/2
3-4	0.00	15.00	10.00	2	5	1
3-5	0.00	85.00	50.00	1/2	1	3
3-6	0.00	20.00	0.00	3	1	1/5
4-5	9.00	65.00	20.00	3	2	1/3
4-6	15.00	50.00	70.00	1/2	1	3
5-6	10.00	25.00	50.00	2	3	1

Step2.1: The weight factors determined using AHP for all pair of facilities are shown in table 6.6. Table 6.7 illustrates a sample calculation for activity 2-4.The weight factors for QF_1, QF_2 and QF_3 are 0.59, 0.28 and 0.13 respectively.

Table 6.6: Weight factors for qualitative factors determined using AHP

1over2	1over3	2over3
0.17	0.67	0.17
0.17	0.63	0.19
0.17	0.67	0.17
0.19	0.63	0.17
0.33	0.33	0.33
0.33	0.33	0.33
0.59	0.28	0.13
0.50	0.25	0.25
0.33	0.33	0.33
0.25	0.25	0.50
0.33	0.33	0.33
0.26	0.33	0.41
0.33	0.41	0.26
0.41	0.33	0.26
0.41	0.26	0.33

Table 6.7: Sample weight factors using AHP

	QF_1	QF_2	QF_3	PV
QF_1	1	2	5	0.59
QF_2	½	1	2	0.28
QF_3	1/5	½	1	0.13

Step 2.2: Fuzzification of weight factors: The weight factor 0.59 belongs to fuzzy subset *very high* with a membership value of 0.966 (see figure 6.5). Similarly, 0.28 and 0.13 belong to fuzzy subsets *medium* and *low* with membership values of 0.844 and 0.856 respectively.

Step 2.3: Fuzzification of qualitative factors: QF_1, QF_2 and QF_3 have values of 87, 50 and 75 respectively (table 6.5). The linguistic variables and membership values for these qualitative factors are *Very High* with 1.0, *Medium* with 1.0 and *High* with 0.5 respectively (see figure 6.4). (in case of a tie choose the lower linguistic variable)

Step 2.4: When this process is completed for all pairs of facilities, IF-THEN decision rules are developed. The IF-THEN rules for the activity 2-4 framed using tables 6.4a, 6.4b, and 6.4c are:

Rule 1: IF QF_1 is *Very High* and its weight factor is *Very High* THEN rating is 'A'

Rule 2: IF QF_2 is *Medium* and its weight factor is *Medium* THEN the rating is 'O'

Rule 3: IF QF_3 is *High* and its weight factor is *Low* THEN the rating is 'I'

Step 2.5: Using the minimum operator; Rule1 results in rating of 'A' with membership value of 0.966 (Minimum {1, 0.966}). Similarly, Rule 2 results in rating of 'O' with membership value of 0.844, and Rule 3 results in rating of 'I' with membership value of 0.5.

Step 2.6: The crisp value for activity 2-4 using the Centre of Area (COA) method is:

$$\frac{6 \times 0.966 + 3 \times 0.844 + 4 \times 0.5}{0.966 + 0.844 + 0.5} = 4.47$$

This process is repeated for all activities (pair of facilities) and subsequently the closeness rating matrix generated is shown in table 6.8. These fuzzy closeness ratings will be used to compute the fitness function (objective value) in the genetic algorithm.

Table 6.8: Fuzzy closeness rating matrix

Activity ▶ ▼	1	2	3	4	5	6
1	-	3.00	3.00	3.74	3.89	2.67
2	-	-	3.35	4.47	5.35	3.50
3	-	-	-	2.85	4.38	3.02
4	-	-	-	-	3.35	4.09
5	-	-	-	-	-	3.67
6	-	-	-	-	-	-

6.5.3 Algorithm of GA based multi-criteria (FUGEN) model

GA based multi-criteria model (FUGEN) for layout of CMS is developed based on the formulation of multi-criteria mathematical formulation, which is developed in the section 6.3. The algorithm of FUGEN model is given below and the flow chart is shown in figure 6.6.

```
Step 1.1: Input the number of cells (C) and machines and parts therein, probability of
          crossover ($P_X$), probability of mutation ($P_M$), $w_1$, number of qualitative factors,
          maximum number of generations ($GEN^{max}$), and number of strings/chromosomes
          (S) in each generation.
Step 1.2: Read demand, transfer batch size and operation sequence of parts
Step 2.1: Set $x=1$
Step 2.2: Randomly generate an initial population (the length of chromosome and the
          value of genes should be between one and number of facilities), set $GEN=1$
Step 2.3: Set $s=1$
Step 3:   Compute objective value ($IM^x$), update $s=s+1$
Step 4:   If $s<S$, go to step 3, else go to step 5
Step 5:   Arrange the strings (chromosomes) in ascending order of objective values
Step 6:   Compute average objective value ($\overline{IM'}$), set $s=1$
Step 7:   Compute Roulette values (Rou) of all strings
Step 8:   Generate a random number (RN) between 0 and 0.99
Step 9:   If $RN<P_M$ go to step 10, else if $RN<P_X$ go to step 11, else go to step 12
Step 10:  Generate random number (RN) between minimum and maximum Roulette value
          ($R^{min}$ and $R^{max}$)
Step 10.1: Accept string $s$ for mutation such that the RN lies between the Roulette values
           of $s^{th}$ and $s+1^{th}$ strings
Step 10.2: Generate two random numbers ($RN_1$ and $RN_2$) between 1 and $n$ for mutation.
Step 10.3: Exchange the genes occupied by $RN_1$ and $RN_2$
Step 10.4: If $IM^x<\overline{IM'}$, accept the string for the new generation, update $s=s+1$ and go to
           step 13, else go to step 8
```

```
Step 11: Generate random number (RN) between minimum and maximum Roulette value ($R^{min}$ and $R^{max}$)
Step 11.1: Accept string $s$ for crossover such that the RN lies between the Roulette values of $s$ and $s+1$ strings
Step 11.2: Similarly select one more string for crossover
Step 11.3: Generate random number (RN) between 1 and $n-1$ for crossover
Step 11.4: Crossover at RN to get children $s_{x1}$ and $s_{x2}$
Step 11.5: If offspring is not feasible (repetition of genes) go to step 11.6, else go to step 11.7
Step 11.6 Repair strings using concept of 'replace the foremost reoccurrence with the foremost vacancy'
Step 11.7: Compute objective values ($IM^{x}_{x1}$ and $IM^{x}_{x2}$) of strings
Step 11.8: If $IM^{x}_{x1} < \overline{IM'}$, accept string $s_{x1}$, update $s=s+1$, else reject string $s_{x1}$
Step 11.9: If $IM^{x}_{x2} < \overline{IM'}$, accept string $s_{x2}$, update $s=s+1$ and go to step 13, else reject string $s_{x2}$ and go to step 8
Step 12: If $IM^{x} < \overline{IM'}$, accept the string for the new generation, update $s=s+1$ and go to step 13, else go to step 8
Step 13: If $s<S$ go to step 8, else go to step 14
Step 14: If $GEN=GEN^{max}$ or $IM^{x}_{1}= IM^{x}_{2}= \ldots =IM^{x}_{S}$ go to step 15, else $GEN=GEN+1$, compute objective values and go to step 5
Step 15: Store $IM^{x}_{minimum}$ and layout
Step 16: If $x<C$, $x=x+1$ and go to step 2.2, else go to step 17
Step 17: Compute and store IM
Step 18: Randomly generate an initial population, set $GEN=1$
Step 19: Set $s=1$
```

```
Step 20: Compute objective value (IC), update $s=s+1$
Step 21: If $s<S$, go to step 20, else go to step 22
Step 22: Arrange the strings (chromosomes) in ascending order of objective values
Step 23: Compute average objective value ($\overline{IC}$), set $s=1$
Step 24: Compute Roulette values of all strings
Step 25: Generate a random number (RN) between 0 and 0.99
Step 26: If $RN<P_M$ go to step 27, else if $RN<P_X$ go to step 28, else go to step 29
Step 27: Generate random number (RN) between minimum and maximum Roulette value ($R^{min}$ and $R^{max}$)
    Step 27.1: Accept string $s$ for mutation such that the RN lies between the Roulette values of $s$ and $s+1$ strings
    Step 27.2: Generate two random numbers ($RN_1$ and $RN_2$) between 1 and $C$ for mutation.
    Step 27.3: Exchange the genes occupied by $RN_1$ and $RN_2$
    Step 27.4: If $IC<\overline{IC}$, accept the string for the new generation, update $s=s+1$ and go to step 30, else go to step 25
Step 28: Generate random number (RN) between minimum and maximum Roulette value ($R^{min}$ and $R^{max}$)
    Step 28.1: Accept string s for crossover such that the RN lies between the Roulette values of $s^{th}$ and $s+1^{th}$ strings
    Step 28.2: Similarly select one more string for crossover
    Step 28.3: Generate random number (RN) between 1 and $C-1$ for crossover
    Step 28.4: Crossover at RN
    Step 28.5: If offspring is not feasible (repetition of genes) go to step 28.6, else go to step 28.7
```

Step 28.6: Repair strings using concept of 'replace the foremost reoccurrence with the foremost vacancy'

Step 28.7: Compute objective values (IC_{x1} and IC_{x2}) of strings

Step 28.8: If $IC_{x1}<\overline{IC}$, accept string s_{x1}, update $s=s+1$, else reject string s_{x1}

Step 28.9: If $IC_{x2}<\overline{IC}$, accept string s_{x2}, update $s=s+1$ and go to step 30, else reject string s_{x2} and go to step 25

Step 29: If $IC<\overline{IC}$, accept the string for the new generation, update $s=s+1$ and go to step 30, else go to step 25

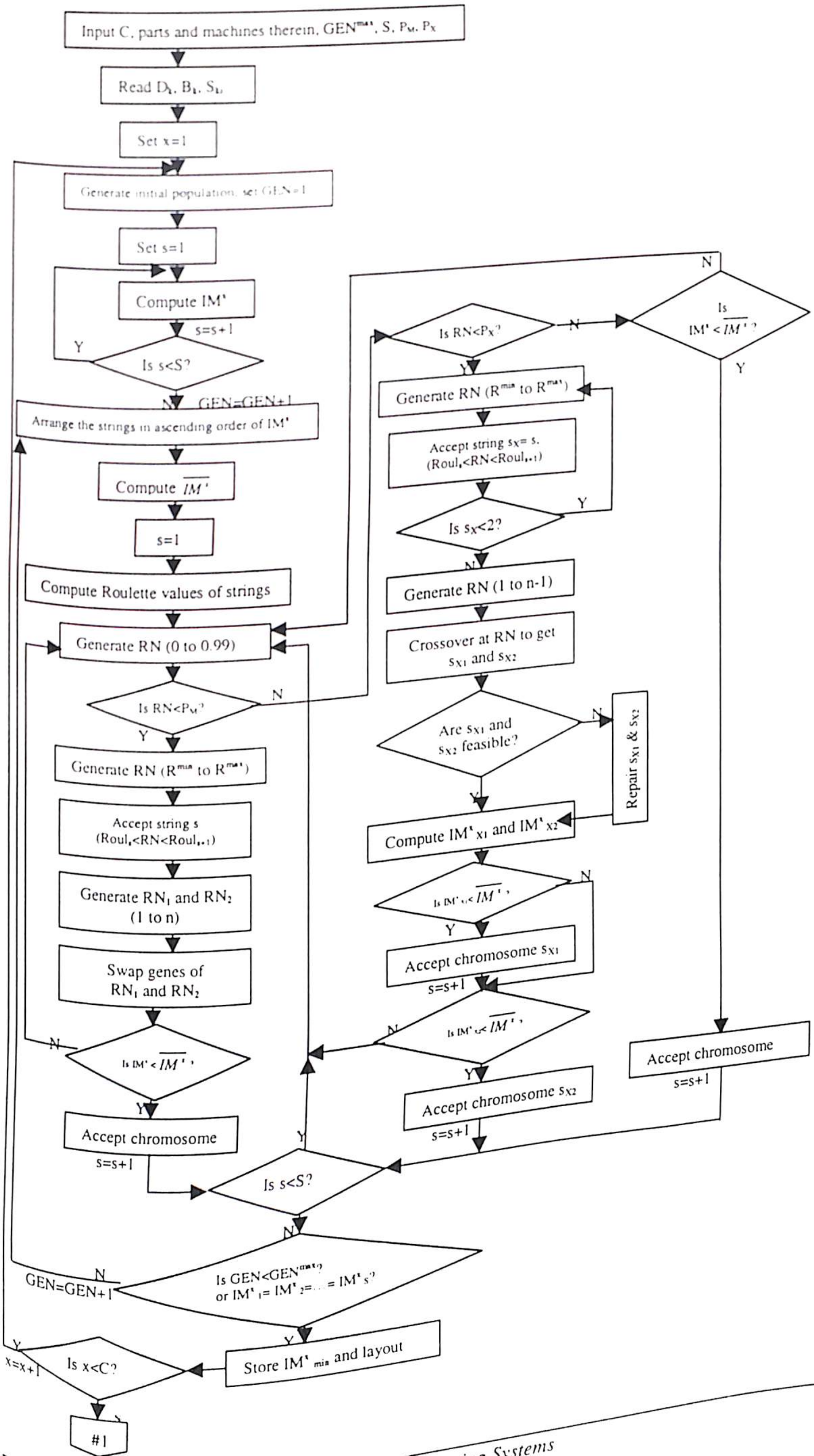
Step 30: If $s<S$ go to step 25, else go to step 31

Step 31: If $GEN=GEN^{max}$ or $IC^{x}_{1}= IC^{x}_{2}= \ldots =IC^{x}_{s}$ go to step 32, else $GEN=GEN+1$, compute objective values and go to step 22

Step 32: Store $IC_{minimum}$ and layout

Step 33: Compute and store z

Step 34: Stop


Input C, parts and machines therein, GEN^{max}, S, P_M, P_X
Read D_{ij}, B_{ij}, S_{ij}
Set x=1
Generate initial population, set GEN=1
Set s=1
Compute IM^s
s=s+1
Y
Is s<S?
N
GEN=GEN+1
Arrange the strings in ascending order of IM^s
Compute $\overline{IM^s}$
s=1
Compute Roulette values of strings
Generate RN (0 to 0.99)
Is $RN<P_M$?
N
Y
Generate RN (R^{min} to R^{max})
Accept string s ($Roul_s<RN<Roul_{s+1}$)
Generate RN_1 and RN_2 (1 to n)
Swap genes of RN_1 and RN_2
N
Is $IM^s < \overline{IM^s}$?
Y
Accept chromosome
s=s+1
Is $RN<P_X$?
N
Y
Generate RN (R^{min} to R^{max})
Accept string s_X= s. ($Roul_s<RN<Roul_{s+1}$)
Y
Is s_X<2?
N
Generate RN (1 to n-1)
Crossover at RN to get s_{X1} and s_{X2}
Are s_{X1} and s_{X2} feasible?
N
Y
Repair s_{X1} & s_{X2}
Compute IM^s_{X1} and IM^s_{X2}
Is $IM^s_{X1}< \overline{IM^s}$?
N
Y
Accept chromosome s_{X1}
s=s+1
Is $IM^s_{X2}< \overline{IM^s}$?
N
Y
Accept chromosome s_{X2}
s=s+1
N
Is $IM^s < \overline{IM^s}$?
Y
Accept chromosome
s=s+1
Y
Is s<S?
N
Is GEN<GEN^{max}? or $IM^s_1 = IM^s_2 = \dots = IM^s_S$?
N
GEN=GEN+1
Y
Store IM^s_{min} and layout
Y
x=x+1
Is x<C?
N
#1

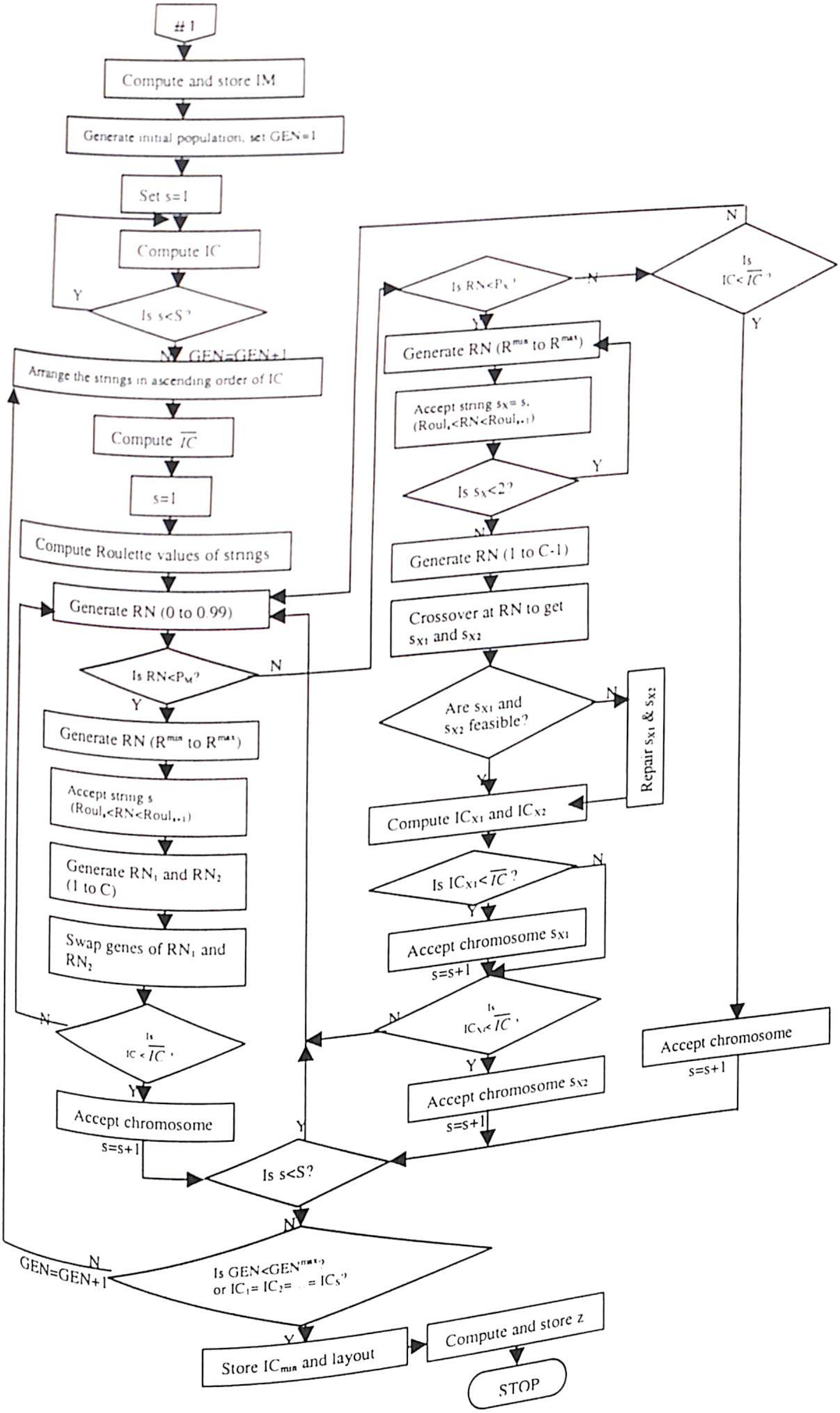


Figure 6.6: Flowchart of the FUGEN model

6.5.4 Validation

This model is also validated for the same problems as MUCH model is validated. All the assumptions are same except that the initial layouts are not required in this model as these are being generated randomly in GA.

Like MUCH model, the layout designs (tables 6.9, 6.10, and 6.11) by this model also show that the best solutions (cells formed) in chapter 5 need not to be the best if layout is considered. As shown in figures 6.7a and 6.7b, the best solutions without considering layout is 3-cell solution but 4-cell solution is best when the layout is considered (w_1=0). For example 4 (table 5.28), as shown in figure 6.7c, the best solution without considering layout is 5-cell solution but 7-cell solution is best when the layout is considered (w_1=0).

It should also be noted that the proposed model could also be used for design of functional layouts just by specifying the number of cells as one during data input. Hence, the model is capable of evaluating cellular layouts vis-à-vis functional layouts. If the designer has any uncertainty in quantitative data then fuzzy logics can also be used to treat this. This can be done by treating the quantitative data generated as qualitative data. For doing this, algorithm is to be run twice, first to get the generated quantitative data and then based on this data select the proper fuzzy membership function and importance. Next the designer should input this as qualitative data and run the algorithm by specifying the weightage for the qualitative factor (w_1=1) as unity. The quantitative data is generated by solving equation 2.2 (intra-cell) and equation 3.1 (inter-cell).

Table 6.9a: Layout for 3-cell solution of table 5.26 using ***FUGEN***

	Cell 1		Cell2		Cell 3		Inter cell		Objective value
Machines	2,3,5,11,14,16,17		4,6,7,13,15		1,8,9,10,12,18,19,20				
Parts	2,4,6,7,11,15,19		5,8,13,16		1,3,9,10,12,14,17,18, 20				
W_1	Layout	IM^1	Layout	IM^2	Layout	IM^3	Layout	IC	Z
0.0	16 14 3 17 11 2 15	21	7 15 4 6 13	11	12 1 9 8 10 18 19 20	25	3 2 1	13	52.9
0.1	5 17 16 11 3 14 2	17.22	15 7 6 4 13	18.17	18 20 19 9 10 8 1 12	21.4	3 2 1	11.07	43.82
0.2	16 14 3 17 11 2 5	11.75	15 7 6 4 13	5.33	12 1 9 8 10 18 19 20	14.08	3 2 1	9.14	30.95
0.3	5 11 2 16 14 3 17	6.52	15 7 6 4 13	2.5	12 1 9 8 10 18 19 20	8.61	3 2 1	7.21	19.55
0.4	16 14 3 17 11 2 5	2.50	13 7 6 4 15	-0.33	12 1 9 8 10 18 20 19	3.09	3 2 1	5.28	8.92
0.5	16 14 3 17 11 2 5	-2.12	15 7 6 4 13	-3.17	12 1 9 8 10 18 20 19	-2.64	3 2 1	3.35	-2.2
0.6	11 5 17 3 14 16 2	-6.96	15 7 6 4 13	-6	12 1 9 8 10 18 20 19	-8.27	3 2 1	1.42	-13.51
0.7	5 17 16 11 3 14 2	-11.43	15 7 6 4 13	-8.83	12 1 9 8 10 18 19 20	-14	3 2 1	-0.51	-24.49
0.8	16 14 5 17 3 11 2	-16.71	15 7 6 4 13	-11.67	9 18 1 19 10 12 20 8	-19.83	3 2 1	-2.44	-36.19
0.9	16 14 5 17 3 11 2	-22.3	13 7 15 4 6	-14.69	10 18 8 19 1 12 20 9	-26.66	2 1 3	-4.88	-49.03
1.0	16 14 5 17 3 11 2	-27.97	6 13 4 15 7	-17.82	10 19 9 18 1 20 8 12	-34.29	2 1 3	-6.87	-62.93

Table 6.9b: Layout for 4-cell solution of table 5.26 using **FUGEN**

	Cell 1		Cell2		Cell 3		Cell 4		Inter cell		Objective value
Machines	2,3,5,11,14,16,17		1,9,10,12,18		8,19,20		4,6,7,13,15				
Parts	2,4,6,7,11,15,19		1,9,12,14,17,20		3,10,18		5,8,13,16				
W_1	Layout	IM^1	Layout	IM^2	Layout	IM^3	Layout	IM^4	Layout	IC	Z
0.0	16 14 3 17 11 2 15	21	9 1 12 18 10	13	20 19 8	7.0	7 15 4 6 13	11	3 2 4 1	16	52.4
0.1	5 17 16 11 3 14 2	17.22	9 1 12 18 10	9.95	20 8 19	5.67	15 7 6 4 13	18.17	4 3 1 2	13.27	41.97
0.2	16 14 3 17 11 2 5	11.75	9 1 12 18 10	6.90	20 19 8	4.34	15 7 6 4 13	5.33	2 1 3 4	10.54	30.36
0.3	5 11 2 16 14 3 17	6.52	10 1 12 18 9	3.85	20 19 8	3.01	15 7 6 4 13	2.5	4 3 1 2	7.81	18.92
0.4	16 14 3 17 11 2 5	2.50	9 1 12 18 10	0.80	20 8 19	1.679	13 7 6 4 15	-0.33	1 4 2 3	5.07	8.32
0.5	16 14 3 17 11 2 5	-2.12	9 1 12 18 10	-2.25	20 8 19	0.35	15 7 6 4 13	-3.17	4 1 3 2	2.34	7.37
0.6	11 5 17 3 14 16 2	-6.96	9 1 12 18 10	-5.3	20 8 19	-0.98	15 7 6 4 13	-6	3 4 2 1	-0.39	-13.86
0.7	5 17 16 11 3 14 2	-11.43	9 1 12 18 10	-8.35	19 8 20	-2.41	15 7 6 4 13	-8.83	1 4 2 3	-3.12	-24.83
0.8	16 14 5 17 3 11 2	-16.71	9 1 12 18 10	-11.39	19 20 8	-3.89	15 7 6 4 13	-11.67	1 4 2 3	-5.85	-36.41
0.9	16 14 5 17 3 11 2	-22.3	9 1 12 18 10	-14.44	19 20 8	-5.38	13 7 15 4 6	-14.69	2 1 3 4	-8.59	-48.36
1.0	16 14 5 17 3 11 2	-27.97	9 1 12 18 10	-17.82	19 20 8	-6.87	6 13 4 15 7	-17.82	1 4 2 3	-11.32	-60.66

Table 6.9c: Layout for 5-cell solution of table 5.26 using ***FUGEN***

	Cell 1		Cell2		Cell 3		Cell 4		Cell 5		Inter cell		Objective value
Machines	1,9,10,12,18		2,3,11,14		4,6,7,13,15		8,19,20		5,16,17				
Parts	1,9,12,14,17,20		2,4,11,19		5,8,13,16		3,10,18		6,7,15				
W_1	Layout	IM^1	Layout	IM^2	Layout	IM^3	Layout	IM^4	Layout	IM^5	Layout	IC	z
0.0	9 1 12 18 10	13	14 3 11 2	11	7 15 4 6 13	11	20 19 8	7.0	17 16 5	6	2 1 4 5 3	21	54.6
0.1	9 1 12 18 10	9.95	3 14 2 11	8.80	15 7 6 4 13	18.17	20 8 19	5.67	16 17 5	4.71	2 1 4 5 3	17.15	43.26
0.2	9 1 12 18 10	6.90	14 11 3 2	6.596	15 7 6 4 13	5.33	20 19 8	4.34	16 17 5	3.43	2 1 4 5 3	13.3	38.82
0.3	10 1 12 18 9	3.85	14 11 3 2	4.39	15 7 6 4 13	2.5	20 19 8	3.01	16 5 17	2.14	3 1 4 5 2	9.45	20.57
0.4	9 1 12 18 10	0.80	11 2 14 3	2.19	13 7 6 4 15	-0.33	20 8 19	1.679	16 5 17	0.85	3 1 4 5 2	5.6	9.23
0.5	9 1 12 18 10	-2.25	11 14 2 3	-0.01	15 7 6 4 13	-3.17	20 8 19	0.35	16 17 5	-0.43	2 1 4 5 3	1.75	-2.11
0.6	9 1 12 18 10	-5.3	11 2 14 3	-2.21	15 7 6 4 13	-6	20 8 19	-0.98	16 5 17	-1.72	2 1 4 5 3	-2.1	-13.45
0.7	9 1 12 18 10	-8.35	2 3 11 14	-4.42	15 7 6 4 13	-8.83	19 8 20	-2.41	16 17 5	-3.01	3 1 4 5 2	-5.95	-24.86
0.8	9 1 12 18 10	-11.39	11 3 14 2	-6.65	15 7 6 4 13	-11.67	19 20 8	-3.89	16 17 5	-4.29	3 1 4 5 2	-9.79	-36.31
0.9	9 1 12 18 10	-14.44	3 11 2 14	-8.99	13 7 15 4 6	-14.69	19 20 8	-5.38	16 5 17	-5.58	2 1 4 5 3	-13.64	-47.99
1.0	9 1 12 18 10	-17.82	2 14 3 11	-11.32	6 13 4 15 7	-17.82	19 20 8	-6.87	16 17 5	-6.87	2 4 1 5 3	-17.82	-60.31

Table 6.10a: Layout for 3-cell solution of table 5.27 using **FUGEN**

	Cell 1		*Cell2*		*Cell 3*		Inter cell		Objective value
Machines	2,3,5,11,14,16,17		4,6,7,13,15		1,8,9,10,12,18,19,20				
Parts	2,4,6,7,11,15,19		5,8,13,16		1,3,9,10,12,14,17,18,19,20				
W_1	Layout	IM^1	Layout	IM^2	Layout	IM^3	Layout	IC	z
0.0	14 11 2 16 5 3 17	84.0	15 7 6 4 13	38.0	12 1 9 19 10 18 20 8	66	1 3 2	41	172.6
0.1	11 5 17 2 14 16 3	74.88	15 7 6 4 13	32.43	12 8 20 1 10 19 9 18	56.27	1 3 2	36.25	150.7
0.2	14 11 2 16 5 3 17	62.09	15 7 6 4 13	26.86	12 1 9 8 10 18 20 19	46.54	1 3 2	31.51	126.3
0.3	14 11 2 16 5 3 17	51.13	15 7 6 4 13	21.29	12 8 20 1 10 19 9 18	36.81	1 3 2	26.76	103.2
0.4	16 14 3 17 11 2 5	38.46	15 7 6 4 13	15.72	12 1 9 8 10 18 19 20	27.08	1 3 2	22.02	78.83
0.5	14 11 2 16 5 3 17	29.22	15 7 6 4 13	10.15	12 8 20 1 10 19 9 18	17.36	1 2 3	17.27	56.97
0.6	16 14 3 17 11 2 5	16.69	15 7 6 4 13	4.58	12 8 20 1 10 19 9 18	7.63	1 3 2	12.53	32.41
0.7	11 14 5 3 16 17 2	7.88	15 7 6 4 13	-0.99	10 1 12 8 9 18 20 19	-0.44	1 3 2	7.78	12.25
0.8	11 5 17 3 14 16 2	-4.37	15 7 6 4 13	-6.56	12 1 9 10 8 18 19 20	-10.8	1 3 2	3.03	-12.18
0.9	11 5 17 3 14 16 2	-15.92	6 13 4 7 15	-12.19	12 1 9 10 8 18 19 20	-21.4	1 3 2	-1.71	-36.35
1.0	11 17 5 16 3 14 2	-29.14	7 13 4 15 6	-19.34	10 19 9 18 1 20 8 12	-34.29	2 3 1	-6.87	-62.93

Table 6.10b: Layout for 4-cell solution of table 5.27 using ***FUGEN***

	Cell 1		*Cell2*		*Cell 3*		*Cell 4*		Inter cell		Objective value
Machines	*2,3,5,11,14,16,17*		*1,9,10,12,18*		*8,19,20*		*4,6,7,13,15*				
Parts	2,4,6,7,11,15,19		1,9,12,14,17,20		3,10,18		5,8,13,16				
W_1	Layout	IM^1	Layout	IM^2	Layout	IM^3	Layout	IM^4	Layout	IC	Z
0.0	14 11 2 16 5 3 17	84.0	9 1 12 18 10	32.0	20 19 8	22.0	15 7 6 4 13	38.0	1 2 4 3	43.0	167.6
0.1	11 5 17 2 14 16 3	74.88	9 1 12 18 10	26.98	20 19 8	19.18	15 7 6 4 13	32.43	3 4 2 1	37.55	144.9
0.2	14 11 2 16 5 3 17	62.09	10 1 12 18 9	21.95	20 19 8	16.37	15 7 6 4 13	26.86	1 4 2 3	32.11	121.1
0.3	14 11 2 16 5 3 17	51.13	10 1 12 18 9	16.93	20 19 8	13.55	15 7 6 4 13	21.29	4 1 3 2	26.66	98.69
0.4	16 14 3 17 11 2 5	38.46	9 1 12 18 10	11.91	20 19 8	10.73	15 7 6 4 13	15.72	4 3 1 2	21.22	74.99
0.5	14 11 2 16 5 3 17	29.22	9 1 12 18 10	6.89	20 19 8	7.92	15 7 6 4 13	10.15	3 4 2 1	15.77	53.69
0.6	16 14 3 17 11 2 5	16.69	9 1 12 18 10	1.86	20 19 8	5.10	15 7 6 4 13	4.58	3 2 4 1	10.33	30.09
0.7	11 14 5 3 16 17 2	7.88	9 1 12 18 10	-3.16	20 19 8	2.29	15 7 6 4 13	-0.99	1 2 4 3	4.88	9.09
0.8	11 5 17 3 14 16 2	-4.37	9 1 12 18 10	-8.18	20 19 8	-0.53	15 7 6 4 13	-6.56	4 1 3 2	-0.56	-14.3
0.9	11 5 17 3 14 16 2	-15.92	10 1 12 18 9	-13.21	19 20 8	-3.47	6 13 4 7 15	-12.19	1 4 2 3	-6.01	-37.36
1.0	11 17 5 16 3 14 2	-29.14	10 12 1 18 9	-19.34	19 8 20	-6.97	7 13 4 15 6	-19.34	3 4 2 1	-11.46	-63.81

Table 6.10c: Layout for 5-cell solution of table 5.27 using **FUGEN**

	Cell 1		Cell2		Cell 3		Cell 4		Cell 5		Inter cell		Objective value
Machines	*5,11,13,14,16,17*		*8,19,20*		*4,6,7,15*		*1,9,10,12,18*		*2,3*				
Parts	*6,7,11,15,19*		*3,10,18*		*5,8,13,16*		*1,9,12,14,17,20*		*2,4*				
W_1	Layout	IM^1	Layout	IM^2	Layout	IM^3	Layout	IM^4	Layout	IM^5	Layout	IC	z
0.0	13 14 11 17 16 5	60	20 19 8	22.0	15 4 7 6	32	9 1 12 18 10	32.0	2 3	8	4 1 5 2 3	64	171.8
0.1	17 16 5 13 14 11	51.63	20 19 8	19.18	7 15 6 4	27.67	9 1 12 18 10	26.98	2 3	6.9	4 1 5 2 3	56.02	148.67
0.2	13 14 11 17 16 5	43.27	20 19 8	16.37	15 7 4 6	23.34	10 1 12 18 9	21.95	2 3	5.8	3 1 5 2 4	48.04	125.56
0.3	5 16 17 11 14 13	34.9	20 19 8	13.55	7 15 6 4	19	10 1 12 18 9	16.93	2 3	4.7	4 1 5 2 3	40.06	102.41
0.4	11 14 13 5 16 17	26.53	20 19 8	10.73	6 4 7 15	14.67	9 1 12 18 10	11.91	2 3	3.6	4 1 5 2 3	32.08	79.29
0.5	5 16 17 11 14 13	18.16	20 19 8	7.92	7 15 6 4	10.34	9 1 12 18 10	6.89	2 3	2.5	3 1 5 2 4	24.1	56.17
0.6	11 14 13 5 16 17	9.8	20 19 8	5.10	7 15 6 4	6.01	9 1 12 18 10	1.86	2 3	1.4	4 1 5 2 3	16.12	33.04
0.7	5 16 17 11 14 13	1.43	20 19 8	2.29	15 4 7 6	1.68	9 1 12 18 10	-3.16	2 3	0.3	4 1 5 2 3	8.14	9.92
0.8	17 16 5 13 14 11	-6.94	20 19 8	-0.53	4 6 15 7	-2.65	9 1 12 18 10	-8.18	2 3	-0.8	4 1 5 2 3	.016	-13.21
0.9	14 11 5 13 16 17	-15.39	19 20 8	-3.47	4 6 15 7	-6.99	10 1 12 18 9	-13.21	2 3	-1.9	3 4 2 5 1	-8.25	-36.92
1.0	5 16 13 14 11 17	-27.36	19 8 20	-6.97	4 15 6 7	-11.32	10 12 1 18 9	-19.34	2 3	-3	2 4 1 5 3	-17.82	-64.28

Table 6.11a: Layout for 5-cell solution of table 5.30 using ***FUGEN***

	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	
Machines	1,2,3,10,11,12, 21,22,23	4,13,24,27	5,7,15,17,18,26	8,9,19,20, 28,29,30	6,14,16,25	Inter cell
Parts	2,10,11,12,20,23, 31,32,33, 39,40,41	15,19,24,25, 28,35,38	7,14,16,17,27,34, 36,37	1,3,8,9,13, 21,22,29,30	4,5,6,18,26	
Layout	12 2 3 10 21 22 23 11 1	27 24 4 13	18 17 5 7 26 15	20 30 9 8 19 29 28	25 14 6 16	4 2 1 3 5
IM/IC	3845	271	1111	1760	288	983
z	6075.5					

Table 6.11b: Layout for 6-cell solution of table 5.30 using **FUGEN**

	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	
Machines	8,9,19,20, 29,30	4,6,14,16, 25,27,28	5,7,15,17, 18,26	3,22	13,24	1,2,10,11,12, 21,23	Inter cell
Parts	1,3,9,13,21, 22,29,30	4,5,6,8,15,18, 24,25,26,28,35	7,14,16,17, 27,34,36,37	23,40	19,38	2,10,11,12,20, 31,32,33,39,41	
Layout	29 19 8 9 30 20	27 6 25 4 16 14 28	18 17 5 7 26 15	3 22	13 24	23 2 11 10 21 1 12	1 2 3 4 6 5
IM/IC	1617	794	1111	503	120	2530	1415
z	6087.5						

Table 6.11c: Layout for 7-cell solution of table 5.30 using **FUGEN**

	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Inter cell
Machines	1,3,22	2,10,11,12, 21,23	14,25	4,6,8,16, 27,28	5,7,15,17, 18,26	9,19,20, 29,30	13,24	
Parts	10,23,31, 32,40	2,11,12,20, 33,39,41	4,5,18	6,8,15,24, 26,28,29,35	7,14,16,17, 27,34,36,37	1,3,9,13, 21,22,30	19,25,38	
Layout	22 3 1	23 10 11 12 21 2	14 25	6 16 8 27 4 28	18 17 5 7 26 15	20 29 9 30 19	13 24	3 4 6 2 7 5 1
IM/IC	713	1986	78	720	1111	1204	120	1885
z	6037.4							

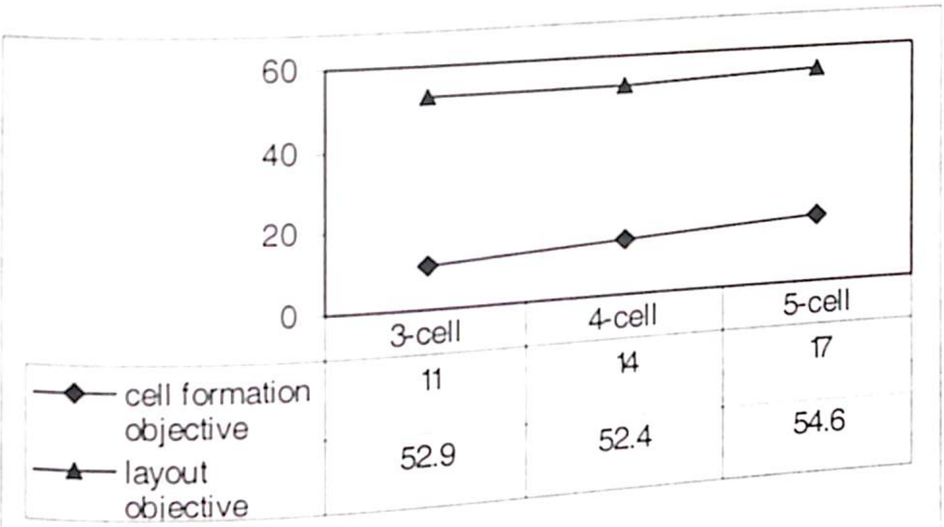


Figure 6.7a

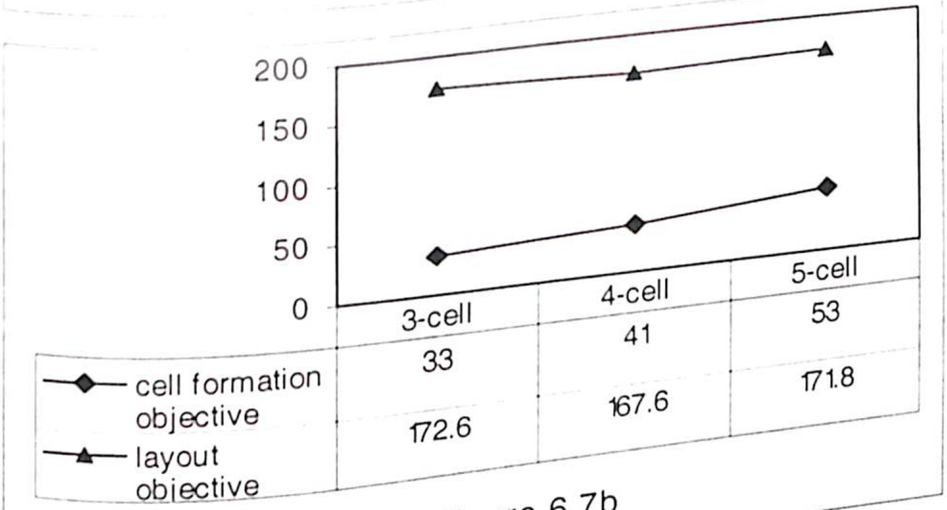


Figure 6.7b

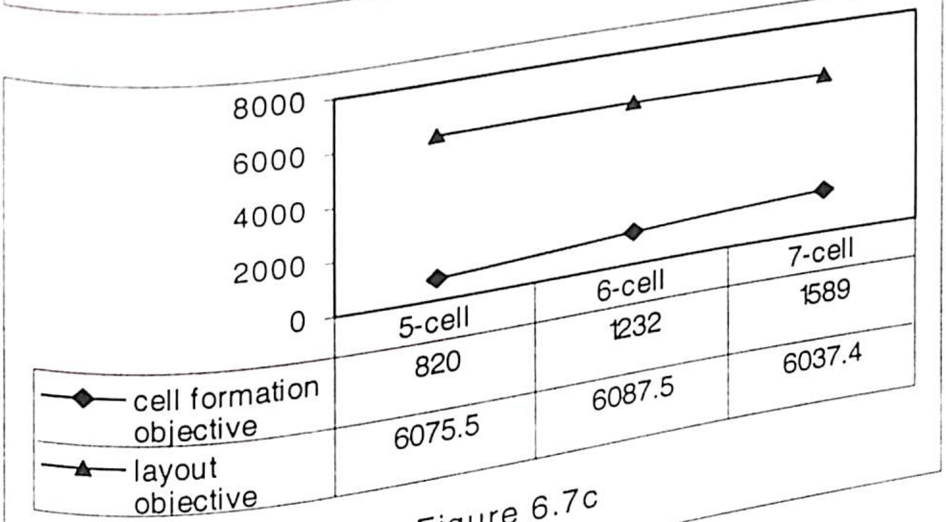


Figure 6.7c

Figure 6.7: Comparison of cell formation objective (chapter 5) and layout objective using FUGEN

6.6 Comparison of Results of MUCH and FUGEN Models

The results (objective value, i.e., integrated material handling cost) of these two models for the problems solved ($w_1=0$) are given in figure 6.8. These results show that the FUGEN model gives better layouts in term of the integrated material handling cost compared to MUCH model. This is because the MUCH model is based on a traditional heuristic, results of which are highly sensitive to the initial solution provided. The results for the smaller size of problems (layout of 3 machines in a cell or layout of 3 cells on shopfloor) are similar, e.g., see the layout of 3 machines in cell 3 of 4-cell solution (tables 6.2b and 6.9b).

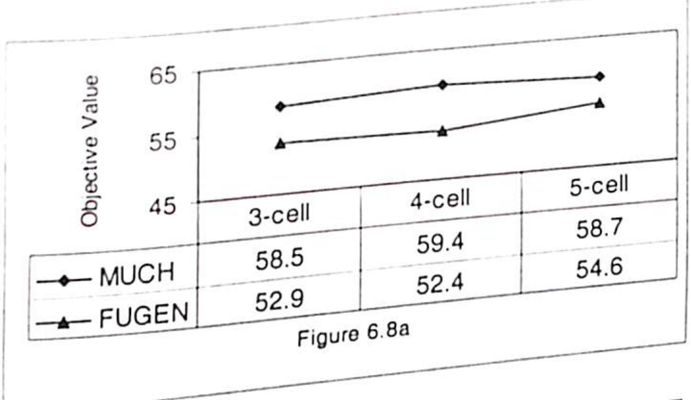


Figure 6.8a

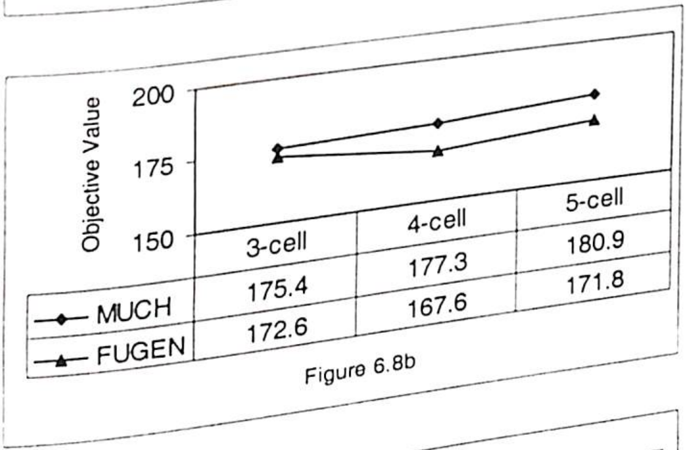


Figure 6.8b

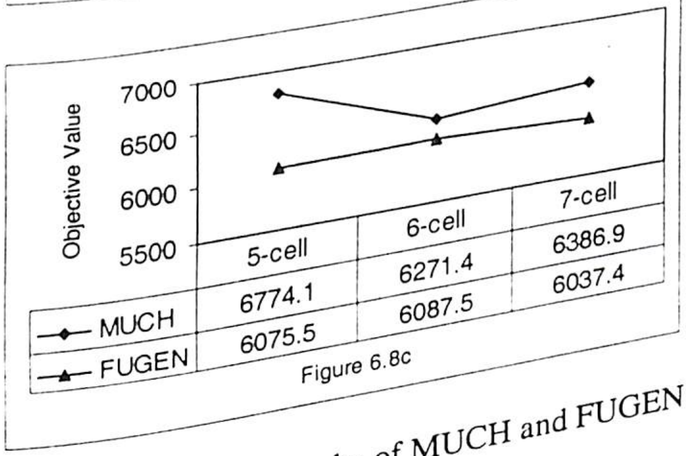


Figure 6.8c

Figure 6.8: Comparison of results of MUCH and FUGEN models

6.7 Conclusions

This chapter presents a literature review on the layout of CMS, a multi-criteria mathematical formulation developed for the design of layout for CMS, and two models developed to solve the multi-criteria mathematical formulation for the design of layout of CMS. The literature review indicates that there is a need to consider the layout of CMS to validate the benefits of CMS. The layout of CMS should include the cell layout on shop floor (cell layout) as well as the machine layout inside cells (machine layout). To make the layout models practical, both, quantitative and qualitative factors must be considered.

The multi-criteria mathematical formulation developed for the layout design of CMS deals with the cell layout as well as machine layout problems. This is formulated as quadratic assignment problem to assign *n* facilities (cells/machines) to *n* locations with a view to minimize the material handling (quantitative) and maximize the closeness rating (qualitative) simultaneously. The formulation considers the production volume, batch size, and non-consecutive visits to the same facility. The quantitative and qualitative factors are considered simultaneously for both cell layout and machine layout.

The MUCH model developed for design of layout for CMS is a multi-criteria heuristic based on a pairwise exchange of facilities to the locations. The FUGEN model developed for layout of CMS is a genetic algorithm based model with an embedded fuzzy logic and AHP models to treat the vagueness and uncertainty of qualitative factors. Single point crossover, mutation, and direct entry (elitism) operators used probabilistically in the model have given efficient solutions. AHP has been used to check the consistency of the designer while assigning the importance of one qualitative factor over other. Both the models are versatile and the designer has many choices like any value between zero and one can be considered for the qualitative criterion ($0 \leq w1 \leq 1$) and intra-cell/inter-cell objective function ($\alpha 1$ and $\alpha 2$) to evaluate the effects of qualitative and intra-cell/inter-cell layout, and any number of qualitative factors (≤ 12) can be considered. However, comparison of layouts of two models shows that the FUGEN model gives better layouts than the MUCH model in term of integrated material handling cost. The layouts of both the models clearly show that the intercellular moves (most common objective for cell formation in literature) does not represent the material handling cost truly. The proposed models are capable of evaluating the cellular layouts vis-a-vis functional layouts but the limitation of models is that the maximum number of machines in any cell and the maximum number of cells are limited to 16.

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Chapter 7

Integrated Approach for Design of Cellular Manufacturing Systems

7.1 Introduction

The design of cellular manufacturing systems (CMS) involves three inter-related phases, namely cell formation which is to identify the machine grouping and part families, intra-cell layout (machine layout) which determines the arrangement of machines within cells, and inter-cell layout (cell layout) which is concerned with the arrangement of cells on the shop floor. Kaebernick and Bazargan-Lari (1996) used the integrated approach for design of CMS. They formed the cells with the objective of reducing the inter-cellular moves and putting the maximum and minimum number of cells as constraints. Next, they designed the intra-cell layout and finally generated the inter-cell layout based on criteria of shape and cost by considering all possible combinations for efficient intra-cell layout designs. In true sense, this is not an integrated approach as they have solved the cell formation and layout problems sequentially (once the machines are grouped to different cells based on the above algorithm for different cell numbers, the intra-cell and inter-cell layout designs can be carried out... Kaebernick and Bazargan-Lari (1996): 423) in a forward pass with no feedback. This approach is called sequential approach. This approach, results in generating solutions, which may be efficient to one particular phase, but it does not necessarily offer a good solution to the overall CMS. Therefore, there is need for integrated approach for design of CMS. The proposed integrated approach will tackle the three phases simultaneously for design of CMS.

This chapter presents the mathematical formulation for the integrated approach and the two models (SAMUCH and SAFUGA) developed for the integrated approach. SAMUCH model uses simulated annealing algorithm (SAA) and multicriteria heuristic. SAFUGA model uses simulated annealing algorithm and genetic algorithm with embedded fuzzy logic and AHP. A simulation model developed for the validation of the integrated approach is also presented in this chapter. The effect of four scheduling philosophies (shortest processing time, longest processing time, shortest batch size, and goal chasing algorithm) on the various performance measures of CMS is also presented in this chapter.

7.2 Development of Mathematical Formulation for Integrated Approach

In this section a mathematical formulation is developed for the integrated approach with the objective of minimizing the integrated (inter-cell and intra-cell material handling) cost function. The model considers the quantitative and qualitative factors for the layout of machines inside the cells as well as for the layout of cells on the shop floor. Alternate routes, production volume, transfer batch sizes, operation sequence, and constraints on maximum number of cells are considered during the formulation of the mathematical model.

Notations:

i, j : variables for machines $(i \neq j)$

n : total number of machines

k : variable for parts

p : total number of parts

D_k : production volume of part k for a given planning horizon

B_k : transfer batch size of part k

x, y : variables for cells ($x \neq y$)

C : total number of cells

p, q : variables for locations ($p \neq q$)

d_{pq} : distance from location p to location q (rectilinear distance)

w_1 : weight for qualitative factors

w_2 : weight for quantitative factors ($w_2 = 1 - w_1$)

F_{ij}^k : flow/interaction between machine i and j for part k

f_{ij} : flow/interaction between machines i and j for all parts

im_{ij}^x : flow/interaction between machines i and j in cell x

ic_{xy} : flow/interaction between cells x and y

S_{ki}^r : operation number for the operation done on part k using machine i and route r

α_1 : weight for intra cell objective function

α_2 : weight for inter cell objective function

n_k^r : number of alternate routes for part k

Integrated objective function (TC)

Minimize $$TC = \alpha_1 IM + \alpha_2 IC \tag{1}$$

where

$$IM = \sum_{x=1}^{C} IM^x \tag{2}$$

$$IM^x = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{p=1}^{n}\sum_{q=1}^{n} c_{ijpq} . x_{ip} . x_{jq} \tag{2.1}$$

$$c_{ijpq} = w_2 a_{ijpq} - w_1 b_{ijpq}$$

$$a_{ijpq} = im_{ij}^x d_{pq}, i \neq j \text{ or } p \neq q$$

$$im_{ij}^{x} = \sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij} a_{ix} a_{jx} \qquad (2.2)$$

$$f_{ij} = \sum_{k=1}^{P}\sum_{r=1}^{n_k^r} F_{ij}^{k} a_{ki}^{r} a_{kj}^{r} x_{kx}^{r} x_{ky}^{r}$$

$$F_{ij}^{k} = \begin{cases} D_k / B_k \, , if \left| S_{ki}^{r} - S_{kj}^{r} \right| = 1 \;\&\; S_{ki}^{r}, S_{kj}^{r} > 0 \\ 0, \text{otherwise} \end{cases}$$

$$a_{ki}^{r} = \begin{cases} 1, \text{if part } k \text{ uses machine } i \text{ in route } r \\ 0, \text{otherwise} \end{cases}$$

$$a_{ix} = \begin{cases} 1, \text{if machine } i \text{ in cell } x \\ 0, \text{otherwise} \end{cases}$$

$$a_{jx} = \begin{cases} 1, \text{if machine } j \text{ in cell } x \\ 0, \text{otherwise} \end{cases}$$

$$b_{ijpq} = \begin{cases} r_{ij}, \text{if location } p \text{ and } q \text{ are neighbours} \\ 0, \text{otherwise} \end{cases}$$

r_{ij} = closeness ranking value when machines i and j are neighbours with common boundary

$$x_{ip} = \begin{cases} 1, \text{if machine } i \text{ is assigned to location } p \\ 0, \text{otherwise} \end{cases}$$

$$\text{IC} = \sum_{x=1}^{C}\sum_{y=1}^{C}\sum_{p=1}^{C}\sum_{q=1}^{C} c_{xypq} . x_{xp} . x_{yq} \qquad (3)$$

where,

$$c_{xypq} = w_2 a_{xypq} - w_1 b_{xypq}$$

$$a_{xypq} = ic_{xy} \, d_{pq}, x \neq y \text{ or } p \neq q$$

$$ic_{xy} = \sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij} a_{ix} a_{jy} \qquad (3.1)$$

$$a_{ix} = \begin{cases} 1, \text{if machine } i \text{ in cell } x \\ 0, \text{otherwise} \end{cases}$$

$$a_{jy} = \begin{cases} 1, \text{if machine } j \text{ in cell y} \\ 0, \text{otherwise} \end{cases}$$

$$b_{xypq} = \begin{cases} r_{xy}, \text{if location } p \text{ and } q \text{ are neighbours} \\ 0, \text{otherwise} \end{cases}$$

r_{xy} = closeness ranking value when cells x and y are neighbours with common boundary

$$x_{xp} = \begin{cases} 1, \text{if machine } x \text{ is assigned to location } p \\ 0, \text{otherwise} \end{cases}$$

Subject to:

$$\sum_{i=1}^{n} x_{ip} = 1 \quad \forall p \tag{4}$$

$$\sum_{p=1}^{n} x_{ip} = 1 \quad \forall i \tag{5}$$

$$\sum_{x=1}^{C} x_{xp} = 1 \quad \forall p \tag{6}$$

$$\sum_{p=1}^{C} x_{xp} = 1 \quad \forall x \tag{7}$$

$$C = C_{max} \tag{8}$$

$$\sum_{r=1}^{n'_k} x'^{r}_{kx}, x'^{r}_{ky} = 1 \quad \forall k, x \neq y \tag{9}$$

$$w_1 + w_2 = 1$$
$$w_1, w_2 \geq 0$$

Constraints (4) and (5) assure that each location and machine can be assigned to one machine and one location only. Constraints (6) and (7) assure that each location and each cell can be assigned to one cell and one location only. Constraint (8) checks that upper limit on the number of cells is not violated. Constraint (9) makes sure that each part can have only one process route and is assigned to one cell only.

7.3 Development of SAMUCH Model for Design of CMS

SAMUCH is a coined term. In this model SAA is used as an outer layer for cell formation and the multicriteria heuristics are used in the inner layer for the design of layout of CMS. Initially machines are allotted to the specified number of cells randomly. For the generated feasible solution (sol_0), multicriteria heuristic algorithm generates the efficient intra-cell and inter-cell layouts and computes the integrated objective value, TC, using equation (1). This objective value is called obj_0. Neighbourhood solutions are generated by randomly choosing two cells and a machine from one cell is *moved* to the other. The developed algorithm is given next. The main steps (step1, 2, 3...) are the steps of SAA and sub-steps (4.1, 4.2, 4.3...) are steps of the multicriteria heuristic algorithm. The flowchart of the SAMUCH model is given in figure 7.1.

7.3.1 Algorithm

```
Step 1    Input P, n, $C_{max}$, $n_k^r$, $AT_{min}$, $r_f$, a, $T_i$
Step 2    Read operation sequence, $D_k$ and $B_k$
Step 3    Initialize I=0
Step 4    Generate an initial solution for cells ($sol^0$)
    Step 4.1    Set x=0
    Step 4.2    Generate initial layout, compute $c_{ijpq}$
    Step 4.3    Set i=0
    Step 4.4    Set j=i+1
    Step 4.5    Exchange i and j, compute $c_{ijpq}^{new}$
    Step 4.6    If $c_{ijpq}^{new} \leq c_{ijpq}^{old}$, update $c_{ijpq}^{new} = c_{ijpq}^{new}$, $layout^{new} = layout^{new}$
                    else $c_{ijpq}^{new} = c_{ijpq}^{old}$, $layout^{new} = layout^{old}$
    Step 4.7    If $j < n$, $j = j+1$ and go to Step 4.5
                    else    if $i < n-1$, $i=i+1$and go to Step 4.4
```

```
            else go to Step 4.8
Step 4.8    Compute $IM^x$
Step 4.9    If $x < C$, $x = x+1$ and go to Step 4.2
            else go to Step 4.10
Step 4.10   Compute IM
Step 4.11   Generate initial layout for cells, and compute $c_{xypq}$
Step 4.12   Set $x=0$
Step 4.13   Set $y=x+1$
Step 4.14   Exchange x and y and compute $c_{xypq}^{new}$
Step 4.15   If $c_{xypq}^{new} \le c_{xypq}^{old}$, update $c_{xypq}^{new} = c_{xypq}^{new}$, $layout^{new} = layout^{new}$
            else $c_{xypq}^{new} = c_{xypq}^{old}$, $layout^{new} = layout^{old}$
Step 4.16   If $y < C$, $y = y+1$ and go to Step 4.14
            else    if $x < C-1$, $x=x+1$ and go to Step 4.13
            else go to Step 4.17
Step 4.17   Compute IC
Step 4.18   Compute TC
Step 5    Set $obj_t^l = TC$
Step 6    If $t > 0$ go to step 8 else go to step 7
Step 7    Generate a neighbourhood solution, $t=t+1$ and go to step 4.1
Step 8    Compute $E = obj_t^l - obj_{t-1}^l$
Step 9    If $E \le 0$ or random no. R between $(0,1) \le e^{-E/T_l}$
          Accept $obj_t^l$ and $sol_t^l$, update $AT = AT + 1$ and go to step 10
          else accept $obj_t^l = obj_{t-1}^l$, $sol_t^l = sol_{t-1}^l$ and go to step 10
Step 10   If $AT < AT_{min}$ or $t < n*n$, go to step 7
          else set $obj'^l_t = obj_t^l$, $sol^l_t = sol_t^l$ and go to step 11
Step11    If $obj^l < obj^{l-1}_t$, accept $obj^l$ and $sol^l_t$
```

```
        else if $obj^{I} = obj^{I-1}_{t}$, accept $obj^{I}$ and $sol^{I}_{t}$ and set $FC = FC + 1$
            else accept $obj^{I} = obj^{I-1}_{t}$ and $sol^{I} = sol^{I-1}_{t}$
Step12  Compute $r = AT/t$. if $r \le r_f$ go to step 14
                else go to step 13
Step13  If $I < I_{max}$ or $FC < 20$, $I = I + 1$, $t = 0$, $AT = 0$, $T_i = a\, T_i$ and go to step 7
        else go to step 14
Step14  Print $sol^{I}$, $obj^{I}$, no. of cells, r, and I
Step15  Stop
```

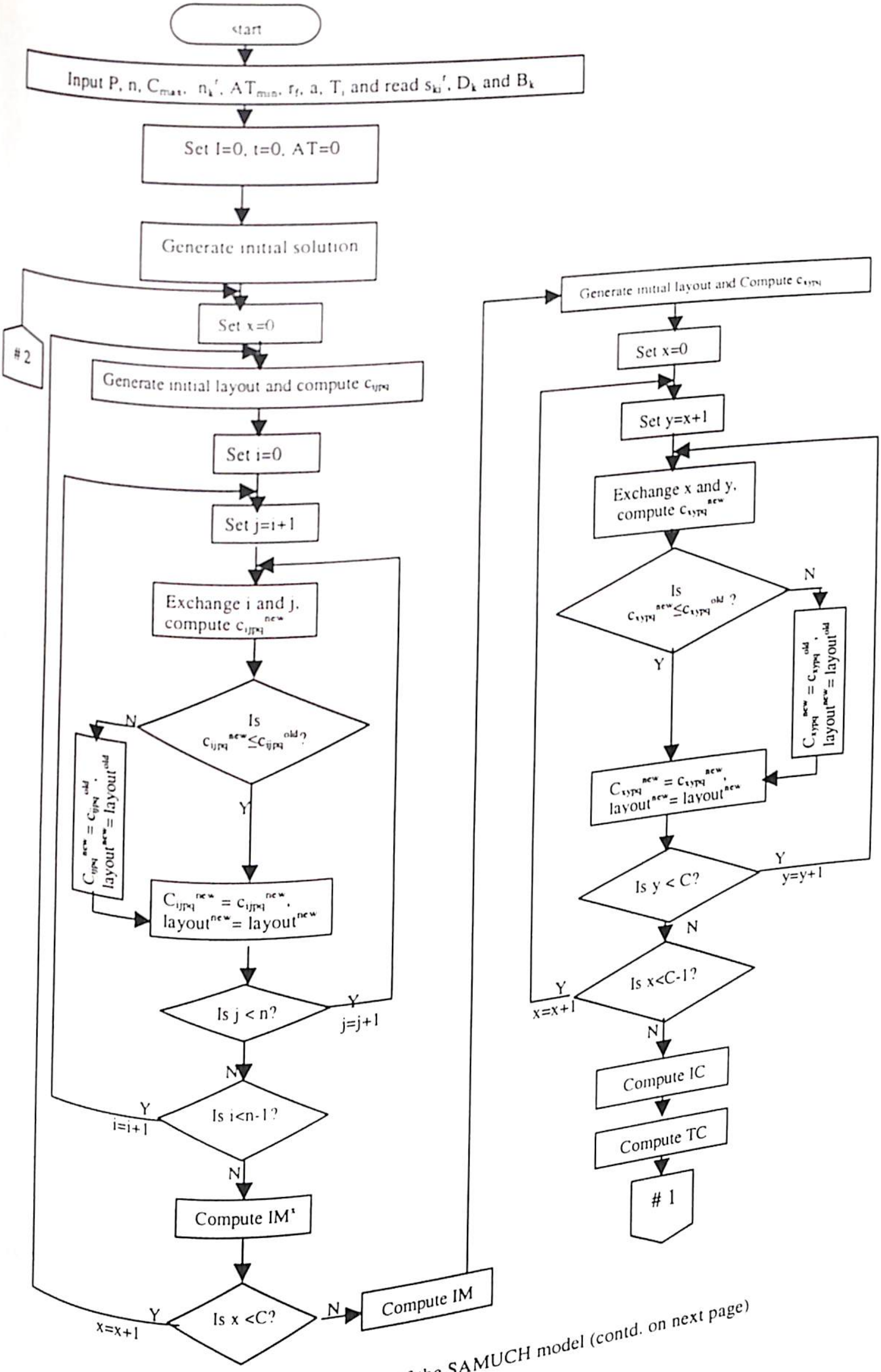


Figure 7.1: Flowchart of the SAMUCH model (contd. on next page)

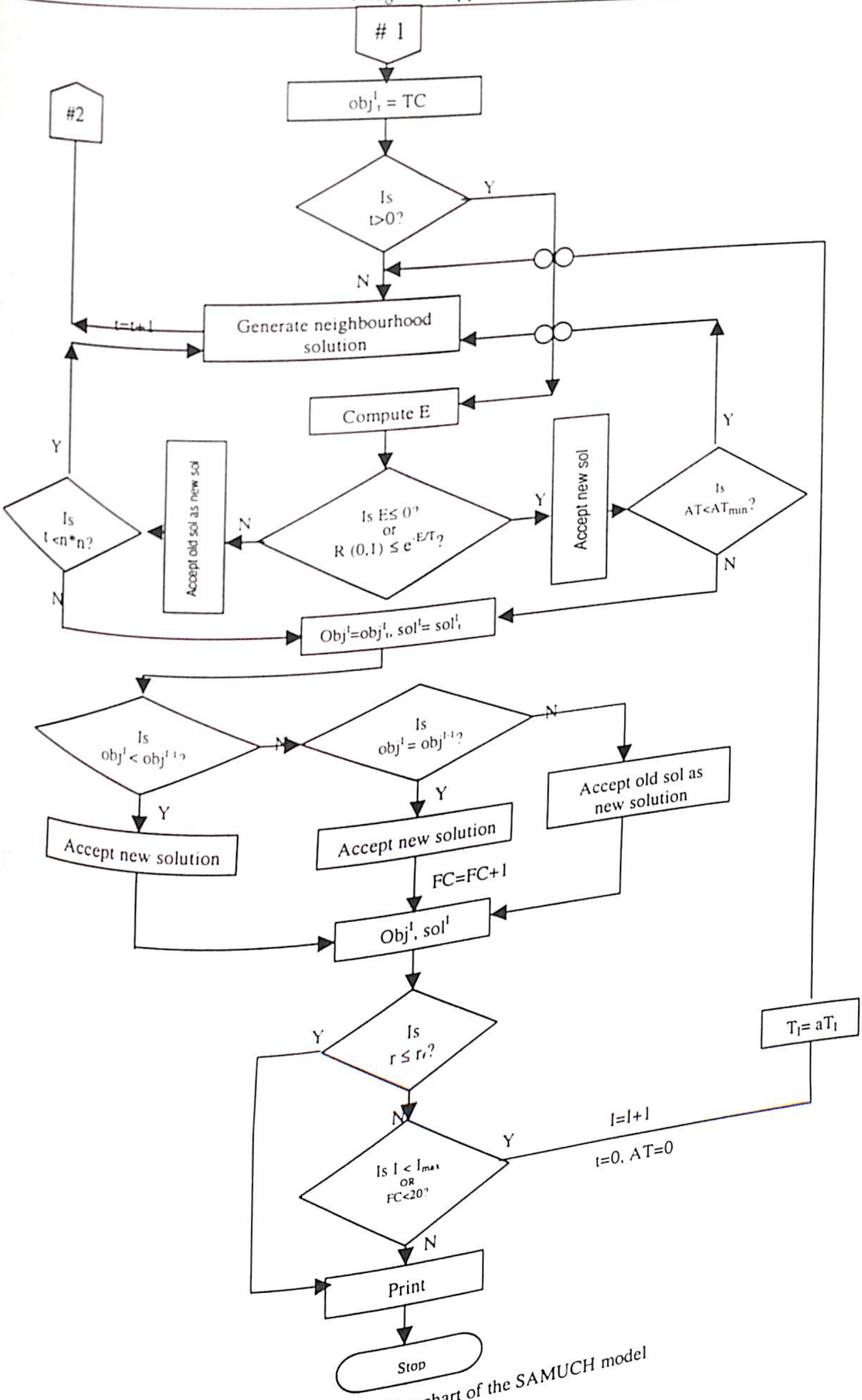


Figure 7.1(contd.): Flowchart of the SAMUCH model

7.3.2 Validation

The model is validated by using two examples (example 3, table 5.25; and example 4 table 5.28) for which the cells are formed in chapter 5 and layout is designed in chapter 6. The formation of efficient cells and then design of the efficient layouts for them is sequential approach. In this chapter, the cell formation and layout design is carried out simultaneously (in each iteration cells will be formed and layout is designed for this formation).

Two main test runs are conducted for example 3 (table 5.25): (i) with production volume (demand) by transfer batch size ratio ($D_k/B_k=1$) of one and (ii) with assumed demand and transfer batch size. For example 4 (table 5.28), only second main test run is conducted. Within these main runs constrain on the number of cells is changed. The weights for the intra and inter cell layout costs are taken from literature as 0.7 and 1.0 respectively as is done in chapter 6. The results of the test runs are tabulated in tables 7.1, 7.2, and 7.3.

The assumptions made in the proposed method are that the machines (cells) are of equal size, the distances between the adjacent machines (cells) are one unit each. It has also been assumed that the cells as well as the shop floor areas are rectangular in shape. This assumption is realistic and practical as pointed out by Black (1983).

Table 7.1: The solution sets and comparison of the integrated objective function with inter-cell moves for the example 3 (table 5.25) with $D_k/B_k=1$

C	Cells	Parts	Machines	Inter-cell moves	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Machine layout	Cell layout
3	1	1,9,12,14 17,20	1,4,9,10, 12,18	13	58.5	10 1 12 18 9 4	1 3 2
	2	2,4,6,7, 11,15,19	2,3,5,11, 14,16,17			2 11 14 16 5 3 17	
	3	3,5,8,10, 13,16,18	6,7,8,13, 15,19,20			15 8 20 7 13 19 6	
4	1	2,4,6,7, 11,15,19	2,3,11, 14,16,17	17	56.3	11 3 2 14 16 17	3 4 2 1
	2	9,12	5,9,18			18 9 5	
	3	1,3,10,14, 17,18,20	1,8,10, 12,19,20			1 12 19 10 8 20	
	4	5,8,13,16	4,6,7, 13,15			13 15 4 7 6	
5	1	3,10,18	8,19,20	17	56.6	20 19 8	5 3 1 4 2
	2	6,7,15	16,17			17 16	
	3	5,8,13,16	4,6,7, 13,15			13 15 4 7 6	
	4	2,4,11,19	2,3,11,14			14 11 3 2	
	5	1,9,12, 14,17,20	1,5,9,10, 12,18			5 10 18 12 1 9	

Table 7.2: The solution sets and comparison of the integrated objective function with inter-cell moves for the example 3 (table 5.25) with given D_k and B_k

C	Cells	Parts	Machines	Inter-cell moves	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Machine layout	Cell layout
3	1	1,2,4,9,11,12, 14,17,19,20	1,2,3,5,9, 11,12,18	38	170.8	5 11 3 18 9 2 12 1	1 3 2
	2	3,10,18	8,10,19,20			20 19 8 10	
	3	5,6,7,8, 13,15,16	4,6,7,13, 14,15,16,17			13 7 6 14 15 4 16 17	
4	1	2,4,6,7, 11,15,19	2,3,5,11, 14,16,17	41	177.3	11 5 17 3 14 16 2	4 3 1 2
	2	1,9,12, 14,17,20	1,9,10, 12,18			18 12 10 9 1	
	3	3,10,18	8,19,20			20 19 8	
	4	5,8,13,16	4,6,7, 13,15			7 15 13 6 4	
5	1	6,7,15	13,14, 16,17	59	176.6	17 16 13 14	5 1 3 4 2
	2	3,10,14,18	8,10,19,20			20 19 8 10	
	3	5,8,13,16	4,6,7,15			15 7 4 6	
	4	1,9,12, 17,20	1,9,12,18			18 12 9 1	
	5	2,4,11,19	2,3,5,11			11 5 2 3	

Table 7.3: The solution sets and comparison of the integrated objective function with inter-cell moves for the example 4 (table 5.28)

C	Cells	Parts	Machines	Inter-cell moves	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Machine layout	Cell layout
5	1	2,10,11,12,23, 31,32,33,39, 40,41	1,2,3,10,11, 21,22,23	1073	6365.1	3 10 23 22 21 2 1 11	3 2 4 5 1
	2	8,15,24,25,28, 35	4,12,27,28			28 27 4 12	
	3	7,14,16,17,19, 27,34,36,37, 38	5,7,13,15, 17,18,24,26			15 26 7 24 17 18 13 5	
	4	1,3,9,13,21, 22,29,30	8,9,19,20, 29,30			29 19 30 9 8 20	
	5	4,5,6,18,26	6,14,16,25			25 14 6 16	
6	1	10,11,12,31,32, 33,39,40,41	1,2,3,11,21, 22	1448	6077.3	11 2 3 1 21 22	5 2 6 3 1 4
	2	2,8,15,19,20, 23,24,28,35	4,10,12,23, 27,28			23 12 27 10 4 28	
	3	7,16,17,27,34, 36,37	5,7,15,17, 18,26			26 17 18 7 15 5	
	4	4,5,6,18,26	6,14,16,25			25 14 6 16	
	5	1,3,9,13,14, 21,22,29,30	8,9,19,20, 29,30			29 19 30 9 8 20	
	6	25,38	13,24			24 13	
7	1	10,23,31, 32,40	1,3,22	1589	6386.9	22 3 1	5 4 6 1 2 3 7
	2	2,11,12,20, 33,39,41	2,10,11,12,21,23			23 10 11 12 21 2	
	3	4,5,18	14,25			14 25	
	4	6,8,15,24, 26,28,29,35	4,6,8,16,27, 28			6 28 8 16 4 27	
	5	7,14,16,17, 27,34,36,37	5,7,15,17,18,26			26 17 18 7 15 5	
	6	1,3,9,13, 21,22,30	9,19,20,29,30			29 19 30 9 20	
	7	19,25,38	13,24			13 24	

7.4 Development of SAFUGA Model for Design of CMS

SAFUGA is a coined term. In this model SAA is used as an outer layer for cell formation and the genetic algorithm, with embedded fuzzy logic and AHP models to treat the vagueness and uncertainty of qualitative factors, is used in the inner layer for the design of layout of CMS. Initially machines are allotted to the specified number of cells randomly. For the generated feasible solution (sol_0), genetic algorithm generates the efficient intra and inter cell layouts and computes the integrated objective value, TC, using equation (1). This objective value is called obj_0. Neighbourhood solutions are generated by randomly choosing two cells and a machine from one cell is *moved* to the other. The developed algorithm is given next. The main steps (step 1, 2, 3…) are the steps of SAA and sub-steps (4.1, 4.2, 4.3…) are steps of the genetic algorithm. The flowchart of the SAFUGA model is given in figure 7.2.

7.4.1 Algorithm

```
Step 1   Input P, n, $C_{max}$, $n_k^r$, $AT_{min}$, $r_f$, a, $T_i$
Step 2   Read operation sequence, $D_k$ and $B_k$
Step 3   Initialize I=0
Step 4   Generate an initial solution for cells ($sol^0$)
    Step 4.1.1: Set x=1
    Step 4.1.2: Randomly generate an initial population for layout, set GEN=1
    Step 4.2: Set s=1
    Step 4.3: Compute objective value ($IM^x$), update s=s+1
    Step 4.4: If s<S, go to step 4.3, else go to step 4.5
    Step 4.5: Arrange the strings (chromosomes) in ascending order of objective
        values
```

```
Step 4.6: Compute average objective value ($\overline{IM'}$), SET GEN=GEN+1, s=1
Step 4.7: Compute Roulette values (Rou) of all strings
Step 4.8: Generate a random number (RN) between 0 and 0.99
Step 4.9: If RN<$P_M$ go to step 4.10, else if RN<$P_X$ go to step 4.11, else go to step
    4.12
Step 4.10: Generate random number (RN) between minimum and maximum
    Roulette value ($R^{min}$ and $R^{max}$)
Step 4.10.1: Accept string s for mutation such that the RN lies between the
    Roulette values of s and s+1 strings
Step 4.10.2: Generate two random numbers ($RN_1$ and $RN_2$) between 1 and n for
    mutation.
Step 4.10.3: Exchange the genes occupied by $RN_1$ and $RN_2$
Step 4.10.4: If $IM^x < \overline{IM'}$, accept the string for the new generation, update s=s+1
    and go to step 4.13, else go to step 4.8
Step 4.11: Generate random number (RN) between minimum and maximum
    Roulette value ($R^{min}$ and $R^{max}$)
Step 4.11.1: Accept string s for crossover such that the RN lies between the
    Roulette values of s and s+1 strings
Step 4.11.2: Similarly select one more string for crossover
Step 4.11.3: Generate random number (RN) between 1 and n-1 for crossover
Step 4.11.4: Crossover at RN to get children $s_{x1}$ and $s_{x2}$
Step 4.11.5: If offspring is not feasible (repetition of genes) go to step 4.11.6, else
    go to step 4.11.7
Step 4.11.6: Repair strings using concept of 'replace the foremost reoccurrence
    with the foremost vacancy'
```

Step 4.11.7: Compute objective values (IM^{x}_{x1} and IM^{x}_{x2}) of strings

Step 4.11.8: If $IM^{x}_{x1} < \overline{IM'}$, go to Step 4.11.9 else go to Step 4.11.11

Step 4.11.9: If $IM^{x}_{x2} < \overline{IM'}$, go to Step 4.11.12

Step 4.11.10: Accept string s_{x1} and go to Step 4.11.14

Step 4.11.11: If $IM^{x}_{x2} < \overline{IM'}$, go to Step 4.11.12 else go to Step 4.8

Step 4.11.12: If $IM^{x}{}_{x2} < IM^{x}{}_{x1}$, go to Step 4.11.13 else go to Step 4.11.10

Step 4.11.13: Accept String s_{x2}.

Step 4.11.14: Update s=s+1 and go to Step 4.13

Step 4.12: If $IM^{x} < \overline{IM'}$, accept the string for the new generation, update s=s+1 and go to step 4.13, else go to step 4.8

Step 4.13: If s<S go to step 4.8, else go to step 4.14

Step 4.14: If $GEN == GEN^{max}$ or $IM^{x}_{1} = IM^{x}_{2} = \dots = IM^{x}_{S}$ go to step 4.15, else GEN=GEN+1, compute objective values and go to step 4.5

Step 4.15: Store $IM^{x}_{minimum}$ and layout

Step 4.16: If x<C, x=x+1 and go to step 4.1.2, else go to step 4.17

Step 4.17: Compute and store IM

Step 4.18: Randomly generate an initial population, set GEN=1

Step 4.19: Set s=1

Step 4.20: Compute objective value (IC), update s=s+1

Step 4.21: If s<S, go to step 4.20, else go to step 4.22

Step 4.22: Arrange the strings (chromosomes) in ascending order of objective values

Step 4.23: Compute average objective value ($\overline{IC}$), set GEN=GEN+1, s=1

Step 4.24: Compute Roulette values of all strings

Step 4.25: Generate a random number (RN) between 0 and 0.99

```
Step 4.26: If $RN<P_M$ go to step 4.27, else if $RN<P_X$ go to step 4.28, else go to step 4.29
Step 4.27: Generate random number (RN) between minimum and maximum Roulette value ($R^{min}$ and $R^{max}$)
Step 4.27.1: Accept string s for mutation such that the RN lies between the Roulette values of s and s+1 strings
Step 4.27.2: Generate two random numbers ($RN_1$and $RN_2$) between 1 and C for mutation.
Step 4.27.3: Exchange the genes occupied by $RN_1$ and $RN_2$
Step 4.27.4: If $IC<\overline{IC}$, accept the string for the new generation, update s=s+1 and go to step 4.30, else go to step 4.25
Step 4.28: Generate random number (RN) between minimum and maximum Roulette value ($R^{min}$ and $R^{max}$)
Step 4.28.1: Accept string s for crossover such that the RN lies between the Roulette values of s and s+1 strings
Step 4.28.2: Similarly select one more string for crossover
Step 4.28.3: Generate random number (RN) between 1 and C-1 for crossover
Step 4.28.4: Crossover at RN
Step 4.28.5: If offspring is not feasible (repetition of genes) go to step 4.28.6, else go to step 4.28.7
Step 4.28.6: Repair strings using concept of 'replace the foremost reoccurrence with the foremost vacancy'
Step 4.28.7: Compute objective values ($IC_{x1}$ and $IC_{x2}$) of strings
Step 4.28.8: If $IC_{x1}<\overline{IC}$, go to Step 4.28.9 else go to Step 4.28.11
Step 4.28.9: If $IC_{x2}<\overline{IC}$, go to Step 4.28.12
```

```
    Step 4.28.10: Accept string $s_{x1}$ and go to Step 4.28.14
    Step 4.28.11: If $IC_{x2} < \overline{IC}$, go to Step 4.28.12 else go to Step 4.25
    Step 4.28.12: If $IC_{x2} < IC_{x1}$, go to Step 4.28.13 else go to Step 4.28.10
    Step 4.28.13: Accept String $s_{x2}$
    Step 4.28.14: Update s=s+1 and go to Step 4.30
    Step 4.29: If $IC < \overline{IC}$, accept the string for the new generation, update s=s+1 and go
        to step 4.30, else go to step 4.25
    Step 4.30: If s<S go to step 4.25, else go to step 4.31
    Step 4.31: If $GEN == GEN^{max}$ or $IC^x_1 = IC^x_2 = \dots = IC^x_S$ go to step 4.32, else
        GEN=GEN+1, compute objective values and go to step 4.22
    Step 4.32: Store $IC_{minimum}$ and layout
    Step 4.33: Compute TC
Step 5   Set $obj_t^I = TC$
Step 6   If $t > 0$ go to step 8 else go to step 7
Step 7   Generate a neighbourhood solution, t=t+1 and go to step 4.1.1
Step 8   Compute $E = obj_t^I - obj_{t-1}^I$
Step 9   If $E \le 0$ or random no. R between $(0,1) \le e^{-E/T_i}$
         Accept $obj_t^I$ and $sol_t^I$, update AT = AT + 1 and go to step 10
         else accept $obj_t^I = obj_{t-1}^I$, $sol_t^I = sol_{t-1}^I$ and go to step 10
Step 10  If $AT < AT_{min}$ or $t < n*n$, go to step 7
         else set $obj^I_t = obj_t^I$, $sol^I_t = sol_t^I$ and go to step 11
Step11   If $obj^I < obj^{I-1}_t$, accept $obj^I$ and $sol^I_t$
         else if $obj^I = obj^{I-1}_t$ accept $obj^I$ and $sol^I_t$ and set FC=FC+1
             else accept $obj^I = obj^{I-1}_t$ and $sol^I = sol^{I-1}_t$
```

```
Step12  Compute $r = AT/t$, if $r \leq r_f$ go to step 14
                    else go to step 13
Step13  If $I < I_{max}$ or $FC<20$, $I = I + 1$, $t=0$, $AT=0$, $T_i = a\,T_i$ and go to step 7
        else go to step 14
Step14  Print $sol^I$, $obj^I$, no. of cells (maximum no. of machines in a cell)
Step15  Stop
```

7.4.2 Validation

This model is also validated for the same problems and in the same way as SAMUCH model is validated. The results (cells formed and the layout of machines and cells) of the test runs are tabulated in tables 7.4, 7.5, and 7.6. Column 6 of these tables shows the objective function (inter-cell and intra-cell material handling cost). All the assumptions of the SAMUCH model are valid in this model also except that the initial layouts in this model are generated randomly by genetic algorithm.

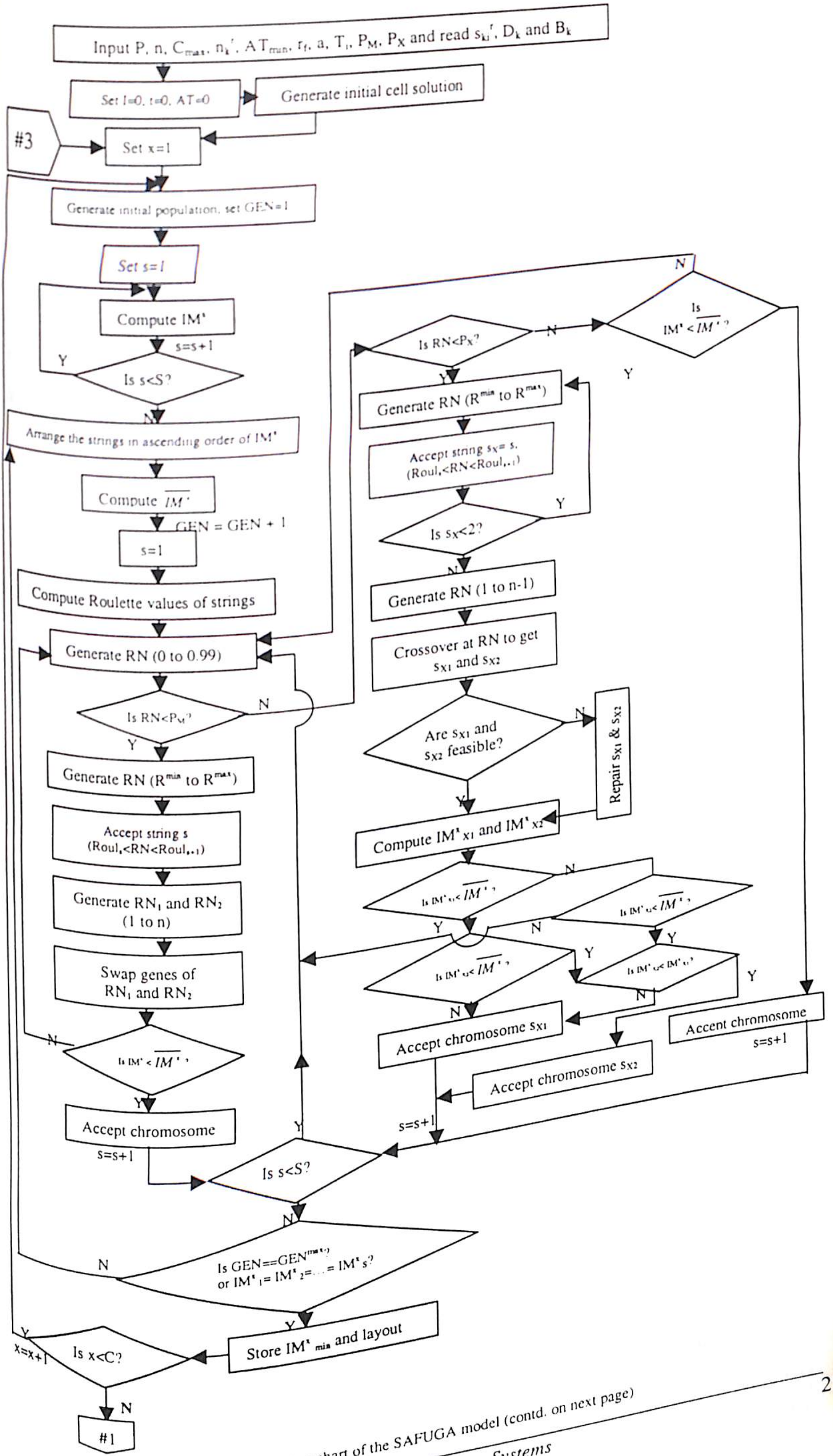


Figure 7.2:Flowchart of the SAFUGA model (contd. on next page)

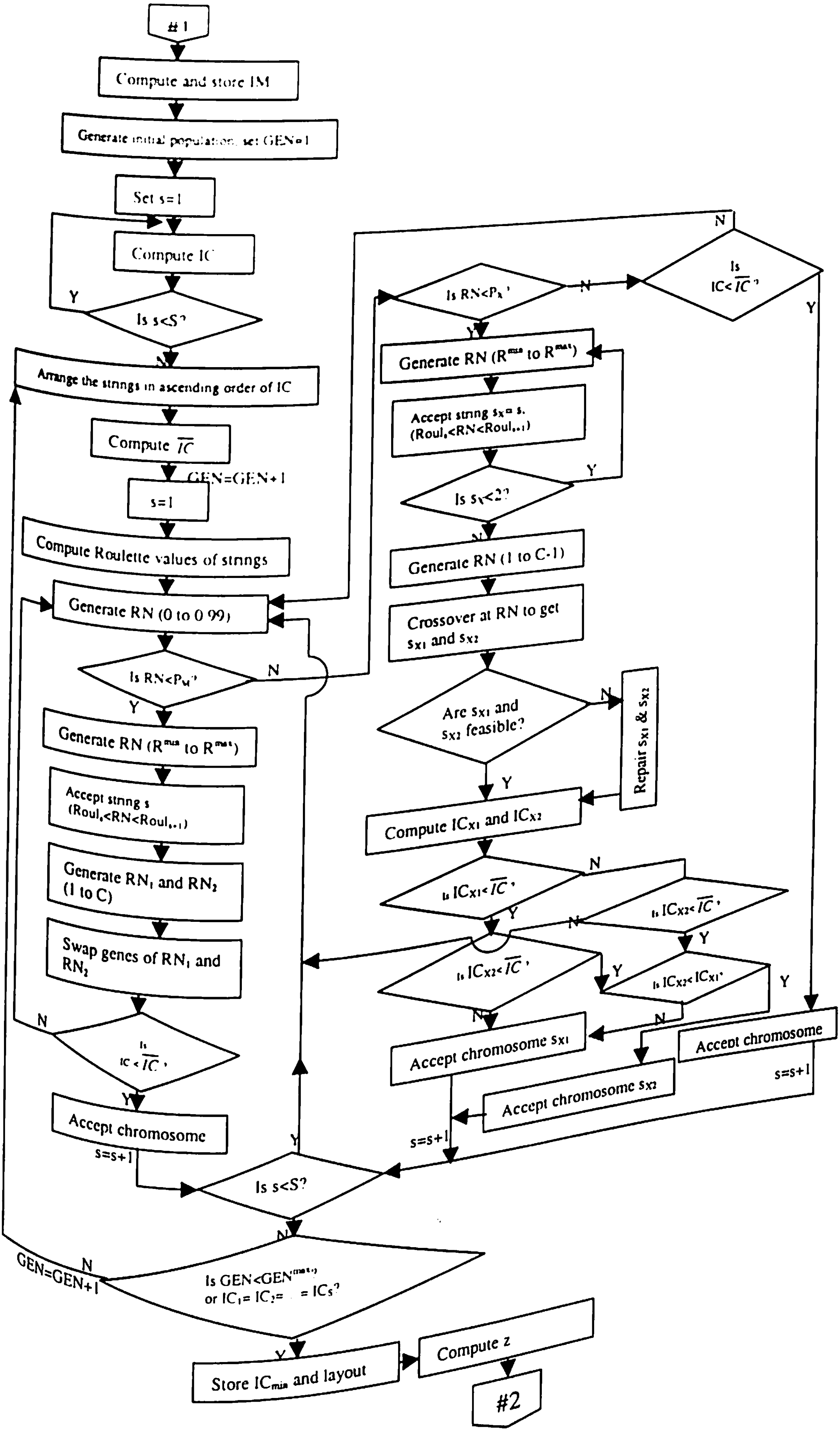


Figure 7.2 (contd.): Flowchart of the SAFUGA model (contd. on next page)

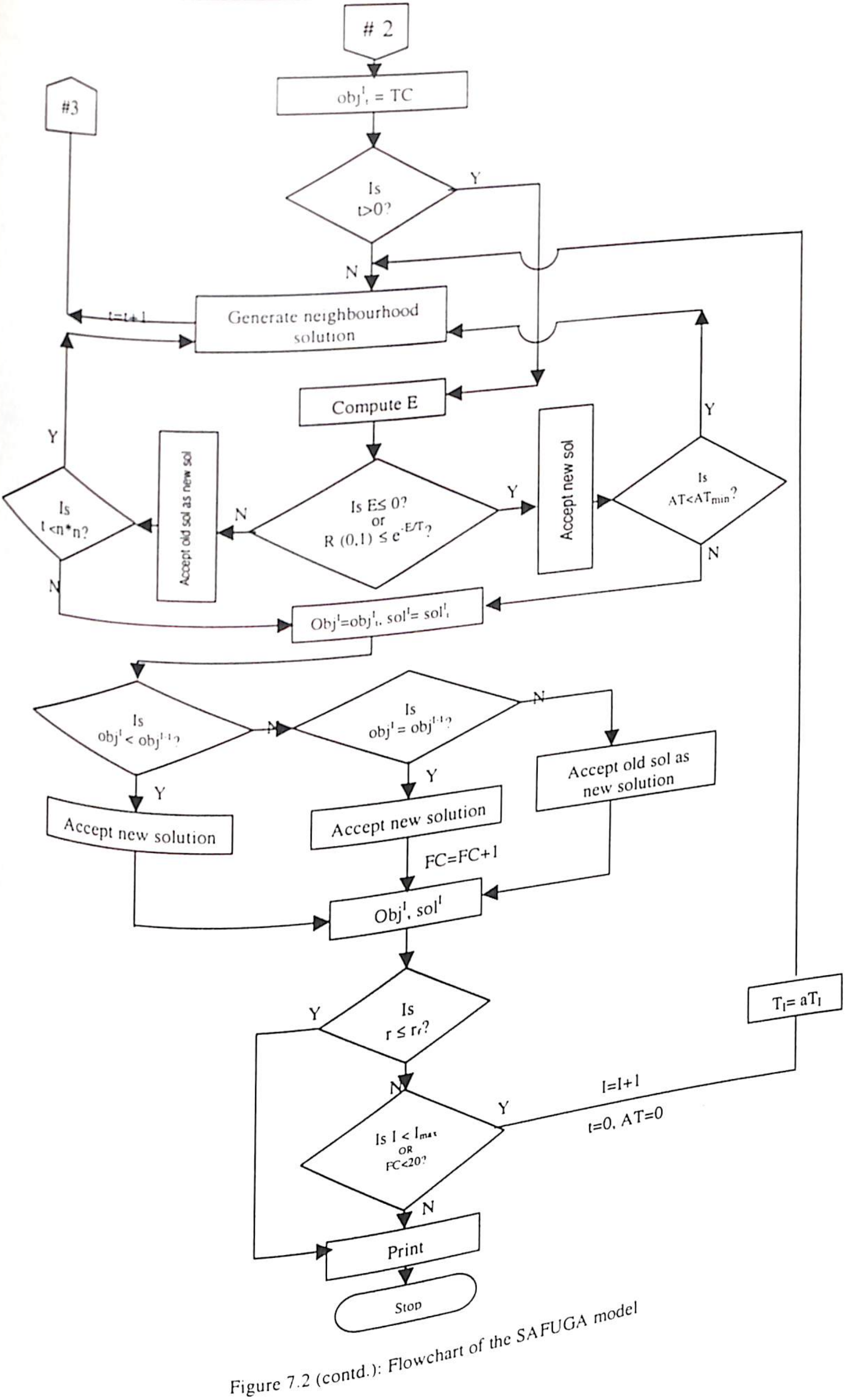


Figure 7.2 (contd.): Flowchart of the SAFUGA model

Table 7.4. The solution sets and comparison of the integrated objective function with inter-cell moves for the example 3 (table 5.25) with $D_k/B_k=1$

C	Cells	Parts	Machines	Inter-cell moves	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Machine layout	Cell layout
3	1	1,9,12,14,17,20	1,4,9,10,12,18	13	50.1	10 1 12 18 9 4	1 3 2
	2	2,4,6,7,11,15,19	2,3,5,11,14,16,17			16 14 3 17 11 2 5	
	3	3,5,8,10,13,16,18	6,7,8,13,15,19,20			7 6 8 15 19 20 13	
4	1	1,9,12,14,17,20	1,9,10,12,18	14	52.4	9 1 12 18 10	3 4 2 1
	2	2,4,6,7,11,15,19	2,3,5,11,14,16,17			16 14 3 17 11 2 5	
	3	5,8,13,16	4,6,7,13,15			7 15 4 6 13	
	4	3,10,18	8,19,20			20 19 8	
5	1	1,9,12,14,17,20	1,9,10,12,18	17	54.6	9 1 12 18 10	2 1 5 4 3
	2	2,4,11,19	2,3,11,14			14 11 3 2	
	3	5,8,13,16	4,6,7,13,15			7 15 4 6 13	
	4	3,10,18	8,19,20			20 19 8	
	5	6,7,15	5,16,17			17 16 5	

Table 7.5. The solution sets and comparison of the integrated objective function with inter-cell moves for the example 3 (table 5.25) with given D_k and B_k

C	Cells	Parts	Machines	Inter-cell moves	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Machine layout	Cell layout
3	1	3,10,18	8,19,20	36	162.5	20 19 8	2 3 1
	2	1,2,4,9,11,12,14,17,19,20	1,2,3,4,5,9,10,11,12,18			5 11 2 3 12 1 10 4 18 9	
	3	5,6,7,8,13,15,16	6,7,13,14,15,16,17			13 14 16 7 15 17 6	
4	1	2,4,6,7,11,15,19	2,3,5,11,14,16,17	41	164.2	14 11 2 16 5 3 17	4 3 1 2
	2	1,9,12,14,17,20	1,9,10,12,18			9 1 12 18 10	
	3	3,10,18	8,19,20			20 19 8	
	4	5,8,13,16	4,6,7,13,15			15 7 6 4 13	
5	1	6,7,15	13,14,16,17	59	168.6	17 16 13 14	3 4 2 1 5
	2	3,10,14,18	8,10,19,20			20 19 8 10	
	3	5,8,13,16	4,6,7,15			15 7 4 6	
	4	1,9,12,17,20	1,9,12,18			18 12 9 1	
	5	2,4,11,19	2,3,5,11			11 5 2 3	

Table 7.6. The solution sets and comparison of the integrated objective function with inter-cell moves for example 4 (table 5.28)

C	Cells	Parts	Machines	Inter-cell moves	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Machine layout	Cell layout
5	1	2,10,11,12, 23,31,32,33, 39, 40,41	1,2,3,10,11, 21,22,23	1073	6061.3	23 10 3 1 21 22 11 2	3 2 4 5 1
	2	8,15,24,25, 28,35	4,12,27,28			28 27 4 12	
	3	7,14,16,17, 19,27,34,36, 37, 38	5,7,13,15, 17,18,24,26			15 5 24 26 17 13 7 18	
	4	1,3,9,13,21, 22,29,30	8,9,19,20, 29,30			29 19 30 9 8 20	
	5	4,5,6,18,26	6,14,16,25			25 14 6 16	
6	1	10,11,12,31, 32,33,39,40, 41	1,2,3,11, 21,22	1448	5979.3	1 22 3 11 2 21	3 5 4 6 2 1
	2	2,8,15,19,20 ,23,24,28,35	4,10,12,23, 27,28			4 28 27 12 23 10	
	3	7,16,17,27, 34,36,37	5,7,15,17, 18,26			18 17 5 7 26 15	
	4	4,5,6,18,26	6,14,16,25			25 14 6 16	
	5	1,3,9,13,14, 21,22,29,30	8,9,19,20,29 ,30			29 19 8 9 30 20	
	6	25,38	13,24			24 13	
7	1	10,23,31, 32,40	1,3,22	1589	6037.4	22 3 1	3 4 6 2 7 5 1
	2	2,11,12,20, 33,39,41	2,10,11,12, 21,23			23 10 11 12 21 2	
	3	4,5,18	14,25			14 25	
	4	6,8,15,24, 26,28,29,35	4,6,8,16, 27,28			6 16 8 27 4 28	
	5	7,14,16,17, 27,34,36,37	5,7,15,17, 18,26			18 17 5 7 26 15	
	6	1,3,9,13, 21,22,30	9,19,20, 29,30			20 29 9 30 19	
	7	19,25,38	13,24			13 24	

7.5 Comparison of Results of SAMUCH and SAFUGA Models

The results of the two models (SAMUCH and SAFUGA) as shown in tables 7.1 to 7.6 indicate that the results (objective value, i.e., inter-cell and intra-cell material handling cost) of the SAFUGA model are better than the results of the SAMUCH model as shown in figure 7.3 ($w_1=0$).

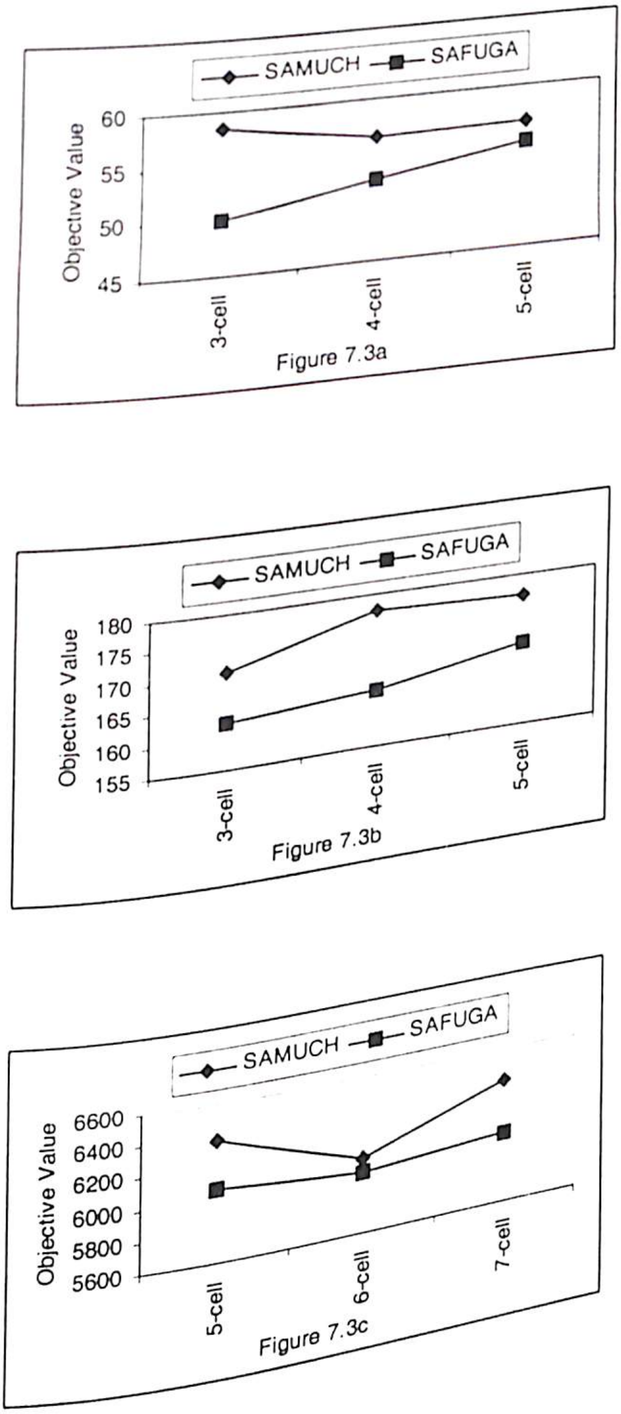


Figure 7.3: Comparison of SAMUCH and SAFUGA results

7.6 Comparison of Integrated Approach Results and Sequential Approach Results

In this section the results of sequential and integrated approaches are compared. These results of the sequential approach are obtained from chapter 5 (cells formed) and chapter 6 (layout), and are for $w_1 = 0$, i.e., without considering the effect of qualitative factors in the layout design. Results (integrated objective function, i.e., inter-cell and intra-cell material handling cost) of both, integrated approach and sequential approach are shown in tables 7.7 to 7.12 for the convenience to have a look at both the results simultaneously. These results indicate that the integrated approach produces better results (cells and their layout) than the sequential approach in term of inter-cell and intra-cell material handling cost. In these tables the number of inter-cell moves are also shown for comparison and the number of moves for the integrated approach solutions are more than the sequential approach solutions. This is because the total distance traveled depends upon not only the number of moves but also the distance between the facilities.

Table 7.7: Comparison of integrated approach (SAMUCH) and sequential approach results for example 3 (table 5.25) $D_k/B_k=1$

Sequential Approach						**Integrated Approach (SAMUCH)**					
C	Cells	Parts	Machines	Inter-cell moves	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Inter-cell moves	Machines	Parts	Cells	C
3	1	2,4,6,7,11, 15,19	2,3,5,11, 14,16,17	11	58.5	58.5	13	1,4,9,10, 12,18	1,9,12,14, 17,20	1	3
	2	5,8,13,16	4,6,7,13,15					2,3,5,11, 14,16,17	2,4,6,7, 11,15,19	2	
	3	1,3,9,10,12, 14,17,18,20	1,8,9,10,12, 18,19,20					6,7,8,13, 15,19,20	3,5,8,10, 13,16,18	3	
4	1	2,4,6,7,11, 15,19	2,3,5,11, 14,16,17	14	59.4	56.3	17	2,3,11, 14,16,17	2,4,6,7, 11,15,19	1	4
	2	1,9,12,14, 17,20	1,9,10,12,18					5,9,18	9,12	2	
	3	3,10,18	8,19,20					1,8,10, 12,19,20	1,3,10,14, 17,18,20	3	
	4	5,8,13,16	4,6,7,13,15					4,6,7, 13,15	5,8,13,16	4	
5	1	1,9,12,14, 17,20	1,9,10,12,18	17	58.7	56.6	17	8,19,20	3,10,18	1	5
	2	2,4,11,19	2,3,11,14					16,17	6,7,15	2	
	3	5,8,13,16	4,6,7,13,15					4,6,7, 13,15	5,8,13,16	3	
	4	3,10,18	8,19,20					2,3,11,14	2,4,11,19	4	
	5	6,7,15	5,16,17					1,5,9,10, 12,18	1,9,12, 14,17,20	5	

Table 7.8: Comparison of integrated approach (SAMUCH) and sequential approach results for example 3 (table 5.25) with given D_k and B_k

Sequential Approach						**Integrated Approach (SAMUCH)**					
C	*Cells*	*Parts*	*Machines*	Inter-cell moves	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Inter-cell moves	Machines	Parts	Cells	C
3	1	2,4,6,7,11,15,19	2,3,5,11, 14,16,17	33	**175.4**	**170.8**	38	1,2,3,5,9, 11,12,18	1,2,4,9,11,12, 14,17,19,20	1	3
	2	5,8,13,16	4,6,7,13,15					8,10,19,20	3,10,18	2	
	3	1,3,9,10,12, 14,17,18,19,20	1,8,9,10,12, 18,19,20					4,6,7,13, 14,15,16,17	5,6,7,8, 13,15,16	3	
4	1	2,4,6,7,11, 15,19	2,3,5,11, 14,16,17	**41**	**177.3**	**177.3**	**41**	2,3,5,11, 14,16,17	2,4,6,7, 11,15,19	1	4
	2	1,9,12,14,17,20	1,9,10,12,18					1,9,10, 12,18	1,9,12, 14,17,20	2	
	3	3,10,18	8,19,20					8,19,20	3,10,18	3	
	4	5,8,13,16	4,6,7,13,15					4,6,7, 13,15	5,8,13,16	4	
5	1	6,7,11,15,19	5,11,13, 14,16,17	**53**	**180.9**	**176.6**	**59**	13,14, 16,17	6,7,15	1	5
	2	3,10,18	8,19,20					8,10,19,20	3,10,14,18	2	
	3	5,8,13,16	4,6,7,15					4,6,7,15	5,8,13,16	3	
	4	1,9,12,14, 17,20	1,9,10,12,18					1,9,12,18	1,9,12, 17,20	4	
	5	2,4	2,3					2,3,5,11	2,4,11,19	5	

Table 7.9: Comparison of integrated approach (SAMUCH) and sequential approach results for example 4 (table 5.28) with given D_k and B_k

Sequential Approach						Integrated Approach (SAMUCH)					
C	Cells	Parts	Machines	Inter-cell moves	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Inter-cell moves	Machines	Parts	Cells	C
5	1	2,10,11,12,20,23, 31,32,33, 39,40,41	12 2 3 10 21 22 23 11 1	820	6774.1	6365.1	1073	3 10 23 22 21 2 1 11	2,10,11,12,23,31, 32,33,39, 40,41	1	5
	2	15,19,24,25, 28,35,38	27 24 4 13					28 27 4 12	8,15,24,25,28,35	2	
	3	7,14,16,17,27,34, 36,37	18 17 5 7 26 15					15 26 7 24 17 18 13 5	7,14,16,17,19,27, 34,36,37, 38	3	
	4	1,3,8,9,13, 21,22,29,30	20 30 9 8 19 29 28					29 19 30 9 8 20	1,3,9,13,21, 22,29,30	4	
	5	4,5,6,18,26	25 14 6 16					25 14 6 16	4,5,6,18,26	5	
6	1	1,3,9,13,21, 22,29,30	29 19 8 9 30 20	1232	6271.4	6077.3	1448	11 2 3 1 21 22	10,11,12,31,32, 33,39,40,41	1	6
	2	4,5,6,8,15,18, 24,25,26,28,35	27 6 25 4 16 14 28					23 12 27 10 4 28	2,8,15,19,20, 23,24,28,35	2	
	3	7,14,16,17, 27,34,36,37	18 17 5 7 26 15					26 17 18 7 15 5	7,16,17,27,34, 36,37	3	
	4	23,40	3 22					25 14 6 16	4,5,6,18,26	4	
	5	19,38	13 24					29 19 30 9 8 20	1,3,9,13,14, 21,22,29,30	5	
	6	2,10,11,12,20, 31,32,33,39,41	23 2 11 10 21 1 12					24 13	25,38	6	

Table 7.9 (contd.): Comparison of integrated approach (SAMUCH) and sequential approach results for example 4 (table 5.28) with given D_k and B_k

Sequential Approach						**Integrated Approach (SAMUCH)**					
C	Cells	Parts	Machines	Inter-cell moves	Integrated objective function (TC) α_1=0.7, α_2=1.0	Integrated objective function (TC) α_1=0.7, α_2=1.0	Inter-cell moves	Machines	Parts	Cells	C
7	1	10,23,31, 32,40	22 3 1	**1589**	**6386.9**	**6386.9**	**1589**	22 3 1	10,23,31, 32,40	1	7
	2	2,11,12,20, 33,39,41	23 10 11 12 21 2					23 10 11 12 21 2	2,11,12,20, 33,39,41	2	
	3	4,5,18	14 25					14 25	4,5,18	3	
	4	6,8,15,24, 26,28,29,35	6 16 8 27 4 28					6 16 8 27 4 28	6,8,15,24, 26,28,29,35	4	
	5	7,14,16,17, 27,34,36,37	18 17 5 7 26 15					18 17 5 7 26 15	7,14,16,17, 27,34,36,37	5	
	6	1,3,9,13, 21,22,30	20 29 9 30 19					20 29 9 30 19	1,3,9,13, 21,22,30	6	
	7	19,25,38	13 24					13 24	19,25,38	7	

Table 7.10: Comparison of integrated approach (SAFUGA) and sequential approach results for example 3 (table 5.25) $D_k/B_k=1$

Sequential Approach						**Integrated Approach (SAFUGA)**					
C	Cells	Parts	Machines	Inter-cell moves	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Inter-cell moves	Machines	Parts	Cells	C
3	1	2,4,6,7,11, 15,19	2,3,5,11, 14,16,17	11	52.9	50.1	13	1,4,9,10, 12,18	1,9,12,14, 17,20	1	3
	2	5,8,13,16	4,6,7,13,15					2,3,5,11, 14,16,17	2,4,6,7, 11,15,19	2	
	3	1,3,9,10,12, 14,17,18,20	1,8,9,10,12, 18,19,20					6,7,8,13, 15,19,20	3,5,8,10, 13,16,18	3	
4	1	2,4,6,7, 11,15,19	2,3,5,11, 14,16,17	14	52.4	52.4	14	1,9,10,12,18	1,9,12,14,17,20	1	4
	2	1,9,12,14, 17,20	1,9,10,12,18					2,3,5,11, 14,16,17	2,4,6,7, 11,15,19	2	
	3	3,10,18	8,19,20					4,6,7,13,15	5,8,13,16	3	
	4	5,8,13,16	4,6,7, 13,15					8,19,20	3,10,18	4	
5	1	1,9,12,14, 17,20	1,9,10, 12,18	17	54.6	54.6	17	1,9,10,12,18	1,9,12,14,17,20	1	5
	2	2,4,11,19	2,3,11,14					2,3,11,14	2,4,11,19	2	
	3	5,8,13,16	4,6,7,13,15					4,6,7,13,15	5,8,13,16	3	
	4	3,10,18	8,19,20					8,19,20	3,10,18	4	
	5	6,7,15	5,16,17					5,16,17	6,7,15	5	

7.11: Comparison of integrated approach (SAFUGA) and sequential approach results for example 3 (table 5.25) with given D_k and B_k

Sequential Approach						**Integrated Approach (SAFUGA)**					
C	Cells	Parts	Machines	Inter-cell moves	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Inter-cell moves	Machines	Parts	Cells	C
3	1	2,4,6,7,11,15,19	2,3,5,11, 14,16,17	33	172.6	162.5	36	8,19,20	3,10,18	1	3
	2	5,8,13,16	4,6,7,13,15					1,2,3,4,5,9, 10,11,12,18	1,2,4,9,11,12, 14,17,19,20	2	
	3	1,3,9,10,12,14,17, 18,19,20	1,8,9,10,12, 18,19,20					6,7,13,14, 15,16,17	5,6,7,8, 13,15,16	3	
4	1	2,4,6,7,11,15,19	2,3,5,11,14, 16,17	41	167.6	164.2	41	2,3,5,11, 14,16,17	2,4,6,7, 11,15,19	1	4
	2	1,9,12,14,17,20	1,9,10,12,18					1,9,10,12,18	1,9,12, 14,17,20	2	
	3	3,10,18	8,19,20					8,19,20	3,10,18	3	
	4	5,8,13,16	4,6,7,13,15					4,6,7,13,15	5,8,13,16	4	
5	1	6,7,11,15,19	5,11,13,14,16,17	53	171.8	168.6	59	13,14,16,17	6,7,15	1	5
	2	3,10,18	8,19,20					8,10,19,20	3,10,14,18	2	
	3	5,8,13,16	4,6,7,15					4,6,7,15	5,8,13,16	3	
	4	1,9,12,14,17,20	1,9,10,12,18					1,9,12,18	1,9,12,17,20	4	
	5	2,4	2,3					2,3,5,11	2,4,11,19	5	

Table 7.12: Comparison of integrated approach (SAFUGA) and sequential approach results for example 4 (table 5.28) with given D_k and B_k

Sequential Approach						**Integrated Approach (SAFUGA)**					
C	Cells	Parts	Machines	Inter-cell moves	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Inter-cell moves	Machines	Parts	Cells	C
5	1	2,10,11,12,20,23, 31,32,33, 39,40,41	12 2 3 10 21 22 23 11 1	820	6075.5	6061.3	1073	23 10 3 1 21 22 11 2	2,10,11,12,23,31, 32,33,39, 40,41	1	5
	2	15,19,24,25, 28,35,38	27 24 4 13					28 27 4 12	8,15,24,25,28,35	2	
	3	7,14,16,17,27,34, 36,37	18 17 5 7 26 15					15 5 24 26 17 13 7 18	7,14,16,17,19,27, 34,36,37, 38	3	
	4	1,3,8,9,13, 21,22,29,30	20 30 9 8 19 29 28					29 19 30 9 8 20	1,3,9,13,21, 22,29,30	4	
	5	4,5,6,18,26	25 14 6 16					25 14 6 16	4,5,6,18,26	5	
6	1	1,3,9,13,21, 22,29,30	29 19 8 9 30 20	1232	6087.5	5979.3	1448	1 22 3 11 2 21	10,11,12,31,32, 33,39,40,41	1	6
	2	4,5,6,8,15,18, 24,25,26,28,35	27 6 25 4 16 14 28					4 28 27 12 23 10	2,8,15,19,20, 23,24,28,35	2	
	3	7,14,16,17, 27,34,36,37	18 17 5 7 26 15					18 17 5 7 26 15	7,16,17,27,34, 36,37	3	
	4	23,40	3 22					25 14 6 16	4,5,6,18,26	4	
	5	19,38	13 24					29 19 8 9 30 20	1,3,9,13,14, 21,22,29,30	5	
	6	2,10,11,12,20, 31,32,33,39,41	23 2 11 10 21 1 12					24 13	25,38	6	

Table 7.12 (contd.): Comparison of integrated approach (SAFUGA) and sequential approach results for example 4 (table 5.28) with given D_k and B_k

Sequential Approach						**Integrated Approach (SAFUGA)**					
C	Cells	Parts	Machines	Inter-cell moves	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Integrated objective function (TC) $\alpha_1=0.7$, $\alpha_2=1.0$	Inter-cell moves	Machines	Parts	Cells	C
7	1	10,23,31,32,40	22 3 1	**1589**	**6037.4**	**6037.4**	**1589**	22 3 1	10,23,31,32,40	1	7
	2	2,11,12,20,33,39,41	23 10 11 12 21 2					23 10 11 12 21 2	2,11,12,20,33,39,41	2	
	3	4,5,18	14 25					14 25	4,5,18	3	
	4	6,8,15,24,26,28,29,35	6 16 8 27 4 28					6 16 8 27 4 28	6,8,15,24,26,28,29,35	4	
	5	7,14,16,17,27,34,36,37	18 17 5 7 26 15					18 17 5 7 26 15	7,14,16,17,27,34,36,37	5	
	6	1,3,9,13,21,22,30	20 29 9 30 19					20 29 9 30 19	1,3,9,13,21,22,30	6	
	7	19,25,38	13 24					13 24	19,25,38	7	

7.7 Evaluation of Integrated Approach Using Simulation Model

One of the largest application areas for simulation modelling is that of manufacturing systems, with the first uses dating back to at least the early 1960's (Law and McComas 1998). A simulation model is a surrogate for actually experimenting with a manufacturing system, which is often infeasible or not cost-effectiveness.

7.7.1 Manufacturing issues addressed by simulation

Following are some of the issues that simulation is used to addressed in manufacturing:

i) The need for and the quantity of equipment and personnel

- Number, type, and layout of machines for a particular objective
- Requirements for transporters, conveyers, and other support equipments (e. g. pallets and fixtures)
- Location and size of inventory buffers
- Evaluation of a change in product volume or mix
- Evaluation of the effect of a new piece of equipment on an existing manufacturing system
- Evaluation of capital investments
- Number of shifts

ii) Performance evaluation

- Throughput analysis
- Time-in-system analysis
- Bottleneck analysis

iii) Evaluation of operational procedures

- Production scheduling
- Inventory policies
- Control strategies (e. g. for an automated guided vehicle system)
- Reliability analysis (e.g. effect of preventive maintenance)
- Quality-control policies

The following are some of performance measures commonly estimated by simulation:

- Throughput time
- Work-in-process (WIP)
- Waiting time
- Queue sizes
- Lateness
- Utilization of equipment or personnel
- Transfer time

7.7.2 Development of the simulation model

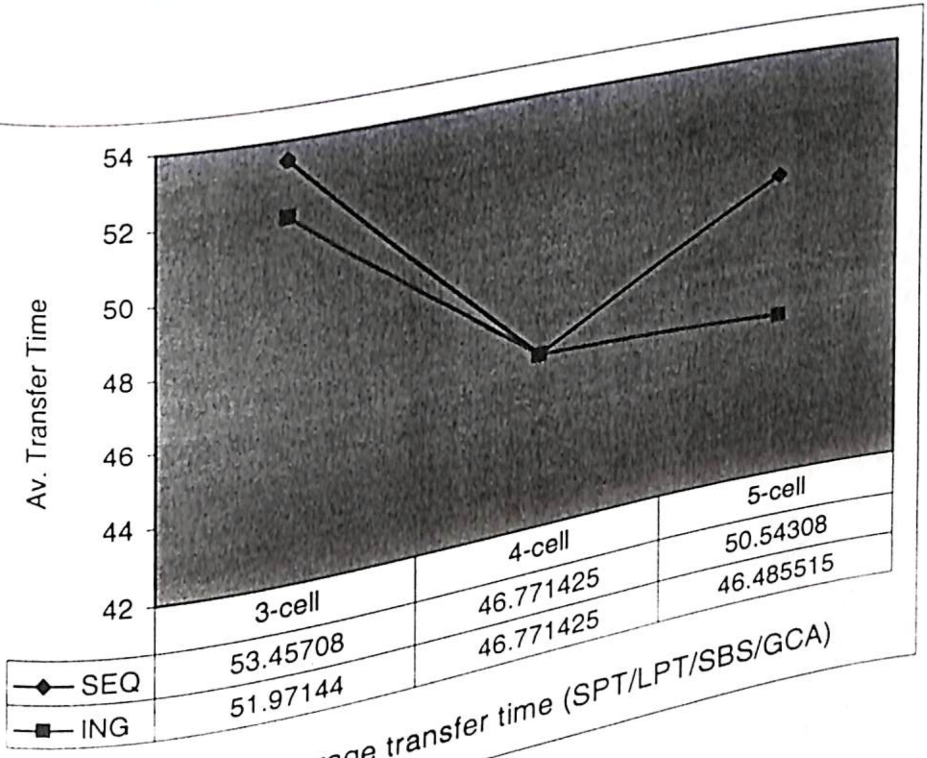
Simulation model for the sequential approach solutions and integrated approach solutions are developed by using ARENA simulation software. Five simulation models are developed for the results given in table 7.11. One solution is same for sequential approach as well as integrated approach (4-cell solution). Simple models are often advocated in the literature on the basis that the project will then be more successful (Brooks and Tobias 2000). The approach to modeling usually suggested is to start by building a simple model and then gradually to add details (Jacoby and

Kowalik 1980, Banks *et al.* 1996, Pidd 1996). Assumptions made in the simulation models are as follows:

- Operating time for each part is known.
- Demand and batch size for each part is known.
- Machine types and parts to be manufactured are placed in predetermined cells.
- Each part has a fixed routing.
- Raw materials required for production during the entire simulation run is available at the beginning.
- The storage capacity of raw materials and finished goods is unlimited.
- The queue length at any machine is unlimited.
- Each cell has only one transporter (this transporter is dedicated to this cell only) and one transporter is available for inter-cell movements between all cells.
- The velocity of transporters is fixed.
- There is only one operation at a time on a machine.
- Processing times are known deterministically, since operations are computer controlled.
- Distance between adjacent stations is unity.
- Transporter capacity is unlimited.
- Machines are continuously available for production.
- Raw material, tools, jigs, fixtures etc. are present and released immediately when required.
- The scheduling philosophies used in the simulation models are: shortest processing time (SPT), longest processing time (LPT), shortest batch size (SBS), goal chasing algorithm (GCA).

7.7.3 Results and discussions

The results of the simulation model are shown in tables 7.13 to 7.31 and figures 7.4 to 7.10 for sequential (SEQ) and integrated (ING) approaches. Figure 7.4 shows the average transfer time for the parts in the system. This average transfer time is proportional to the distance traveled by the parts. As the figure 7.4 shows the integrated approach solutions (average transfer time) are better than the sequential approach solutions for 3-cell and 5-cell solutions, same for 4-cell solution. This validates the models developed for the integrated approach. Figures 7.5 to 7.10 show the results of some other performance measures (throughput time, average throughput time, average waiting time, average WIP, inter-cell transporter utilization, and average intra-cell transporter utilization) for sequential and integrated approaches for scheduling philosophies. As is evident from the figures 7.4 to 7.10, there is no clear trend about the best scheduling philosophy. However, SBS seems a good scheduling philosophy for the integrated approach.



	3-cell	4-cell	5-cell
◆ SEQ	53.45708	46.771425	50.54308
■ ING	51.97144	46.771425	46.485515

Figure 7.4: Average transfer time (SPT/LPT/SBS/GCA)

Table 7.13: Transfer time (SPT)

PART	3-cell		4-cell		5-cell	
	SEQ	ING	SEQ	ING	SEQ	ING
PART01	53.7143	53.7143	49.7143	49.7143	55.4286	49.7143
PART02	28	44	36	36	55.4286	28
PART03	20	24	20	20	20	20
PART04	61.7143	52	79.4286	79.4286	86.8571	51.4286
PART05	36	79.4286	28	28	28	28
PART06	109.14	89.1429	44	44	36	77.1429
PART07	71.4286	63.4286	28	28	28	59.4286
PART08	103.43	77.7143	74.8571	74.8571	110.29	113.71
PART09	44	36	54.8571	54.8571	55.4286	67.4286
PART10	28	24	28	28	28	28
PART11	79.4286	79.4286	52	52	45.7143	43.4286
PART12	44	36	78.8571	78.8571	63.4286	51.4286
PART13	36	36	41.7143	41.7143	47.4286	49.7143
PART14	79.4286	87.4286	94.8571	94.8571	98.2857	59.4286
PART15	28	28	28	28	28	28
PART16	67.4286	59.4286	47.4286	47.4286	49.7143	39.4286
PART17	36	28	20	20	20	20
PART18	28	53.7143	57.7143	57.7143	63.4286	28
PART19	36	52	44	44	63.4286	28
PART20	79.4286	36	28	28	28	59.4286
Average	53.4570	51.9714	46.7714	46.7714	50.5430	46.4855

Table 7.14: Transfer time (LPT)

	3-cell		4-cell		5-cell	
PART	SEQ	ING	SEQ	ING	SEQ	ING
PART01	53.7143	53.7143	49.7143	49.7143	55.4286	49.7143
PART02	44	28	36	36	55.4286	28
PART03	24	20	20	20	20	20
PART04	52	61.7143	79.4286	79.4286	86.8571	51.4286
PART05	79.4286	36	28	28	28	28
PART06	89.1429	109.14	44	44	36	77.1429
PART07	63.4286	71.4286	28	28	28	59.4286
PART08	77.7143	103.43	74.8571	74.8571	110.29	113.71
PART09	36	44	54.8571	54.8571	55.4286	67.4286
PART10	24	28	28	28	28	28
PART11	79.4286	79.4286	52	52	45.7143	43.4286
PART12	36	44	78.8571	78.8571	63.4286	51.4286
PART13	36	36	41.7143	41.7143	47.4286	49.7143
PART14	87.4286	79.4286	94.8571	94.8571	98.2857	59.4286
PART15	28	28	28	28	28	28
PART16	59.4286	67.4286	47.4286	47.4286	49.7143	39.4286
PART17	28	36	20	20	20	20
PART18	53.7143	28	57.7143	57.7143	63.4286	28
PART19	52	36	44	44	63.4286	28
PART20	36	79.4286	28	28	28	59.4286
Average	53.4570	51.9714	46.7714	46.7714	50.5430	46.4855

Table 7.15: Transfer time (SBS)

	3-cell		4-cell		5-cell	
PART	SEQ	ING	SEQ	ING	SEQ	ING
PART01	53.7143	53.7143	49.7143	49.7143	55.4286	49.7143
PART02	28	44	36	36	55.4286	28
PART03	20	24	20	20	20	20
PART04	61.7143	52	79.4286	79.4286	86.8571	51.4286
PART05	36	79.4286	28	28	28	28
PART06	109.14	89.1429	44	44	36	77.1429
PART07	71.4286	63.4286	28	28	28	59.4286
PART08	103.43	77.7143	74.8571	74.8571	110.29	113.71
PART09	44	36	54.8571	54.8571	55.4286	67.4286
PART10	28	24	28	28	28	28
PART11	79.4286	79.4286	52	52	45.7143	43.4286
PART12	44	36	78.8571	78.8571	63.4286	51.4286
PART13	36	36	41.7143	41.7143	47.4286	49.7143
PART14	79.4286	87.4286	94.8571	94.8571	98.2857	59.4286
PART15	28	28	28	28	28	28
PART16	67.4286	59.4286	47.4286	47.4286	49.7143	39.4286
PART17	36	28	20	20	20	20
PART18	28	53.7143	57.7143	57.7143	63.4286	28
PART19	36	52	44	44	63.4286	28
PART20	79.4286	36	28	28	28	59.4286
Average	53.4570	51.9714	46.7714	46.7714	50.5430	46.4855

Table 7.16: Transfer time (GCA)

PART	3-cell		4-cell		5-cell	
	SEQ	ING	SEQ	ING	SEQ	ING
PART01	53.71	53.71	49.7143	49.7143	55.43	49.7143
PART02	28	44	36	36	55.43	28
PART03	20	24	20	20	20	20
PART04	61.71	52	79.4286	79.4286	86.86	51.4286
PART05	36	79.43	28	28	28	28
PART06	109.14	89.14	44	44	36	77.1429
PART07	71.43	63.43	28	28	28	59.4286
PART08	103.43	77.71	74.8571	74.8571	110.29	113.71
PART09	44	36	54.8571	54.8571	55.43	67.4286
PART10	28	24	28	28	28	28
PART11	79.43	79.43	52	52	45.71	43.4286
PART12	44	36	78.8571	78.8571	63.43	51.4286
PART13	36	36	41.7143	41.7143	47.43	49.7143
PART14	79.43	87.43	94.8571	94.8571	98.29	59.4286
PART15	28	28	28	28	28	28
PART16	67.43	59.43	47.4286	47.4286	49.71	39.4286
PART17	36	28	20	20	20	20
PART18	28	53.71	57.7143	57.7143	63.43	28
PART19	36	52	44	44	63.43	28
PART20	79.43	36	28	28	28	59.4286
Average	53.457	51.971	46.7714	46.7714	50.5435	46.4855

Table 7.17: Throughput time (SPT)

	3-cell		4-cell		5-cell	
	SEQ	ING	SEQ	ING	SEQ	ING
PART01	523.32	595.28	503.29	503.29	569.99	677.64
PART02	984	1224	1148	1148	1209.49	1233.63
PART03	1061.29	1023.25	1042.97	1042.97	1051.6	1055.6
PART04	1100.57	1160	973.78	973.78	832.14	944.12
PART05	1177.87	1270.16	1058.67	1058.67	1049.85	1062.48
PART06	2159.95	2184.17	1964.67	1964.67	2053.15	2052.17
PART07	764	668	706	706	496	581.58
PART08	2559.27	2819.95	2527.41	2527.41	2454.01	2497.57
PART09	2065.4	2224	1977.32	1977.32	1881.21	1819.73
PART10	922.85	1008.13	1025.18	1025.18	1035.34	1023.83
PART11	840	1256	490	490	664.3	605.56
PART12	1840.08	1868	1538.69	1538.69	1473.21	1403.75
PART13	987.87	758	1071.02	1071.02	809.59	896.06
PART14	1645.63	1821.43	1486.4	1486.4	1264.05	1236.73
PART15	1545.79	1481.38	1654.46	1654.46	1205.44	1239.99
PART16	1299.08	1110.18	1268.15	1268.15	1274.01	1281.94
PART17	1200.8	1376.8	572.78	572.78	582.15	514.27
PART18	1253.48	1400	1322.53	1322.53	1296.64	1236.43
PART19	3344.42	3356.08	3316.28	3316.28	3252.05	3260.08
PART20	1108	1044	561.4	561.4	563.39	609.45
Average	1419.184	1482.441	1310.45	1310.45	1250.881	1261.631
Throughput time	4232	4200	4199	4199	4125	4109

Table 7.18: Throughput time (LPT)

PART	3-cell		4-cell		5-cell	
	SEQ	ING	SEQ	ING	SEQ	ING
PART01	1388.28	1358.17	1635.82	1635.82	1639.63	1711.95
PART02	4424.57	1212	4391	4391	4371.5	4387.67
PART03	1282.68	1194.3	1560.32	1560.32	1571.36	1647.57
PART04	4074.5	2888.93	4091.44	4091.44	4055.7	4021.24
PART05	1807.75	1794.5	1750.51	1750.51	1755.17	1748.43
PART06	3498.84	2549.1	3496.44	3496.44	2927.39	3361.59
PART07	1506.16	1279.71	1066	1066	1637.01	1437.07
PART08	1753.52	2226.09	1771.21	1771.21	1751.27	1785.79
PART09	2172.65	1976	3052.38	3052.38	2034.4	1961.93
PART10	243.59	234.43	279.8	279.8	305.38	400.26
PART11	4328.98	2251.34	2480.67	2480.67	4033.79	4052.23
PART12	1498.44	1858.25	1650.37	1650.37	1392.54	1323.74
PART13	1866.32	2075.01	2025.24	2025.24	1887.71	1849.75
PART14	1643.11	2549.85	1219.21	1219.21	1878.36	1914.51
PART15	1209.52	1220.22	1386.02	1386.02	1110.98	961.24
PART16	1530.5	1609.16	1359.82	1359.82	1369.74	1446.73
PART17	1593.1	1657.64	1215.34	1215.34	1248.88	1252.92
PART18	664.85	988	909.04	909.04	908.63	997.03
PART19	2112.62	2881.99	2010.34	2010.34	2182.88	2143.25
PART20	1392	1184	662.22	662.22	568.57	837.43
Average	1999.599	1749.435	1900.66	1900.66	1931.545	1962.117
Throughput time	4517	4377	4496	4496	4475	4493

Table 7.19: Throughput time (SBS)

PART	3-cell		4-cell		5-cell	
	SEQ	ING	SEQ	ING	SEQ	ING
PART01	899.48	710.19	797.95	797.95	999.52	1028.67
PART02	4462.95	4461.67	4406.02	4406.02	4325.8	4327.28
PART03	1508.85	1519.04	1591.46	1591.46	1625.89	1709.87
PART04	1948.78	1875.35	1344.15	1344.15	2356.22	1572.84
PART05	1521.72	1405.87	1299.17	1299.17	1298.23	1291.73
PART06	2146.27	2176.93	2216.94	2216.94	2214.46	2244.15
PART07	756	700	676	676	575.68	514.54
PART08	2537.99	2531.92	2435.27	2435.27	2476.07	2476.97
PART09	1204	1300	977.13	977.13	1022.75	895.54
PART10	201.82	224.32	242.65	242.65	237.76	258.72
PART11	604	768	388	388	287.61	342
PART12	1982.03	1851.35	1814.45	1814.45	1779.55	1721.39
PART13	928	845.9	1052	1052	862.6	830.27
PART14	1237.6	1616.54	758.4	758.4	659.93	563.17
PART15	1557.31	1531.54	1773.91	1773.91	1516.11	1421.09
PART16	1039.22	917.26	852.09	852.09	852.55	838.28
PART17	1432.8	1600.8	1246.52	1246.52	1300.23	1215.73
PART18	730.16	824	1094.96	1094.96	1159.74	1280.93
PART19	3109.41	3123.28	3040.79	3040.79	3083.12	3073.42
PART20	1308	1148	934.31	934.31	933.91	1087.8
Average	1555.82	1556.598	1447.109	1447.109	1478.387	1434.72
Throughput time	4568	4569	4511	4511	4429	4432

Table 7.20: Throughput time (GCA)

PART	3-cell		4-cell		5-cell	
	SEQ	ING	SEQ	ING	SEQ	ING
PART01	23311.73	20544.16	6364.28	6364.28	6844.97	7435.4
PART02	22355.3	20617.8	20649.95	20649.95	3895.14	6436.75
PART03	4771.8	5141.58	4017.86	4017.86	4074.56	4580.66
PART04	23318.66	20544.8	20669.37	20669.37	6044	8634.43
PART05	21644.48	33089.21	7561.53	7561.53	6467.68	7020.93
PART06	23825.39	45623.57	20786.67	20786.67	13696.37	14964.61
PART07	22799.68	33045.35	20608	20608	13693.6	11440.76
PART08	22685.44	32964.6	14706.57	14706.57	12289.87	8023.97
PART09	22594.93	20737.6	11566.06	11566.06	11540.85	9105.34
PART10	4768.8	5135.8	4007.4	4007.4	4105.6	4519.6
PART11	23467.6	37886	20611	20611	13529.63	11093
PART12	22689.92	20847.04	11544.9	11544.9	11498.79	9061.53
PART13	21613.9	15131.8	14545.45	14545.45	11303	7467.8
PART14	24755.04	37882.72	12632.08	12632.08	8635.4	9358.88
PART15	21695.63	15232.67	20863.89	20863.89	13769.34	6975.87
PART16	22738.03	15323	7905.18	7905.18	7318.58	9305.35
PART17	22450.8	20588.24	5903.28	5903.28	6195.44	4478.84
PART18	4832.8	14629.12	4213.04	4213.04	5631.68	4648.08
PART19	22449.81	20761.71	20842.65	20842.65	19481.99	6475.23
PART20	24812.4	20692.8	5979.1	5979.1	6388	7481.33
Average	20179.11	22820.98	12798.91	12798.91	9320.225	7925.418
Throughput time	45140	54804	40670	40670	27152	19138

Table 7.21: Waiting time (SPT)

PART	3-cell		4-cell		5-cell	
	SEQ	ING	SEQ	ING	SEQ	ING
PART01	455.6	527.57	439.55	439.55	500.51	613.84
PART02	944.07	1167.93	1100.03	1100.03	1142.11	1193.62
PART03	1030.31	988.26	1011.98	1011.98	1020.61	1024.59
PART04	1022.75	1091.94	878.4	878.4	729.36	876.63
PART05	1123.97	1172.76	1012.68	1012.68	1003.82	1016.48
PART06	2026.83	2071.06	1896.65	1896.65	1993.13	1951.07
PART07	677.6	589.57	662.95	662.95	453.09	507.18
PART08	2431.88	2718.11	2428.61	2428.61	2319.77	2359.92
PART09	1981.4	2147.99	1882.52	1882.52	1785.76	1712.27
PART10	881.71	971.2	984.12	984.12	994.34	982.86
PART11	747.66	1163.7	425.1	425.1	605.67	549.13
PART12	1769.08	1804.94	1432.76	1432.76	1382.87	1325.39
PART13	935.89	706.01	1013.29	1013.29	746.1	830.38
PART14	1549.21	1716.98	1374.52	1374.52	1148.73	1160.34
PART15	1498.77	1434.38	1607.5	1607.5	1158.42	1192.96
PART16	1213.6	1032.78	1202.71	1202.71	1206.28	1224.48
PART17	1153.79	1337.86	541.77	541.77	551.13	483.28
PART18	1209.47	1330.38	1248.89	1248.89	1217.2	1192.4
PART19	3271.47	3267.15	3235.3	3235.3	3151.68	3195.14
PART20	1015.55	995.06	520.48	520.48	522.53	537.04
Average	1347.03	1411.78	1244.99	1244.99	1181.7	1196.45

Table 7.22: Waiting time (LPT)

PART	3-cell		4-cell		5-cell	
	SEQ	ING	SEQ	ING	SEQ	ING
PART01	1320.6	1290.58	1572.06	1572.06	1570.14	1648.21
PART02	4384.59	1156.01	4343.01	4343.01	4304.08	4347.67
PART03	1251.7	1159.32	1529.35	1529.35	1540.35	1616.56
PART04	3996.84	2820.96	3995.97	3995.97	3952.85	3953.9
PART05	1753.71	1697.15	1704.48	1704.48	1709.17	1702.46
PART06	3365.76	2435.93	3428.49	3428.49	2867.47	3260.49
PART07	1419.82	1201.31	1023.11	1023.11	1594.02	1362.58
PART08	1626.07	2124.42	1672.35	1672.35	1616.97	1648.05
PART09	2088.52	1900	2957.45	2957.45	1939.02	1854.47
PART10	202.55	197.43	238.88	238.88	264.32	359.35
PART11	4236.54	2159.02	2415.82	2415.82	3974.92	3995.87
PART12	1427.45	1795.31	1544.51	1544.51	1302.12	1245.42
PART13	1814.33	2023.01	1967.62	1967.62	1824.26	1784.06
PART14	1546.66	2445.46	1107.2	1107.2	1763.13	1838.13
PART15	1162.52	1173.21	1339.02	1339.02	1063.97	914.29
PART16	1445.1	1531.68	1294.44	1294.44	1302.11	1389.32
PART17	1546.09	1618.64	1184.31	1184.31	1217.87	1221.9
PART18	620.9	918.25	835.32	835.32	829.19	953.07
PART19	2039.61	2792.99	1929.36	1929.36	2082.45	2078.2
PART20	1299.65	1135.1	621.26	621.26	527.71	764.97
Average	1927.451	1678.789	1835.2	1835.2	1862.3	1896.949

Table 7.23: Waiting time (SBS)

PART	3-cell		4-cell		5-cell	
	SEQ	ING	SEQ	ING	SEQ	ING
PART01	831.68	642.43	734.09	734.09	930.18	965
PART02	4422.98	4405.69	4358.05	4358.05	4258.42	4287.34
PART03	1477.87	1484.04	1560.44	1560.44	1594.89	1678.82
PART04	1871.11	1807.45	1248.81	1248.81	2253.37	1505.35
PART05	1467.66	1308.42	1253.19	1253.19	1252.2	1245.69
PART06	2013.13	2063.78	2148.9	2148.9	2154.46	2143.05
PART07	669.51	621.64	633.12	633.12	532.74	440.11
PART08	2410.65	2430.12	2336.54	2336.54	2341.84	2339.27
PART09	1119.92	1223.88	882.36	882.36	927.18	788.09
PART10	160.74	187.29	201.67	201.67	196.71	217.81
PART11	511.61	675.47	323.11	323.11	228.87	285.61
PART12	1910.91	1788.36	1708.5	1708.5	1689.11	1643.01
PART13	876.1	793.91	994.27	994.27	799.2	764.69
PART14	1141.25	1512.17	646.46	646.46	544.71	486.66
PART15	1510.33	1484.56	1726.95	1726.95	1469.12	1374.07
PART16	953.84	839.87	786.71	786.71	784.86	780.9
PART17	1385.82	1561.83	1215.52	1215.52	1269.24	1184.73
PART18	686.2	754.38	1021.24	1021.24	1080.32	1237
PART19	3036.38	3034.32	2959.81	2959.81	2982.7	3008.45
PART20	1215.58	1098.99	893.27	893.27	893.02	1015.37
Average	1483.66	1485.93	1381.65	1381.65	1409.2	1369.55

Table 7.24: Waiting time (GCA)

PART	3-cell		4-cell		5-cell	
	SEQ	ING	SEQ	ING	SEQ	ING
PART01	23244.06	20476.58	6300.54	6300.54	6775.38	7371.54
PART02	22315.33	20561.82	20601.96	20601.96	3827.75	6396.77
PART03	4740.81	5106.61	3986.9	3986.9	4043.58	4549.68
PART04	23241.02	20476.86	20574.03	20574.03	5941.19	8566.96
PART05	21590.53	32991.8	7515.52	7515.52	6421.74	6975.01
PART06	23692.27	45510.45	20718.65	20718.65	13636.41	14863.49
PART07	22713.33	32966.99	20565	20565	13650.51	11366.41
PART08	22557.93	32862.89	14607.73	14607.73	12155.6	7886.31
PART09	22511.03	20661.56	11471.21	11471.21	11445.46	8997.95
PART10	4727.79	5098.8	3966.42	3966.42	4064.59	4478.59
PART11	23375.11	37793.49	20545.97	20545.97	13470.95	11036.66
PART12	22618.88	20784.06	11438.99	11438.99	11408.35	8983.15
PART13	21561.91	15079.84	14487.72	14487.72	11239.55	7402.07
PART14	24658.6	37778.37	12520.23	12520.23	8520.06	9282.44
PART15	21648.65	15185.65	20816.91	20816.91	13722.31	6928.83
PART16	22652.58	15245.56	7839.73	7839.73	7250.91	9247.89
PART17	22403.81	20549.21	5872.3	5872.3	6164.44	4447.85
PART18	4788.74	14559.37	4139.36	4139.36	5552.32	4604.1
PART19	22376.8	20672.69	20761.7	20761.7	19381.61	6410.18
PART20	24720.05	20643.85	5938.09	5938.09	6346.91	7409
Average	20106.96	22750.32	12733.45	12733.45	9250.981	7860.244

Table 7.26: WIP (LPT)

PART	3-cell		4-cell		5-cell	
	SEQ	ING	SEQ	ING	SEQ	ING
PART01	6.221	6.2849	7.3303	7.3303	7.3946	7.6539
PART02	78.5634	22.3668	78.3303	78.3303	78.2189	78.1949
PART03	56.9093	54.6945	69.537	69.537	70.3709	73.4929
PART04	45.2849	33.3366	45.6861	45.6861	45.3984	44.822
PART05	40.4194	41.5403	39.0614	39.0614	39.3576	39.0401
PART06	117.28	88.5126	117.71	117.71	98.5513	112.67
PART07	13.5703	11.8209	9.6961	9.6961	14.7541	12.8977
PART08	31.2621	40.931	31.6769	31.6769	31.4245	31.9051
PART09	14.5857	14.0834	20.4457	20.4457	13.7653	13.1848
PART10	1.1949	1.2235	1.3914	1.3914	1.5295	1.9597
PART11	19.3943	10.5684	11.2459	11.2459	18.1315	18.1246
PART12	16.7574	21.7282	18.484	18.484	15.671	14.81
PART13	33.5209	38.2679	36.219	36.219	33.9554	33.1223
PART14	19.2283	30.9702	14.1519	14.1519	21.4838	21.6052
PART15	41.0663	42.5728	47.4179	47.4179	37.6601	32.3863
PART16	27.5922	29.8255	24.3572	24.3572	24.6602	25.9285
PART17	36.2946	39.1938	27.3621	27.3621	28.2271	28.0714
PART18	7.3934	11.4014	10.1743	10.1743	10.2315	11.1326
PART19	71.3166	101.03	68.0833	68.0833	73.621	71.8103
PART20	12.6631	11.2285	5.9916	5.9916	5.1823	7.5584
Average	34.5259	32.5790	34.2176	34.2176	33.4794	34.0185

Table 7.27: WIP (SBS)

PART	3-cell		4-cell		5-cell	
	SEQ	ING	SEQ	ING	SEQ	ING
PART01	3.172	4.0301	3.5826	3.5826	4.5984	4.6765
PART02	78.5588	78.4853	78.3367	78.3367	78.2044	78.1785
PART03	66.6502	66.1779	70.6958	70.6958	73.5597	77.3022
PART04	20.9952	21.7072	15.0788	15.0788	26.6915	17.8223
PART05	31.3967	33.9185	28.9605	28.9605	29.4728	29.3001
PART06	72.7258	71.8122	74.8535	74.8535	75.477	76.3929
PART07	6.2864	6.8178	6.1493	6.1493	5.3113	4.728
PART08	44.5112	44.6667	43.2929	43.2929	44.8526	44.8345
PART09	8.8364	8.1581	6.6491	6.6491	7.0662	6.1562
PART10	1.1161	1.0009	1.2315	1.2315	1.2273	1.335
PART11	3.6388	2.8508	1.8335	1.8335	1.3688	1.6362
PART12	20.6579	22.048	20.2637	20.2637	20.1994	19.511
PART13	15.198	16.7285	19.0374	19.0374	15.7625	15.1571
PART14	19.2549	14.7013	9.027	9.027	7.9278	6.7023
PART15	51.2273	52.2892	60.2067	60.2067	51.8346	48.4144
PART16	16.5148	18.742	15.2921	15.2921	15.5867	15.3054
PART17	36.4789	32.5978	27.9922	27.9922	29.674	27.6018
PART18	9.123	8.0382	12.2037	12.2037	13.1678	14.4974
PART19	104.69	103.74	102.34	102.34	105.01	104.36
PART20	10.409	11.833	8.3877	8.3877	8.5384	9.9178
Average	31.07207	31.01718	30.27074	30.27074	30.77656	30.19148

Table 7.28: Transporter utilization (SPT)

	3-cell		4-cell		5-cell	
Transporter	SEQ	ING	SEQ	ING	SEQ	ING
Inter-cell	0.13	0.13	0.15	0.15	0.22	0.21
Cell 1	0.58	0.17	0.16	0.16	0.18	0.24
Cell 2	0.23	0.67	0.28	0.28	0.29	0.2
Cell 3	0.46	0.43	0.5	0.5	0.17	0.17
Cell 4			0.16	0.16	0.4	0.19
Cell 5					0.13	0.28
Average intra-cell	0.423	0.423	0.275	0.275	0.234	0.216

Table 7.29: Transporter utilization (LPT)

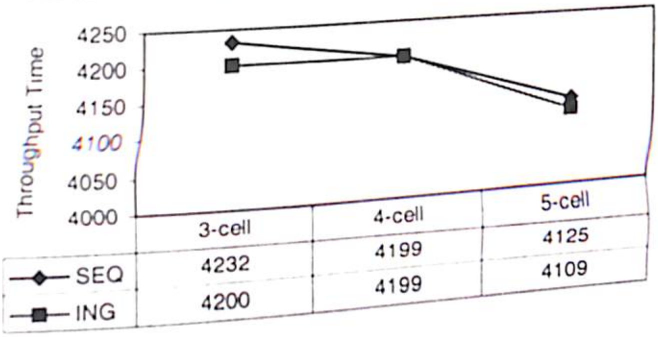
	3-cell		4-cell		5-cell	
Transporter	SEQ	ING	SEQ	ING	SEQ	ING
Inter-cell	0.12	0.13	0.13	0.13	0.22	0.19
Cell 1	0.57	0.17	0.16	0.16	0.17	0.23
Cell 2	0.2	0.65	0.26	0.26	0.27	0.18
Cell 3	0.44	0.43	0.51	0.51	0.14	0.16
Cell 4			0.14	0.14	0.4	0.18
Cell 5					0.11	0.27
Average intra-cell	0.403	0.416	0.267	0.267	0.218	0.204

Table 7.30: Transporter utilization (SBS)

	3-cell		4-cell		5-cell	
Transporter	SEQ	ING	SEQ	ING	SEQ	ING
Inter-cell	0.11	0.12	0.13	0.13	0.22	0.2
Cell 1	0.54	0.16	0.16	0.16	0.17	0.23
Cell 2	0.2	0.62	0.26	0.26	0.27	0.18
Cell 3	0.44	0.4	0.47	0.47	0.15	0.16
Cell 4			0.14	0.14	0.39	0.17
Cell 5					0.1	0.26
Average intra-cell	0.393	0.393	0.257	0.257	0.216	0.2

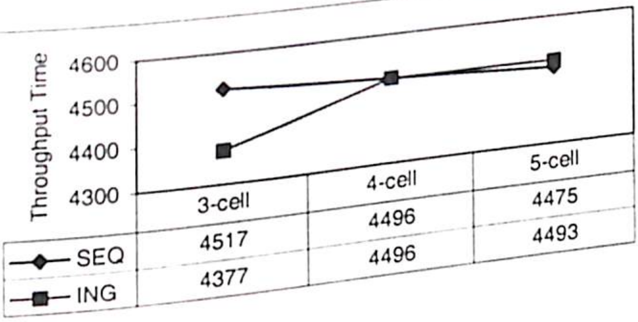
Table 7.31: Transporter utilization (GCA)

	3-cell		4-cell		5-cell	
Transporter	SEQ	ING	SEQ	ING	SEQ	ING
Inter-cell	0.23	0.2	0.29	0.29	0.58	0.8
Cell 1	1	0.23	0.41	0.41	0.54	0.88
Cell 2	0.36	1	0.37	0.37	0.54	0.64
Cell 3	0.96	0.72	1	1	0.37	0.74
Cell 4			0.24	0.24	1	0.62
Cell 5					0.33	1
Average intra-cell	0.773	0.65	0.505	0.505	0.556	0.776



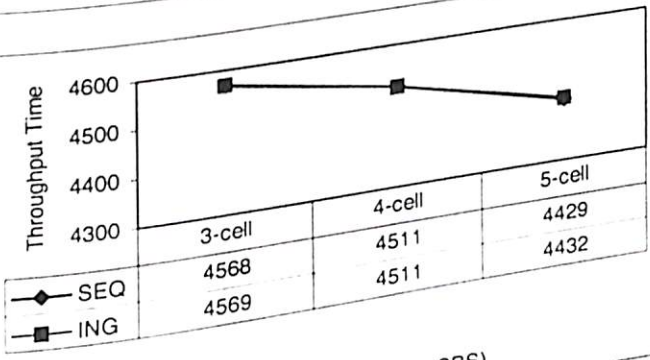
	3-cell	4-cell	5-cell
SEQ	4232	4199	4125
ING	4200	4199	4109

Figure 7.5a: Throughput time (SPT)



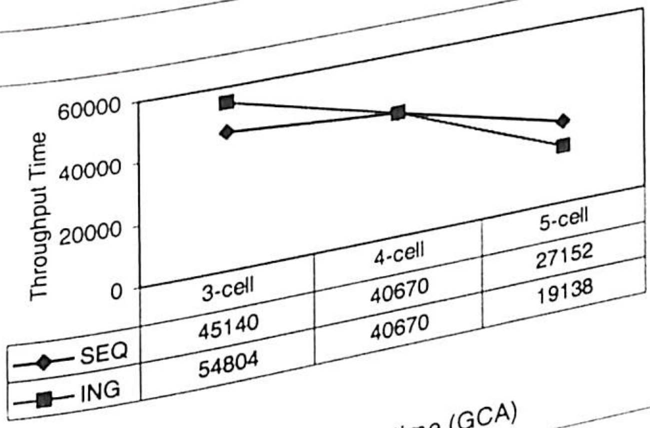
	3-cell	4-cell	5-cell
SEQ	4517	4496	4475
ING	4377	4496	4493

Figure 7.5b: Throughput time (LPT)



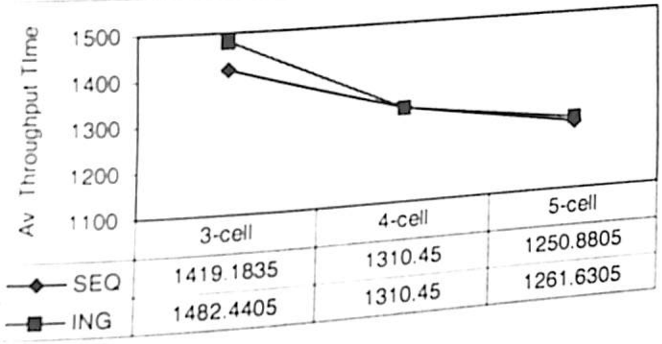
	3-cell	4-cell	5-cell
SEQ	4568	4511	4429
ING	4569	4511	4432

Figure 7.5c: Throughput time (SBS)



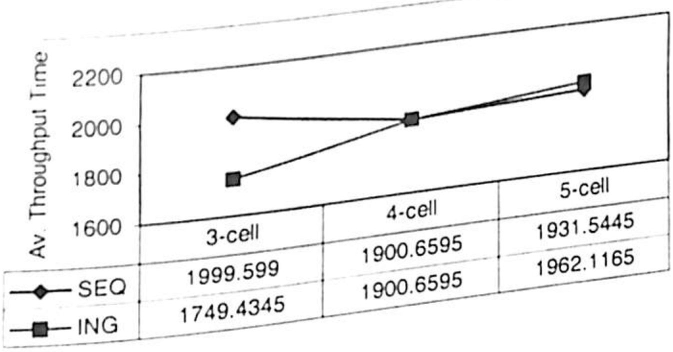
	3-cell	4-cell	5-cell
SEQ	45140	40670	27152
ING	54804	40670	19138

Figure 7.5d: Throughput time (GCA)



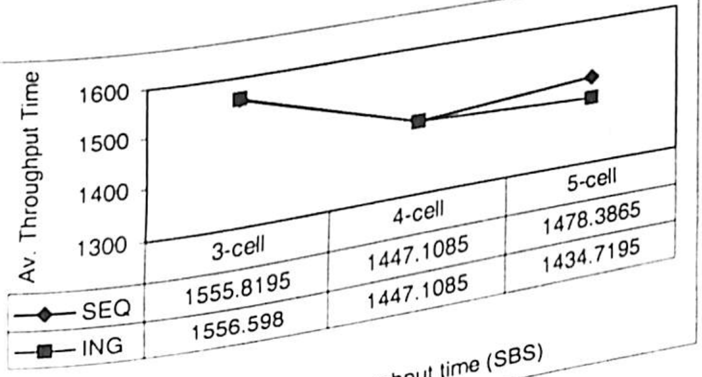
	3-cell	4-cell	5-cell
SEQ	1419.1835	1310.45	1250.8805
ING	1482.4405	1310.45	1261.6305

Figure 7.6a: Average throughput time (SPT)



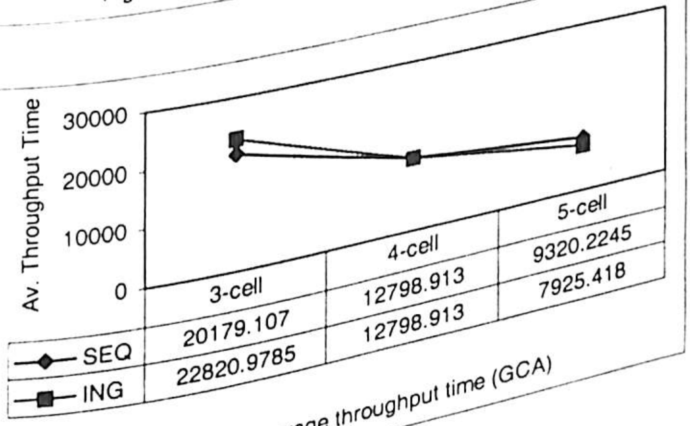
	3-cell	4-cell	5-cell
SEQ	1999.599	1900.6595	1931.5445
ING	1749.4345	1900.6595	1962.1165

Figure 7.6b: Average throughput time (LPT)



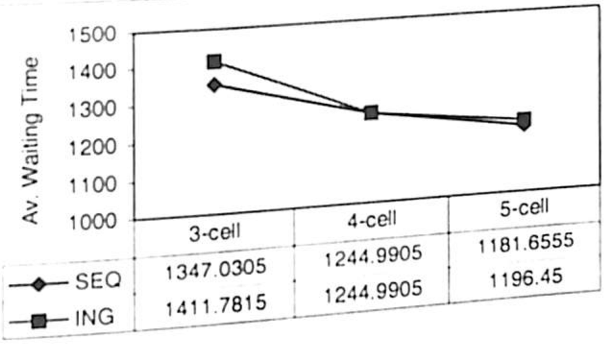
	3-cell	4-cell	5-cell
SEQ	1555.8195	1447.1085	1478.3865
ING	1556.598	1447.1085	1434.7195

Figure 7.6c: Average throughput time (SBS)



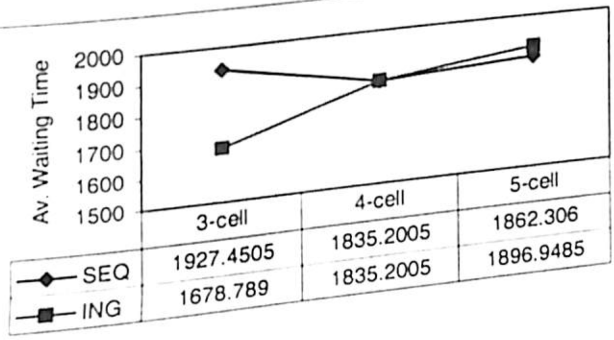
	3-cell	4-cell	5-cell
SEQ	20179.107	12798.913	9320.2245
ING	22820.9785	12798.913	7925.418

Figure 7.6d: Average throughput time (GCA)



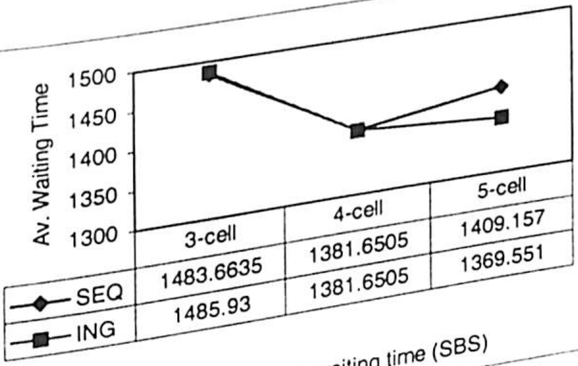
	3-cell	4-cell	5-cell
SEQ	1347.0305	1244.9905	1181.6555
ING	1411.7815	1244.9905	1196.45

Figure 7.7a: Average waiting time (SPT)



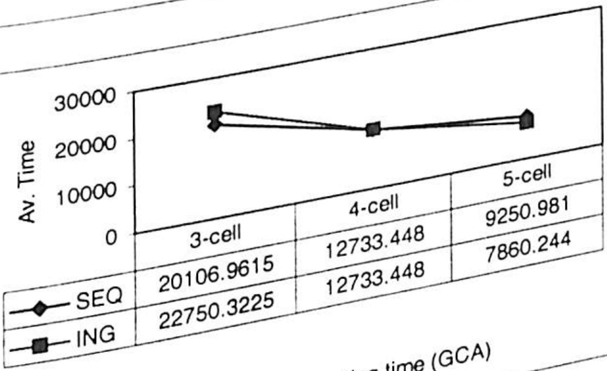
	3-cell	4-cell	5-cell
SEQ	1927.4505	1835.2005	1862.306
ING	1678.789	1835.2005	1896.9485

Figure 7.7b: Average waiting time (LPT)



	3-cell	4-cell	5-cell
SEQ	1483.6635	1381.6505	1409.157
ING	1485.93	1381.6505	1369.551

Figure 7.7c: Average waiting time (SBS)



	3-cell	4-cell	5-cell
SEQ	20106.9615	12733.448	9250.981
ING	22750.3225	12733.448	7860.244

Figure 7.7d: Average waiting time (GCA)

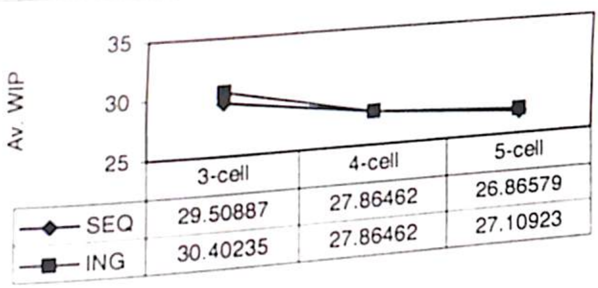


Figure 7.8a: Average WIP (SPT)

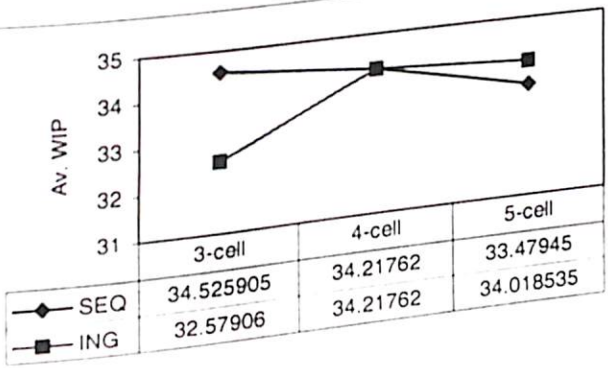


Figure 7.8b: Average WIP (LPT)

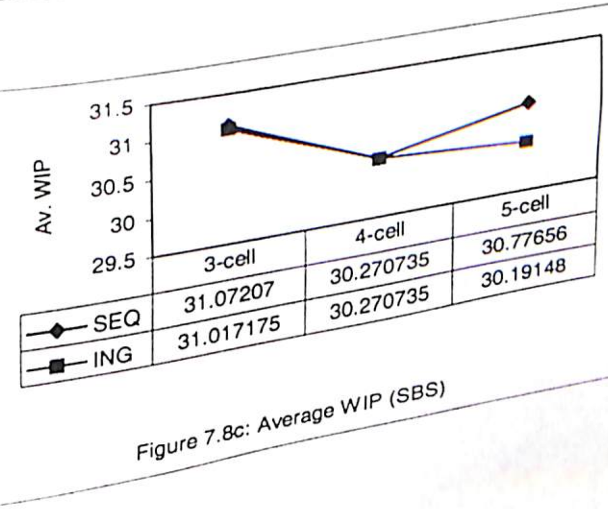
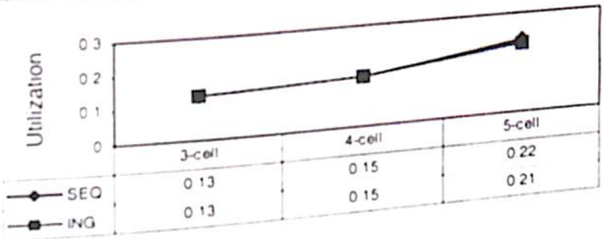
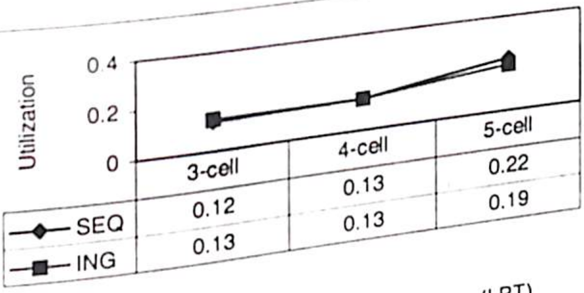


Figure 7.8c: Average WIP (SBS)



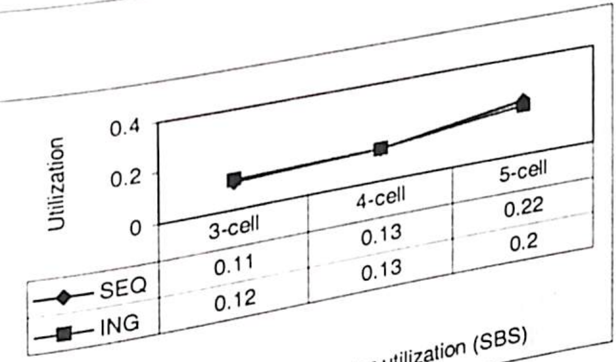
	3-cell	4-cell	5-cell
SEQ	0.13	0.15	0.22
ING	0.13	0.15	0.21

Figure 7.9a: Inter-cell transporter utilization (SPT)



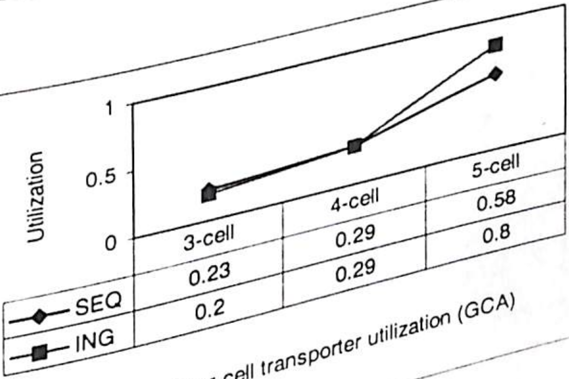
	3-cell	4-cell	5-cell
SEQ	0.12	0.13	0.22
ING	0.13	0.13	0.19

Figure 7.9b: Inter-cell transporter utilization (LPT)



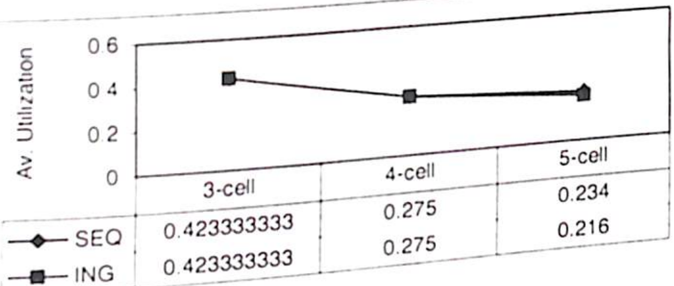
	3-cell	4-cell	5-cell
SEQ	0.11	0.13	0.22
ING	0.12	0.13	0.2

Figure 7.9c: Inter-cell transporter utilization (SBS)



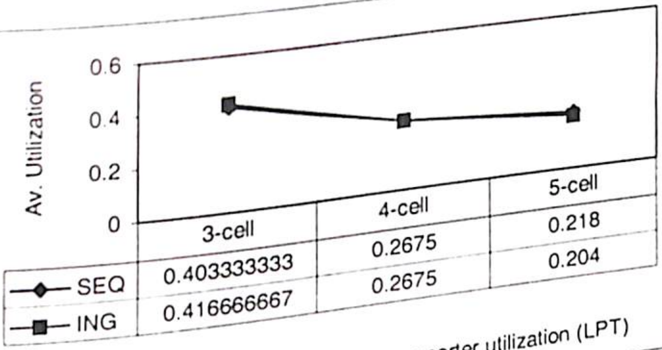
	3-cell	4-cell	5-cell
SEQ	0.23	0.29	0.58
ING	0.2	0.29	0.8

Figure 7.9d: Inter-cell transporter utilization (GCA)



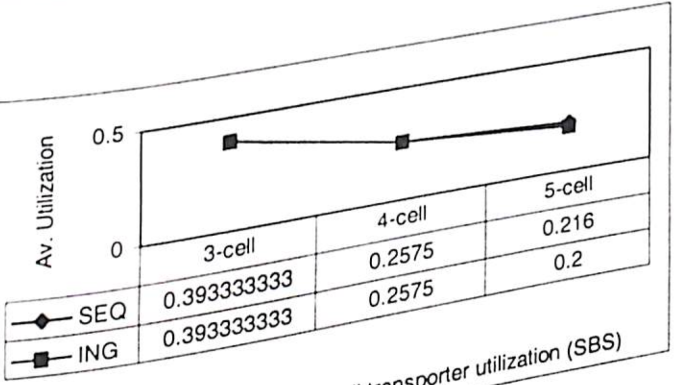
	3-cell	4-cell	5-cell
◆ SEQ	0.423333333	0.275	0.234
■ ING	0.423333333	0.275	0.216

Figure 7.10a: Average intra-cell transporter utilization (SPT)



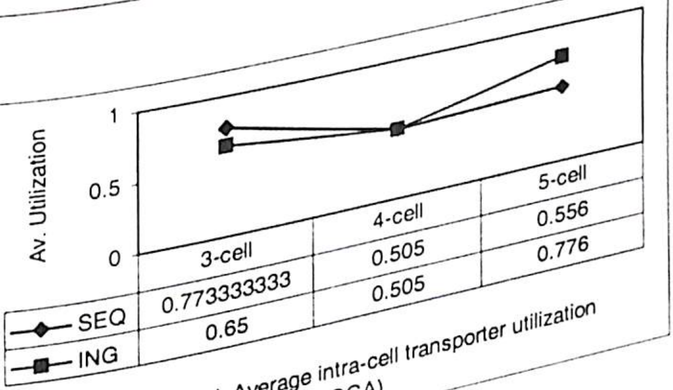
	3-cell	4-cell	5-cell
◆ SEQ	0.403333333	0.2675	0.218
■ ING	0.416666667	0.2675	0.204

Figure 7.10b: Average intra-cell transporter utilization (LPT)



	3-cell	4-cell	5-cell
◆ SEQ	0.393333333	0.2575	0.216
■ ING	0.393333333	0.2575	0.2

Figure 7.10c: Average intra-cell transporter utilization (SBS)



	3-cell	4-cell	5-cell
◆ SEQ	0.773333333	0.505	0.556
■ ING	0.65	0.505	0.776

Figure 7.10d: Average intra-cell transporter utilization (GCA)

7.8 Conclusions

An integrated approach for design of cellular manufacturing systems has been presented in this chapter. In the integrated approach, cell formation and layout design (inter-cell and intra-cell) have been evaluated simultaneously and not sequentially. It has been shown that the individual efficient solutions for cell formation need not to be the best for the overall CMS design. A mathematical formulation has been developed for the integrated approach considering the practical inputs like production volume per unit planning horizon, transfer batch size, operation sequence, and multiple nonconsecutive visits to the same machine. Qualitative factors have been considered during the layout phase to make the approach more practical.

Two models (SAMUCH and SAFUGA) developed for the integrated approach are presented in this chapter. SAMUCH model has two layers - the outer layer consists of simulated annealing algorithm to form cells and the inner layer consists of multicriteria heuristic algorithm to find the objective function for the SAA after designing the layout (inter-cell and intra-cell) for each solution generated by the SAA.

SAFUGA model developed for the integrated approach has three layers - the outer layer consists of simulated annealing algorithm, the middle layer consists of a genetic algorithm and the inner layer consists of a combination of fuzzy logic and AHP models. The inner layer treats the qualitative factors for the layout to give crisp factors in a mathematically rigorous way. The middle layer layouts the machines and cells and the outer layer forms the cells. Both the models are versatile and give the designer or the management of the organization a wide range of choices: different weights for the intra-cell and inter-cell layouts, different weights for the quantitative and qualitative factors for layouts, upper limits on the number of cells, different closeness ratings, and decision tables for qualitative factors.

The simulation model developed for the evaluation of the integrated approach is also presented in this chapter. It has been validated by the simulation model that the integrated approach for design of CMS gives better results than the sequential approach in terms of the average transfer time. The effect of four scheduling philosophies has also been studied in this chapter on various performance measures (throughput time, average throughput time, average waiting time, average WIP, inter-cell transporter utilization, and average intra-cell transporter utilization) for sequential and integrated approaches. There is no clear trend about the best scheduling philosophy, however, SBS seems a good scheduling philosophy for the integrated approach.

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Chapter 8

Production Planning and Control of Cellular Manufacturing Systems

8.1 Introduction

The performance of a CMS depends not only on the quality of the decomposition of the system into cells and departments but also on the quality of the production planning and control system used to plan and control the flow of work. However, the goodness of fit between both systems is of the greatest importance to take full advantage of the benefits of cellular manufacturing. The design of the production planning and control system should meet the requirements of the production system. Cellular manufacturing creates coordination needs that cannot be tackled by existing planning systems. These needs concern both the handling and determination of batches that contain families of parts and the consideration of the cell as one planning unit. Batch sizes cannot be determined in the traditional way, due to set up similarities of various parts within the same family and tooling constraints on the (automated) machines. Considering the cell as a planning unit affects the planning with respect to the cell loading procedure applied and the possibility to control production. Here, we have to take a look at the design of production planning and control system that can be applied to in cellular manufacturing.

In this chapter, a review of various frameworks for production planning and control of cellular manufacturing systems is discussed. Two models, one model for the production planning and another for control of CMS are developed. Production planning model is based on the integrated GT and MRP approach and the control model is based on the goal chasing algorithm. Simulation models are developed to study the effect of various scheduling philosophies (smallest processing time, largest processing time, smallest batch size, goal chasing algorithm) on sequential and integrated approaches.

8.2 Literature Review

One of the first who noted that a redesign of the production planning and scheduling system is required when applying group technology principles to production organization was Petrov (1968). He considered various types of flow line cells that can be constructed using group technology and determined the planning conditions that are required to improve both the performance of these cells and the performance of complete system, as this consists of interrelated cells. Dale and Russell (1983) reported on typical production control problems in flow line-manufacturing systems. The load-balancing problem in a cellular system is one of these problems. The cells consist of various types of machines and operators, which often are not equally qualified. In such configurations it can become a problem to maintain a good balance between key machines utilization and operator utilization. Fluctuations in product mix and volume, and introduction of new products can exaggerate these problems. Redesigning the production system itself to solve these problems is often not possible or acceptable, so the production control system has to deal with these problems. The same holds for the problems caused by sharing of key machines between cells. In these cases the realisation of the full potential of cellular manufacturing depends mainly on the production planning and control system design. Dale and Russell stated that many problems in firms that reorganised their shop floor layout along GT lines have been caused by still applying conventional control thinking which had worked in a functional organized production system.

Many authors proposed to use an MRP II framework (Manufacturing Resource Planning) in a cellular production system (Singh and Rajamani 1996). However, an MRP II framework specifies what planning modules are required and how they are related, but does not give attention to the contents of the relation between the planning modules and the configuration of the production system that has to be controlled. The information content of these frameworks is restricted. Hyer and Wemmerlov (1982) proposed a general framework for production planning and control, and applied to cellular manufacturing in the components parts manufacturing. Their framework is a hierarchical decision process that consists of three levels:

i) determine when and in what quantities final products are to be produced;

ii) determine what parts are to be produced during a specific time period and in what quantities;

iii) determine when and in what order jobs should be processed at various workstations.

At each level capacity check are required to ensure feasibility of a particular decision. The hierarchical levels specify the sequence of decision-making. Feedback loops between the levels are not considered. One of the questions Hyer and Wemmerlov (1982) raised is whether an MRP II system is compatible with the production planning and control requirements of production cells. They explore this question with the production planning and control requirements of production cells. They explore this question within their framework of the tri level hierarchical decision-making process. They conclude that MPS generation (level 1) would be unchanged and performing rough-cut capacity checks will be easier. The impact on the second level is highly significant. Lead times will be shorter and more predictable as queue times, set-up times and transfer times are smaller due to the proximity of machines in a cell. This results in modifications of some parameters in the MRP system. The same holds for the lot sizes that are used, as the product families in cellular manufacturing require similar set ups of the machines in the cell. Short throughput times in a cell and the possibility of applying lot streaming, make it often not necessary to monitor the status of production orders within the cells. This could make it difficult to use CRP in its standard form. If the manufacturing lead-time for a released batch exceeds the planning period that is used in the CRP profiles, the problem of allocation capacity requirements to the individual machines over time arises. Finally, according to Hyer and Wemmerlov, the third level of their hierarchical framework is not important in cellular manufacturing. They state it will suffice to monitor and record only order releases and order completions for a cell. That means the cell is considered as black box and is unit for planning. Wemmerlov (1988) gave more attention to the choice of the cell as the basic planning unit. He identified a number of relevant factors that have to be taken into account in the decision what layer of the production system to consider as the basic planning unit. Factors he mentioned are the appropriate level of delegation of planning decisions to cells, the nature of the production process in the cell, the length and variability of throughput times, and the internal flow patterns in the cell. His thinking can be summarized by stating that the more unpredictable the flow within the cell is, the more problematic a black box approach to the cell in the production planning system of the firm will be. Wemmerlov (1988) also addressed the problem how to utilize the advantages of cellular manufacturing in an MRP planning system. The advantage of producing similar parts in one cell should be recognized and handled by the MRP system in order to obtain the benefits of cellular manufacturing. However, the nature of MRP is to convert independent (end item) demand to dependent demand of parts and components. This process does not count for similarities between parts. Lot sizing rules that can be used in MRP try to find a suitable number of subsequent period requirements that can be combined in one order. Bauer *et al.* (1991) developed a manufacturing controls systems hierarchy for a batch oriented discrete parts manufacturing environment. Their hierarchical framework represents a hybrid approach to production planning, e.g., it is said to be based on ideas from materials requirements planning, optimised production technology, and just in time. Production activities that require planning can be strategic, tactical, or operational in nature. Strategic activities relate to the products to be manufactured, and the design of the production system. These strategic activities have to result in a reliable master production schedule. The tools that can be used to generate such schedules can as well be obtained from JIT planning techniques as from MPS scheduling techniques (Vollmann *et al.* 1997). It depends on the specific situation which of these techniques is appropriate and what level of detail in modelling the production system is required. The tactical planning level consists of a requirement planning function, which is considered to translate the master schedule into weekly or daily requirements of parts and components in the system. The operational planning consists of cell controllers (production activity control) and a factory coordination level, which coordinates the activities of the various cells. Factory coordination can be divided into a production environment design task (short term redesign of the production system and the product routings) and an inter cell goods flow control task. The main contribution of this framework for planning in cellular manufacturing is the recognition that a direct translation from tactical requirements planning, based on planned operation lead times, to operational detail planning of the production process is problematic. The characteristics of the cells can vary, for example with respect to the degree of autonomy, multi-functionality of employees, presence of bottlenecks, shared resources, *etc*. Therefore, each cell has to be planned and controlled separately (the PAC planning function), while at the same time another planning function is required for coordinating activities between cells (Factory Coordination). If cells are totally independent, both with respect to goods flow and use of resources, this latter function can be omitted. This approach to consider cells as autonomous organizational units in the design of a production planning system is further elaborated upon in German literature. Rohloff (1993) developed a framework that decentralizes planning to the autonomous units (e.g., cells) as much as possible. The framework places a strong emphasis on the horizontal coordination level, e.g., the direct coordination between various autonomous units. The vertical coordination level can be considered as an attempt to solve certain remaining planning problems using a hierarchical approach. The planning hierarchy has to take explicit notice of the available capacity in the cell within a certain time frame. This can be accomplished by a load oriented order release planning function (Bechte 1994). Habich (1989) developed a production-planning framework that recognizes the essential planning problem resulting from giving planning autonomy to cells that are interrelated in their primary production process. He views the essential problem of the central planning level to generate an overall optimum from the various local optima that were generated by the decentralized planning of the cells. His approach to this central planning is to consider the set of orders that require subsequent processing in various cells, determine for these orders appropriate sequences between the cells and plans throughput times per cell (e.g. order due dates), such that the cells will be able to finish these orders within their due dates while at the same time enough flexibility is available to optimise the planning within the cell. Shtub (1990) discussed many of these lot-sizing rules and concluded that they do not consider common set-ups required for a family of components and therefore are not suitable for the MRP/Group Technology lot-sizing problem. At the other hand, Wemmerlov (1988) states that he does not see family lot sizing during the MRP explosion process as a realistic for most cellular systems, because of the implementation costs and the inflexibility in execution. Lockwood *et al.* (2000) examined scheduling cellular manufacturing systems in the presence of lot splitting. They also utilized various scheduling policies to test formally the underlying principles of the synchronous manufacturing philosophy. This is accomplished by utilizing exhaustive and non-exhaustive scheduling heuristics simultaneously at bottleneck and non-bottleneck workcentres. Sum and Hill (1993) criticised the MRP II framework with respect to the tactical planning level, e.g., the basic MRP I requirements planning function. Their critique is that MRP does not apply finite scheduling in generating the requirements plan. MRP uses fixed planned order lead times that are based on static planned operation lead times, and these parameters are usually determined independently of order sizes, work centre loads, and capacities. In many production situations, e.g., cellular manufacturing, this may not result in realistic plans. Leu (1999) investigated the performance of order-input sequencing heuristics in a cellular flexible assembly system (CFAS) by computer simulation. The CFAS produces low-volume, large products in an assemble-to-order environment. Leu examined two types of heuristic: two-stage (group scheduling) heuristics and single-stage heuristics. Two-stage heuristics attempt to serially process similar orders and eliminate major setups required between subfamilies. Suresh (1979) describes an example of using an MRP approach within Group Technology. Compared with a functional organized production system, the operation of MRP effects: (i) the length of the planned manufacturing lead times, which could be shortened; (ii) lot sizing, resulting in economical justification of the lot for lot ordering rule; (iii) production control effort, which could be reduced, resulting in less documentation and expediting; (iv) inventory, which could be reduced for both finished goods and work in process, partly due to more accurate records. Figure 8.1 shows an example of a production planning framework (Suresh 1979) for a CM situation that specifies relations between various elements in the production system, e.g., various production cells, and the remainder shop. However, the framework gives no information on the aggregation and abstraction levels applied.

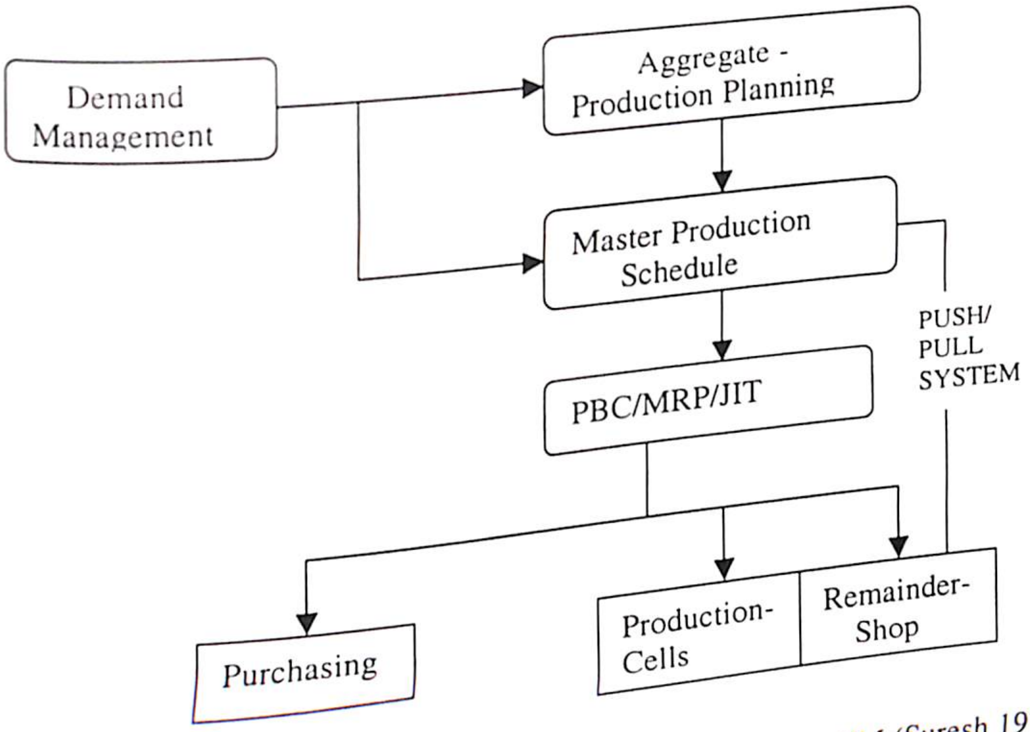

Figure 8.1. Framework for production planning and control in CM (Suresh 1979)

For example, it specifies that coordination between production and sales have to take place (system level: the master production schedule), but do not indicate if this coordination has to be performed at end item level or that it suffices to define some product families (higher aggregation level). Neither does it specify what abstraction levels are applied. For example, demand management has direct relations with both aggregate production planning and master production scheduling. For the latter planning function, information on demand of spare parts may be important, while this can be neglected in determining an aggregate production plan (higher abstraction level). The framework doesn't give information on the frequency planning functions are performed. The hierarchical decompositions is an indication for the distance between a long term planning phase (APP), a medium term planning phase (MPS) and a short term planning phase (PBC/MRP/JIT) that plans and controls the procurement and transformation of materials in the production system. This planning level initiates the purchase of common items with very long lead times, for example some metal castings. The next level consists of *Master Production Scheduling*. This planning function uses customer order information, hence no more aggregate order information, and performs a capacity check at cluster layer, so the available capacity of various clusters (a rough measure) is compared with the capacity required by the master schedule. This schedule is weekly updated. Next, MRP uses information on the planned production of the end items (including, for example, spare parts) and the preferred lot sizes and safety stocks to time phase the requirements for the various clusters and production units, using the expected (standard) throughput times. The remainder shop and the production cells construct schedules on the basis of this information. However, the component cells use also information of the assembly cell coordinator on the planned start times of the various assemblies to determine the actual priority of the various released work orders. The component cells daily obtain orders from the cell coordinator. The available capacity in these cells is controlled by the coordinator function, and reallocating work to one of the other cells or an (external) subcontractor is used to solve short term loading problems. Work order release to the cells is performed by the cell coordinator function. The component cells obtain new material from the raw material cell through a kanban system. This cell is therefore not controlled from the MRP planning function. MRP does present information on the expected amount of raw material needed to the suppliers. The flow of this material is also controlled through kanban. The framework also shows that the FMS schedule is being updated far more frequently than the remainder shop schedule. New (1977) argues that MRP is well equipped to determine the component requirements to meet assembly needs, but that it is not suitable for detailed production control.

The problem is that the MRP model of how the production system operates differs too much from the actual situation at the shop floor. Updated priority lists for already released work orders are often not used at all at the floor, making the outcome of the system less predictable. Through reducing the planned lead times, reducing the fluctuations in the workload of cells over time and improving the possibility of using set-up similarities, cellular systems can benefit from MRP. However, this requires fundamental modifications of the basic MRP I approach. Adding a standard CRP analysis is not sufficient in CM. Chamberlain and Thomas (1995) discusses the required modifications of MRP systems. They stress the importance of building information systems that can easily be modified with respect to the organization of the production system. Flow-line cells are sometimes formed for a period of 3 months, and after this period production will again be performed in other cells. This requires MRP systems that are very flexible in modelling the available capacities and their allocations to cells. Restructuring the Planning Bill of Materials should be made very easy. In general, the number of levels in BOM can be reduced, as there is less need to control production progress, due to the reduced through put times. The number of parts that have to be controlled using MRP can also be reduced, as simple two bin systems with short cycle shipments often functions very well in practice. However, MRP is still considered to be useful as a tactical planning instrument. To summarize, there are a number of problems if MRP is used in Cellular Manufacturing, for example:

- MRP is found to treat the part family lot sizing problem inadequately.
- MRP does not give enough support for finding a balanced loading of the cells.
- MRP is not flexible with respect to the restructuring of routing of products.
- MRP does not consider actual information on the production progress in determining due dates and planned lead times.

Period / Level	1	2	3	4	5	6
Final Assembly				Lot 3	Lot 4	Lot 5
Sub. Assembly			Lot 3	Lot 4	Lot 5	
Component		Lot 3	Lot 4	Lot 5		
Fabrication	Lot 3	Lot 4	Lot 5			

Figure 8.2: Period Batch Control (PBC) system illustration

The PBC system can be characterized as a single cycle flow control ordering system (Burbridge, 1988). Like MRP, it uses time phased planning of the goods flow between stages and applies explosion of the end item demand to determine parts requirements. The essential feature of PBC is the periodicity with which the system operates, causing a synchronization of the goods flow within the production system. All the products have equal throughput time *T*, determined by the product of the number of stages *N* in the production system and the length of the period P, the selection of suitable values for *N* and *P* is hence an important design problem in PBC (Riezebos 1997), yet most prescriptions for its choice have been without analytical basis. Burbridge (1975) has proposed some practical but very general guidelines for choosing the cycle length: it must be no less than the processing time for a batch of any component (lead time), nor so small that the number of setups reduces effective capacity. These guidelines provide lower bounds on the choice of cycle length, but the final decision is arbitrary. Kellock (1976) and Kruse *et al*. (1975) suggest cycle lengths of 4 weeks in one month, while Zelenovic and Tesic (1988) found that companies in their survey used cycle times of one or two weeks. Leonard and Koenigsberger (1971) suggested that a prime condition for group technology is small batches, while Sinha and Hollier (1984) pointed out that large batches (i) minimizes time losses associated with setups; and (ii) ensure a high degree of continuity in the workloads on the group tooling and high utilizations; but (iii) cause high work-in-process and extra inventory costs. Specific guidelines for balancing these tradeoffs are not offered. Kaku and Krajewski (1995) developed a cost minimization model for examining the choice of cycle length and choosing a common cycle time in a PBC system under conditions of stochastic demands. The number of firms known to apply PBC is restricted. Burbidge *et al.* (1991) reported that it would be difficult to find 30 companies in the UK, which use PBC. Zelenovic and Tesic (1988) reported on several applications in Yogoslavia, Whybark (1984) described an application of a related concept in Finland. More recently, a renewed interest in the performance, design, and characteristics of PBC systems has evolved; see for example Yang and Jacobs (1992), Kaku and Krajewski (1995), Steele and Malhotra (1994), Steele *et al.* (1995), and Rachamadugu and Tu (1997). Steele and Malhotra (1997) evaluated the design and operation of period batch control system for cellular manufacturing. It was shown that the firms currently using MRP in a CM environment can readily convert to the similar but potentially simpler and easier to use PBC systems. Hyer and Wemmerlov (1982) presented the following hierarchical decision process based on the PBC concept of a single cycle:

Level 1:

The planning horizon is divided into cycles of equal length,say n weeks. Based on a sales forecast, the MPS is generated for end items in each cycle.

Level 2:

The MPS in a specific cycle is exploded into its parts requirements by using a list order form analogous to a bill of materials. Lot-for-lot sizing procedures are used for component parts.

Level 3:

All the parts scheduled for production in a given cycle are categorized by family. The families formed by similarities in processing requirements are assigned to cells with the required capabilities. Planned loading sequences created to take advantage of similar tooling requirements are used to sequence the jobs into the cells.

If there is little variation in the loading of the cells over time, the dispatching level can accomplish high quality schedules that make use of similar set ups within part families and transfer batches that are smaller than process batches. In the sense, use of PBC can easily be combined with insights from just-in-time (JIT) (Burbidge 1987,1989) and OPT (Burbidge 1990).

Advantages of using PBC

A number of advantages of using PBC have been documented (Singh and Rajamani 1996):

- The single –cycle ordering approach is a planned order release mechanism in which orders are placed at regular intervals with a timing independent of the rate of demand (as opposed to reorder point system).
- All parts have common lead time and all orders in a specific cycle have the same due date.
- There is only one order release to a cell, resulting in less paper work.
- Work-in-progress and component-parts inventories are reduced.

- Direct material costs are reduced and common raw materials may be cut, thus reducing scrap and obtaining maximum material usage.
- The use of a short planning period enables the system to react rapidly to changes in market demand.

One of the main braw backs of PBC is the absence of clear guidelines for determining the correct cycle length. Some attempts have been made to determine the optimal cycle length based on expected costs consisting of inventory holding and overtime incurred in satisfying the demand for all end-items. Models for both general flowline-type fabrication and assembly cells have been developed. Benders (2002) presented the data on the history of the period batch control system, which suggests that Mr. R. J. Gigli in about 1926 devised PBC and has been widely applied in a great many batch production industries by the firm of consultants of which he (Gigli) was director.

Wemmerlov and Johnson (1997) report in an empirical study that 80% of the firms indicated that production planning and control had become simplified with cells. Olarunniwo (1996) reports on the changes in production planning and control systems when cellular manufacturing is implemented in a firm. Most firms he were only partially cellurized, e.g., there existed a remaining shop in more than 90% of the firms. The most remarkable results he found were that almost all firms that used MRP before the implementation of cellular manufacturing continued with this after cellularization took place. However, the number of firms that combined the use of MRP with a kanban system increased from 3.6% to 32.7%. After cellularization, 30.9% of the firms operated MRP alone, while 12.7% only used kanban. The popularity of kanban therefore increases rapidly (more than 50% of the firms) after implementation of cellular manufacturing. His survey makes clear that a lot of firms not simply choose between various production planning and control (PPC) systems, but also apply a hybrid approach to planning.

Zolfaghari and Liang (1999) proposed a hybrid tabu-simulated annealing approach to solve the group scheduling problem. The main advantage of this process is that a short term memory provided by the tabu list can be used to avoid solution revisits while preserving the stochastic nature of the simulated annealing method. Schonberger (1983) already pointed to the possibility of combining several elements from JIT in MRP, amongst which the so-called Synchro-MRP approach that was applied by Yamaha. Flapper *et al*. (1991) further discussed how to embed JIT into MRP. Kanban is only one of the available JIT techniques. To use MRP for planning raw material and component deliveries and for looking forward, while kanban is used to control the actual assembly process, is therefore only one of the possibilities of embedding JIT into MRP. Klein (1989) reported on the effect of kanban on the stress of the human system and concluded that JIT eliminates the ability of workers to control their own work pace, but kanban makes workers to react on each other rather than answering a computer printout or a supervisor. Kanban therefore leads to a perception of increased control over the flow of production, although the reality may be otherwise. There are many contributions that theoretically compares the effectiveness of a JIT approach to other production control strategies for various types of layout in a batch manufacturing environment (Wainwright *et al*. 1993, Krajewski *et al*. 1987). Buzacott and Shanthikumar (1992) described a general approach for inter-cell goods flow coordination that can be used for a more systematic comparison of several approaches, such as kanban, conwip and MRP. However, their framework assumes that a multi cell production system is used and gives only attention to the sequential coordination between cells. Another interesting approach to production planning for cellular manufacturing originated from the work of Hax and Meal (1975). The hierarchical production planning framework they developed has been applied to group technology manufacturing (Kistner et al. 1992). In this approach a strong focus exists on capacity allocation to various layers of production units. Much effort is given to the disaggregation of the complex production planning problem in several less complex sub problems. The type of disaggregation that should be applied strongly depends on the specific characteristics of the cellular manufacturing system, e.g., relations between the cells and flexibility of the system. Askin and Iyer (1993) compared three approaches for assigning workers to tasks and controlling the movement of jobs through cellular manufacturing systems with objective of minimizing the throughput time for part batches. The scheduling approaches considered include i) individual machine loading with batches being sequenced on the first come, first served basis; ii) a cell dedication strategy wherein the cell is devoted to a single product type at a time; and iii) a job enrichment strategy where each batch is assigned, cross-trained operator who must perform all batch operations. Mahmoodi and Martin (1997) developed an efficiency-oriented subfamily queue selection heuristic for the cellular manufacturing environment. With the goal of minimizing aggregate times required for major sequence dependent machine setups at a workcentre, this heuristic includes a feature for dynamically assessing variations in a subfamily's arrival rate, enhancing its suitability for realistic transient-state condition. Chen and Lin (1999) presented a multi-factor priority rule to improve the weighted COVERT (cost over time) rule. They combined job processing time, job routing, job due date, and job-dependent tardiness cost for the scheduling in a manufacturing cell. The objective was to reduce total tardiness cost. The central idea of this multi-factor priority rule is to give higher priority to those jobs that have longer expected waiting time, shorter slack time, and higher ratio of tardiness cost over processing time. Suer *et al*. (1999) emphasized the need of considering multi-cell environment where cell loading becomes crucial for controlling the entire system.

8.3 Development of Integrated GT and MRP Framework

The objective of an integrated GT and MRP framework is to exploit the similarities of setups and operations from GT and time-phased requirements from MRP. This can be accomplished through a series of simple steps (Ham *et al.* 1985):

Step 1: Gather the data normally required for both the GT and MRP concepts (i.e., parts and their description, machine capabilities, a breakdown of each final product into its individual components, a forecast of final product demand, *etc.*).

Step 2: Use GT procedures to determine part families. Designate each family as GI(I=1,2,.......N).

Step 3: Use MRP to assign each component part to a specific time period.

Step 4: Arrange the component part/time period assignments of step 3 according to the part family groups of step 2.

Step 5: Use a suitable group scheduling algorithm to determine the optimal schedule for all those parts within a given group for each time period.

8.3.1 Illustration of the integrated GT and MRP framework

In this section, application of integrated GT and MRP framework is shown by solving two examples.

Example1: Five products, designated P1-P5, are to be assembled using parts A1-A20. These parts are grouped into three families (G1, G2, and G3). The product structure is given in Table 8.1. The monthly parts requirements and planned order releases are shown in tables 8.2 and 8.3. The combined GT/MRP data obtained is shown in table 8.4. The group setup times and unit processing times are shown in table 8.5. Finally, the capacity requirements for part families/groups are shown in table 8.6.

Table 8.3: Planned order releases for the products

Part name	Week1	Week2	Week3	Week4
P1	55	55	55	55
P2	75	75	75	75
P3	105	105	105	105
P4	50	50	50	50
P5	100	100	100	100

Table 8.4: Combined GT/MRP data

Group	Part name	Week1 demand	Week2 demand	Week3 demand	Week4 demand
G1	A1	1100	1100	1100	1100
	A9	1500	1500	1500	1500
	A12	5000	5000	5000	5000
	A14	2500	2500	2500	2500
	A17	7500	7500	7500	7500
	A20	3105	3105	3105	3105
G2	A2	4400	4400	4400	4400
	A4	1555250	1555250	1555250	1555250
	A6	465750	465750	465750	465750
	A7	2200	2200	2200	2200
	A11	1000	1000	1000	1000
	A15	1575	1575	1575	1575
	A19	15000	15000	15000	15000
G3	A3	621000	621000	621000	621000
	A5	5000	5000	5000	5000
	A8	4400	4400	4400	4400
	A10	62155	62155	62155	62155
	A13	6000	6000	6000	6000
	A16	6000	6000	6000	6000
	A18	5000	5000	5000	5000

Table 8.5: Group setup time and processing time for parts

Group name	Group set-up time	Parts name	Unit Processing time
G1	6	A1	14
		A9	40
		A12	27
		A14	22
		A17	16
		A20	16
G2	7	A2	20
		A4	21
		A6	24
		A7	23
		A11	21
		A15	23
		A19	41
G3	7	A3	20
		A5	22
		A8	24
		A10	21
		A13	21
		A16	21
		A18	28

Similarly parts within a a group can be sequenced using SPT rule :

G1: A1, A9, A14, A20, A12, A17

G2: A11, A15, A7, A2, A19, A6, A4

G3: A8, A5, A18, A13, A16, A10, A3

Example 2: In this example parts are grouped into four families (G1, G2, G3, and G4). The product structure is shown in Table 8.7. The monthly parts requirements and planned order releases are shown in tables 8.8 and 8.9. The combined GT/MRP data obtained is shown in table 8.10. The group setup times and unit processing times are given in table 8.11. Finally, the capacity requirements for part families/groups are shown in table 8.12.

Table 8.7: Product structure

Product name	Part name	Number of units Required
P1	A1	20
	A2	80
	A7	40
	A8	80
P2	A13	80
	A16	80
	A17	100
	A20	40
P3	A4	50
	A6	150
	A10	20
	A3	200
P4	A11	20
	A14	50
	A9	30
	A5	100
P5	A19	150
	A18	50
	A12	50
	A15	15

Table 8.8: Monthly parts requirement in each group

Group	Part name	Monthly requirement
G1	A6	63000
	A7	8800
	A11	4000
	A15	60000
	A19	60000
G2	A1	4400
	A3	84000
	A9	6000
	A10	8400
	A12	20000
	A18	20000
G3	A5	20000
	A8	17600
	A13	24000
	A16	24000
G4	A2	17600
	A4	21000
	A14	10000
	A17	30000
	A20	12000

Table 8.9: Planned order releases for the products

Part name	Week1	Week2	Week3	Week4
P1	55	55	55	55
P2	75	75	75	75
P3	105	105	105	105
P4	50	50	50	50
P5	100	100	100	100

Table 8.12: Capacity requirements for part families/groups

Group name	Week1	Week2	Week3	Week4
G1	12211335	12211335	12211335	12211335
G2	14075661	14075661	14075661	14075661
G3	467608	467608	467608	467608
G4	3572940	3572940	3572940	3572940
Total Capacity	30327544	30327544	30327544	30327544

Sequence of groups considering the total processing time required by all the jobs in the group and the group setup time using shortest processing time (SPT) rule is:

Week1: G3, G4, G1, G2

Week2: G3, G4, G1, G2

Week3: G3, G4, G1, G2

Week4: G3, G4, G1, G2

Similarly parts within a group can be sequenced using SPT rule:

G1: A11, A7, A19, A15, A6

G2: A1, A9, A12, A18, A10, A3

G3: A8, A5, A13, A16

G4: A14, A20, A2, A17, A4

8.4 Development of Goal Chasing Model for Scheduling

This deals with the sequencing procedure adopted by the Toyota Kanban System. Under this "pulling" system, the variation in production quantities or conveyance times at preceding processes must be minimized. Also, their respective work-in-process inventories must be minimized. To do so, the quantity used per hour (i.e., consumption speed) for each part in the mixed model assembly line must be kept as constant as possible. The several notations used in the process are defined as:

Q = Total production quantity of all products A_i ($i=1, 2 \ldots \alpha$)

$= \sum_{i=1}^{\alpha} Q_i$ (Q_i = Production quantity of each product A_i)

where, b_{ij}= Necessary quantity of the part a_j ($j=1, 2\ldots\beta$) for producing one unit of the product A_i ($i=1, 2\ldots \alpha$).

Step 3. If all units of a product A_{i^*} were ordered and included in the sequence schedule, then

$$\text{Set } S_k = S_{k-1} - \{i^*\}.$$

If some units of a product A_{i^*} are still remaining as being not ordered, then set $S_k = S_{k-1}$.

Step 4. If $S_k = \phi$(empty set), the algorithm will end.

If $S_k = 0$, then compute $X_{jk} = X_{j,k-1} + b_{i^* j} (j = 1,2,\ldots,\beta)$ and go back to step 2 by setting $K = K+1$

8.4.1 Illustration of goal chasing model for scheduling

This section shows the application of goal chasing model for scheduling with the help of an example.

Example 1: For analysing the goal chasing algorithm a problem is extracted from the example 3 in section 5.4.2.3. The parts are assumed as the products to be produced and each product is composed of just one part. The production quantity Q_i ($i=1,2\ldots20$) of each product $A_1, A_2,\ldots A_{20}$ is taken as the actual demand of the product divided by a common number 5. The required unit b_{ij} ($i=1,2,3; j=1,2\ldots20$) of each part $a_1, a_2\ldots a_{20}$ for producing these products is unity as shown in the table 8.13. The sequence schedule for this example using goal chasing algorithm is given in table 8.14. This model is also used as scheduling philosophy in the simulation model developed in the last chapter. A comparison of the results of this model with some well known scheduling philosophies is done by using simulation model. Figures 7.4 to 7.10 show the results of

N_j = Total necessary quantity of the part a_j to be consumed for producing all products A_i ($i=1, 2 \ldots \alpha; j=1, 2 \ldots \beta$)

X_{jk} = Total necessary quantity of the part a_j to be utilized for producing the products of determined sequence from first to K_{th}.

With these notations in mind the following two values can be developed:

N_j/Q = Average necessary quantity of the part a_j per unit of a product.

$\frac{KN_j}{Q}$ = *Average necessary quantity of the part a_j for producing* K units of products.

In order to keep the consumption speed of a part a_j constant, the amount of X_{jk} must be as close as possible to the value of $\frac{KN_j}{Q}$.

In order for a sequence schedule to assure the constant speed of consuming each part, the distance D_k must be minimized.

where, $$D_k = \sqrt{\sum_{j=1}^{\beta}\left(\frac{KN_j}{Q} - X_{jk}\right)^2}$$

The algorithm developed on this basic idea is known as goal chasing method. The goal chasing algorithm developed by Toyata (Monden 1994) as given below is used to control the CMS:

Step 1. Set K = 1, $X_{j,k-1} = 0$, $(j = 1 \ldots \beta)$, $S_{k-1} = \{1, 2 \ldots \alpha\}$

Step 2. Set as K^{th} order in the sequence schedule the product A_{i^*}, which minimizes the distance D_K. The minimum distance will be found by the following formula:

$$D_{ki^*} = \min\{D_{ki}\}, i \in S_{k-1}, \text{ where } D_{ki} = \sqrt{\sum_{j=1}^{\beta}\left(\frac{KN_j}{Q} - X_{j,k-1} - b_{ij}\right)^2}$$

where, b_{ij}= Necessary quantity of the part a_j ($j=1, 2\ldots\beta$) for producing one unit of the product A_i ($i=1, 2\ldots \alpha$).

Step 3. If all units of a product A_{i^*} were ordered and included in the sequence schedule, then

Set $S_k = S_{k-1} - \{i^*\}$.

If some units of a product A_{i^*} are still remaining as being not ordered, then set $S_k = S_{k-1}$.

Step 4. If $S_k = \phi$(empty set), the algorithm will end.

If $S_k = 0$, then compute $X_{jk} = X_{j,k-1} + b_{i^*j} (j = 1,2,\ldots,\beta)$ and go back to step 2 by setting $K = K+1$

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Table 8.13: Product quantity and structure for example 1

Product A_i	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}	A_{16}	A_{17}	A_{18}	A_{19}	A_{20}
Planned production quantity Q_i	4	16	40	10	20	30	8	16	6	4	4	10	16	10	30	16	20	10	30	8

Parts a_j Products A_i	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}	a_{16}	a_{17}	a_{18}	a_{19}	a_{20}
A_1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A_2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A_3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A_4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A_5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A_6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A_7	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
A_8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
A_9	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
A_{10}	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
A_{11}	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
A_{12}	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
A_{13}	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
A_{14}	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
A_{15}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
A_{16}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
A_{17}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
A_{18}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
A_{19}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
A_{20}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

8.5 Conclusions

The review of literature shows the various approaches to planning and control of cellular manufacturing systems but nothing can be said which one is the best approach. The characteristics of CMS, such as the cell formation and layout *etc*. have to be studied in detail before a suitable production planning and control system can be designed. In this chapter, two models, one for production planning and another for the control of CMS are presented. Production planning model is the integrated model using MRP and GT. Control model is based on the goal chasing algorithm. Simulation model are developed to compare the sequential approach and integrated approach for different scheduling philosophies (SPT, LPT, SBS, GCA). Results show that none of these scheduling philosophies can be said to be better than the other, but the smallest batch size scheduling seems to give fairly consistent results compared to others.

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Chapter 9

Conclusions

Manufacturing industries are under intense pressure from the increasingly competitive global market place to improve the efficiency and productivity of their production activities. In addition, the manufacturing system should be able to adjust or respond quickly to changes in the product design and demand without major investment. Traditional manufacturing systems such as job shops and flow lines are not capable of satisfying such requirements. As a result, cellular manufacturing system (CMS), an application of group technology (GT), has emerged as a promising alternative manufacturing system. The design of CMS involves three inter-related phases, namely cell formation which is to identify the machine grouping and part families, intra-cell layout (machine layout) which determines the arrangement of machines within cells, and inter-cell layout (cell layout) which is concerned with the arrangement of cells on the shop floor. A common strategy adopted by many researchers, to address these sub-problems, has been to handle each phase separately and sequentially without evaluating the effect of each phase on the previous phase(s). In this thesis, it has been shown that this (sequential approach) results in generating solutions, which may be efficient to one particular phase, but it does not necessarily offer a good solution to the overall CMS. The integrated approach developed, which tackles the three phases simultaneously, is better than the sequential approach for the design of CMS.

In chapter 2, the literature review presented shows that all except few papers discuss only cell formation/design (part family formation and machine cell formation) as the design of CMS.

In chapter 3, two multi-criteria decision models for the justification of CMS are presented. One is analytical hierarchy process and the other is performance value analysis. From the results of both the models, it is evident that the CMS is the best alternative for implementation and to maintain competitive advantage. This chapter demonstrates the usefulness of the multi-attribute decision models for justification of CMS.

Chapter 4 presents two models developed for the part family formation. Model 1 is based on the fuzzy logic and AHP and model 2 is based on fuzzy equivalence and AHP. Both the models eliminate the scaling problem of different attributes, handles generally vague and imprecise part design attributes in a mathematical rigorous way, and can be integrated with the existing coding systems in the organizations to form the part families. However, in model 1 AHP is used to assign the weightages to the attributes for each relationship of part pairs and in model 2 AHP is used to assign the weightages to the different attributes, which are same for all parts. Both the models show that different importance for the different attributes changes the part clustering.

Chapter 5 presents the three models developed for the cell formation. The literature review indicates the need of cell formation methods that consider the factors like operation sequence, production volume of parts, number of cells, cell size, capacity of machines, workload on machines, processing time on parts, machine utilization, size of the problem, product mix, cost, *etc*. There is a growing need to develop methods based on the artificial intelligence techniques like neural networks, simulated annealing, and genetic algorithms. Model 1 presents a ART1 network based algorithm for solving the cell formation problem with a view to generating feasible solutions that satisfy real-world constraints of production volume, processing time, number of cells, minimum acceptable utilization levels for individual machines, machine downtime, desirable machine utilization, maximum permissible workload on machines and other management constraints like number of shifts, working days and maintenance philosophy. The model also introduces the cost of inter-cell material handling and voids in a practical way by accounting for the production volumes of the parts making inter-cell moves and the total workload of the machines in the cells. The neural network can be structured on the basis of the number of machines as well as the upper bound specified on the number of cells. The network is also capable of handling the problem of product flexibility in a CMS. Other cell design constraints like machine duplication and alternate process plans are not included in the algorithm but these can be accounted for by looking at the feasible solutions and individual machine utilization as the algorithm is user interactive. The objective of model 1 is to form cells with minimization of weighted sum of costs associated with exceptional elements and voids. Model 2 presents a simulated annealing model for cell formation with an objective to minimize the weighted sum of exceptional elements and voids. This model considers the alternate process plans for the parts and the binary part-machine incidence matrix as input. The model is versatile as any value of weights ($0 \le w_1 \le 1$) for individual exceptional elements and voids can be given. Model 3 is also a simulated annealing based model that considers the alternate process plans, operation sequence, demand, and batch size of parts. The objective of this model is to minimize the intercellular moves. In this model the maximum number of cells are specified *a prior*. The limit on the cells may arise due to many causes such as better utilization of employees, manufacturing equipments, and space; and safety and technological considerations.

In chapter 6, a mathematical formulation developed for the design of layout for CMS, and two models (MUCH and FUGEN) developed to solve the mathematical formulation for the design of layout of CMS are presented. The layout of CMS should include the cell layout on shop floor (cell layout) as well as the machine layout inside cells (machine layout). To make the layout models practical, both, quantitative and qualitative factors are considered. The multicriteria mathematical formulation, developed as quadratic assignment problem to assign n facilities (cells/machines) to n locations with an objective to minimize the material handling (quantitative) and maximize the closeness rating (qualitative) simultaneously for the layout design of CMS, deals with the cell layout as well as machine layout problem. The multicriteria mathematical formulation considers the production volume, batch size, and non-consecutive visits to the same facility. The MUCH model developed for design of layout of CMS is a multicriteria heuristic based on a pairwise exchange of facilities to the locations. The FUGEN model developed for layout of CMS is a genetic algorithm based model with embedded fuzzy logic and AHP model to treat the vagueness and uncertainty of qualitative factors. Single point crossover, mutation, and direct entry (elitism) operators used probabilistically in the model provides efficient solutions. Both the models are versatile and the designer has many choices like any value between zero and one can be considered for the qualitative criterion ($0 \leq w_1 \leq 1$) and intra-cell/inter-cell objective function (α_1 and α_2) to evaluate the effects of qualitative and intra-cell/inter-cell layout, and any number of qualitative factors (≤ 12) can be considered. However, comparison of results of two models shows that the FUGEN model gives better results than the MUCH model. The results of both the models clearly show that the intercellular moves (most common objective for cell formation in literature) does not represent the material handling cost truly. The proposed models are capable of evaluating the cellular layouts vis-a-vis functional layouts.

In chapter 7, an integrated approach for design of cellular manufacturing systems is presented. In the integrated approach, cell formation and layout design (inter-cell and intra-cell) are evaluated simultaneously and not sequentially. It is shown that the individual efficient solutions for cell formation need not to be the best for the overall CMS design. Multicriteria mathematical formulation developed for the integrated approach considers the practical inputs like production volume per unit planning horizon, transfer batch size, operation sequence, and multiple non-consecutive visits to the same machine. Quantitative factors as well as qualitative factors are considered during the layout phases to make the approach more practical. Two models (SAMUCH and SAFUGA) developed for the integrated approach are presented in this chapter. SAMUCH model has two layers - the outer layer consists of simulated annealing algorithm to form cells and the inner layer consists of multicriteria heuristic algorithm to find the objective function for the SAA after designing the layout (inter-cell and intra-cell) for each solution generated by the SAA. SAFUGA model developed for the integrated approach has three layers - the outer layer consists of simulated annealing algorithm, the middle layer consists of a genetic algorithm and the inner layer consists of a combination of fuzzy logic and AHP model. The inner layer treats the qualitative factors for the layout to give crisp factors in a mathematically rigorous way. The middle layer layouts the machines and cells and the outer layer forms the cells. Both the models are versatile and give the designer or the management of the organization a wide range of choices: different weights for the intra-cell and inter-cell layouts, different weights for the quantitative and qualitative factors for layouts, different closeness ratings, and decision tables for qualitative factors. It has been validated by the simulation model that the integrated approach for design of CMS gives better results than the sequential approach in terms of the average transfer time. The effect of four scheduling philosophies is also studied in this chapter on various performance measures (throughput time, average throughput time, average waiting time, average WIP, inter-cell transporter utilization, and average intra-cell transporter utilization) for sequential and integrated approaches. There is no clear trend about the best scheduling philosophy, however, SBS seems a good scheduling philosophy for the integrated approach.

Chapter 8 presents planning and control of CMS. The characteristics of CMS, such as the cell formation and layout *etc.*, have to be studied in detail before a suitable planning system can be designed. In this chapter, two models developed for planning and control of CMS are presented. One model is the integrated model using MRP and GT for production planning of CMS. Another model is based on the goal chasing algorithm for scheduling.

Chapter 9 presents the conclusions and the main contributions of the research work in nutshell.