

**EFFICIENT CLUSTERING AND KNOWLEDGE-BASED APPROACH  
FOR SOLVING CELLULAR MANUFACTURING PROBLEMS**

**BY**

**WING-SING CHOW**

A Thesis Submitted to the  
Faculty of Graduate Studies in Partial Fulfilment  
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**DEPARTMENT OF MECHANICAL AND INDUSTRIAL ENGINEERING  
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EFFICIENT CLUSTERING AND KNOWLEDGE-BASED APPROACH FOR  
SOLVING CELLULAR MANUFACTURING PROBLEMS

BY

WING-SING CHOW

A Thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in  
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I would like to dedicate this thesis to my beloved mother, Madam Ooi Ying CHOO, and commemorate my father, Mr. Chin Siew CHOW, and brother, Mr. Weng Wah CHOW.

## ABSTRACT

In this thesis, the cellular manufacturing (CM) environment, problem representation, and systems are firstly addressed. Two general approaches used to implement CM systems are also reviewed.

Two new algorithms of the CM problems are presented: the Cluster Identification Algorithm (CIA) and the Machine Grouping Algorithm (MGA). The CIA is used to solve CM problems that are related to the mutually separable cluster problems (MSCP). The CIA provides the most efficient computational time yet reported in the literature. An extension of the CIA to solve the partially separable cluster problems (PSCP) - known as the Cost Analysis Algorithm (CAA) - is also addressed.

The MGA, which is based on the "new machine unit" concept, solves the PSCP that was related to the machine chaining problems. The MGA provides a local optimal solution for grouping  $(n+2)$  total number of machine cells into  $(n+1)$  total number of machine cells. Computational results with the selected data set show that our proposed MGA outperformed the other two in CM literature when the total number of machine cells is greater than 3 - which is always true in real, practical cases in industry. The behaviour of intercellular parts in PSCP when the machine grouping approach is used is

also discussed.

A knowledge-based system is also developed to solve both well- and semi-structured types of CM problems. The system, known as CEMIS, is an expert system which allows users to consider practical CM constraints - such as the maximum capacity of machine cells, the total number of required cells, technological constraints, and the selection of material handling systems for parts. The CEMIS is coded in PASCAL and can be used in both PC and mini/main-frame computers. Numerical examples for the proposed algorithms and CEMIS are also presented.



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## NOMENCLATURE

$A$	A matrix A
$A^T$	Transpose of matrix A
$A_i$	$i$ th submatrix of matrix
$A^{(k)}$	Matrix A in iteration k
$M$	Total number of machines in matrix A
$N$	Total number of parts in matrix A
$\{X\}$	The set of elements X
TMC	Total number of machine cells
MC-i	Machine cell i
PF-k	Part family k
$M_i$	Machine i represented by a $1 \times N$ array
$P_j$	Part j
$M_{i[k]}$	Entry value of column k in $M_i$
$M_{(i,j)}$	A machine cell that has been grouped by new machine unit concept and consists of machines $M_i$ and $M_j$ . The value of column k in $(M_i, M_j)$ is equivalent to "1" if at least one of $M_{i[k]} = 1$ or $M_{j[k]} = 1$ ; otherwise "0" entry.
$M_{(i,j),k}$	Entry value of column k in a machine cell $M_{(i,j)}$ , or $M_{(i,j)[k]}$ .
$\cap(M_i, M_j)$	Intersection set of $M_i$ and $M_j$ . The value of column k in $(M_i, M_j)$ is equivalent to "1" if $M_{i[k]} = M_{j[k]} = 1$ ; otherwise 0 entry.
$M_i \Omega M_j$	is $1 \times N$ array product in which the value of column k in $(M_i \Omega M_j)$ is equivalent "1" if $M_{i[k]} = M_{j[k]} = 0$ ; otherwise 0 entry.



$\Phi(M_i)$	Total number of "1" values in machine $M_i$
$S_{ij}$	Total number of parts that require processing by both machines $M_i$ and $M_j$ .
$D_{ij}$	Total number of parts that do not require processing by both machines $M_i$ and $M_j$ .
$c_j$	cost factor for $P_j$
$C_{(i,j),k}$	The C value score between machine cell $M_{(i,j)}$ and $M_k$ .
$\underline{c}$	Subset
$\phi$	Null set

## Chapter I

### INTRODUCTION

The introduction of Group Technology concepts in the mid-fifties changed the face of manufacturing practices from functional to cellular manufacturing (CM). Since then, a large numbers of CM systems have been implemented world-wide, mainly because CM promises not only high efficiency rates of production but also other advantages such as: better management of labour and tooling systems, reduction of scrap, work-in-process inventory and paper work. CM is a manufacturing system which identifies and collects information about similar and recurring activities. Based on this collected information, CM decomposes an entire complex manufacturing system into smaller, simpler subsystems that result in better managed and controlled shop floors.

The basis for the design of a CM system lies in an identification and grouping procedure for those production parts that share similar processes into families and of their associated machines into cells. The ideal solution of a CM is to have all parts belonging to a "family" fully processed within one cell. This case is known as the "mutually separable CM solution". The other type of CM solution relates to those parts that require processing by more than one machine cell and is referred to as the "partially separable solution". Since clustering analysis is the most commonly used method to

solve CM problems (Kusiak and Chow, 1988), we shall refer to the first type CM problems as "mutually separable clustering problems (MSCP)", and to the latter type as "partially separable clustering problems (PSCP)".

Although literature describing CM applications and methodologies dates from the early 1960's, existing models and algorithms have certain limitations. At the moment all existing models and algorithms developed for CM problems belong to the PSCP group. It is clear that solutions to PSCP also solve MSCP, but all algorithms for PSCP involve high computation complexities. Since solving a CM problem is a nonpolynomial (NP) complete (Lawler et al., 1985), it is desirable to have an efficient algorithm to solve MSCP directly. The other main shortcoming of existing CM literature concerns the still unsolved so-called "machine chaining problem". Machine chaining problems occur when a solution to a PSCP derived by means of a clustering method known as the "machine grouping approach", generates a higher number of intercellular of part movements. An attempt has been made in this thesis to develop efficient algorithms for a) solving MSCP and b) solving machine chaining problems. A knowledge-based system using our proposed algorithms under a set of real, practical constraints such as: the size of machine cells, technological limitations, and the total number of desired machine cells, is also developed to solve a CM problem.

The thesis is organized as follows. In the remainder of this chapter, a CM environment, a CM problem representation, and CM assumptions are addressed.

Existing models, algorithms and knowledge-based systems (KBS) developed for solving CM problems are surveyed in the next chapter. In Chapter 3, a new and efficient algorithm for solving MSCP is presented. An extension work on the proposed MSCP model is discussed in Chapter 4. Numerical examples, computational results, and practical applications of the proposed model are also outlined in the respective chapters. Another heuristic algorithm together with computational results for solving the machine chaining problems are presented in Chapters 5 and 6. A novel knowledge-based system named CEMIS using our proposed algorithms is presented in Chapter 7. Finally, conclusions are given in the last chapter.

## **1.1 The Cellular Manufacturing Environment**

To design a CM system is to first group production parts into part families (PF) and the associated machines into machine cells (MC). These groupings are used for two main purposes. The first application is typically for the case of a new manufacturing firm that wishes to analyze available information to allow smarter purchases of new machines and material handling systems for better production planning. The second application occurs when analysis of the information in existing companies results in two CM layouts: a) physical machine layout, and b) logical machine layout. The physical machine layout requires rearrangement of machines such that the shop floor is altered, as shown in Figure 1. With the logical machine layout, machines are grouped into logical machine cells and the physical position of machines is not altered (see Figure 2).

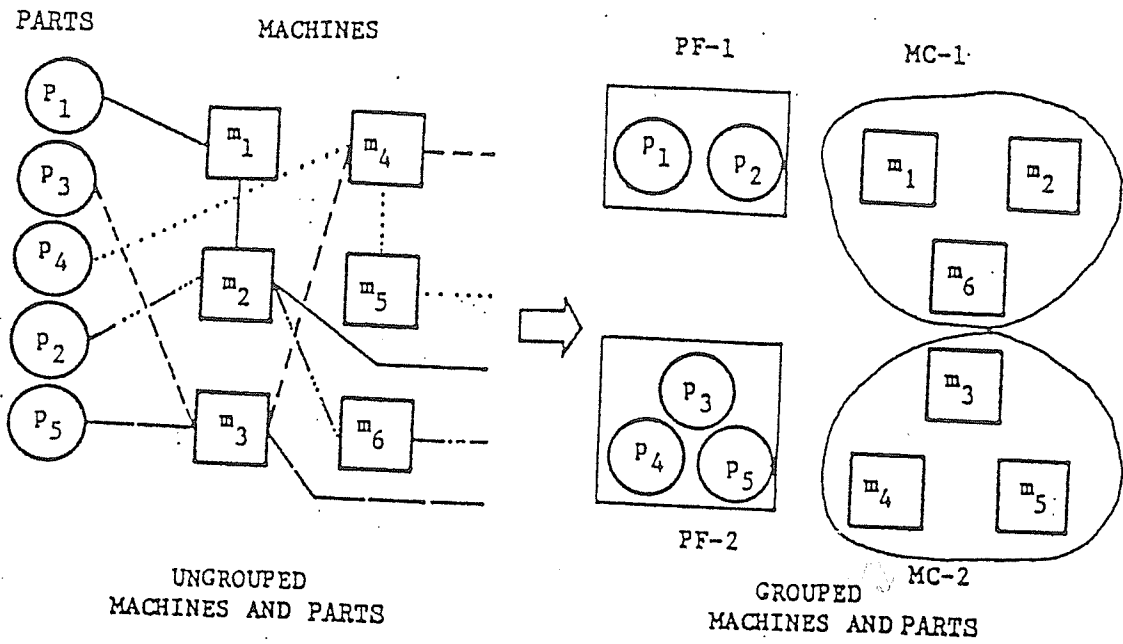


Figure 1: The Physical Machine Layout in a CM Environment

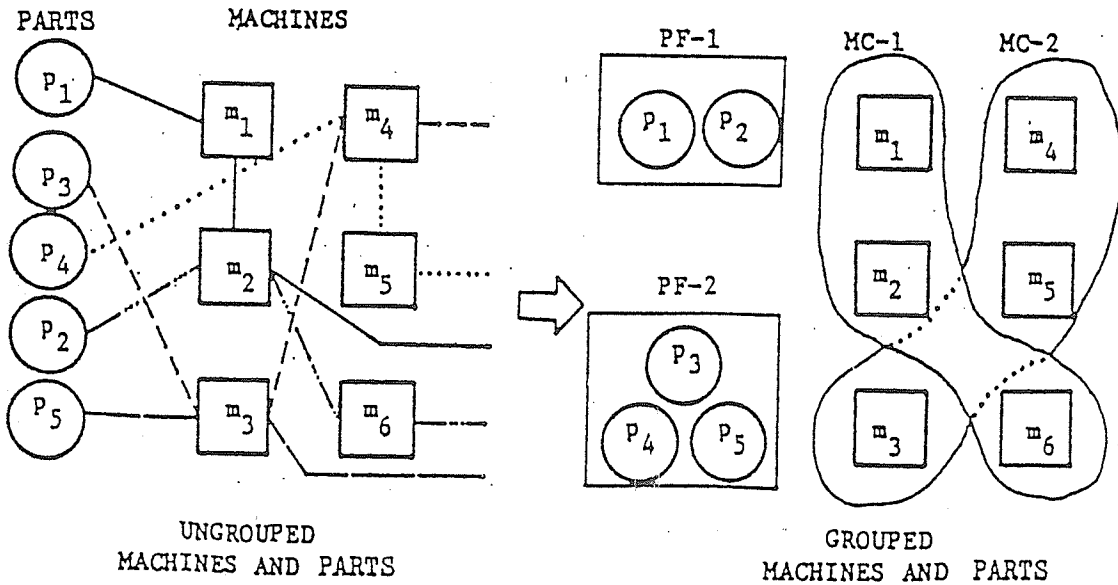
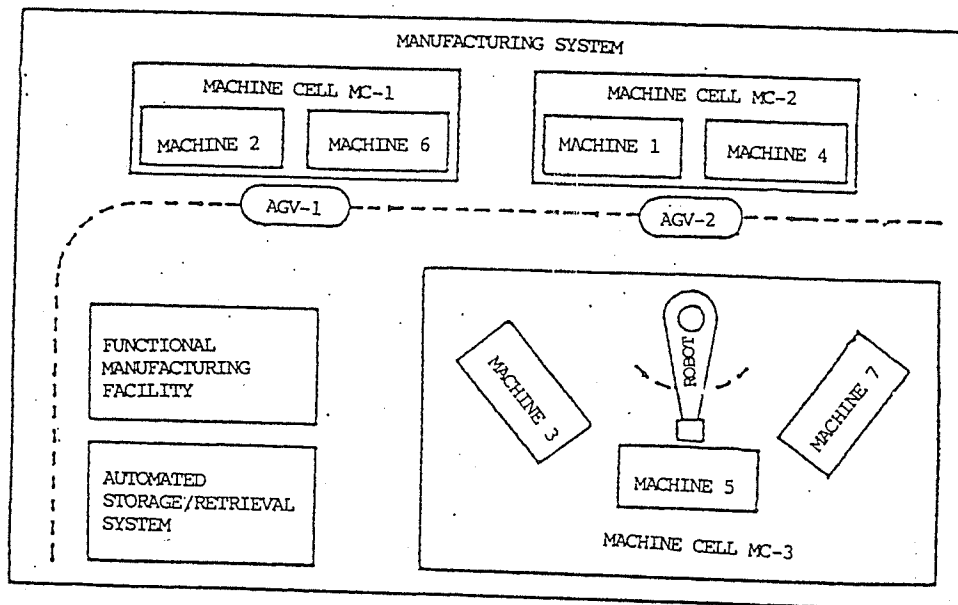


Figure 2: The Logical Machine Layout in a CM Environment

Logical grouping can be applied in cases where the production content is changing frequently so that a physical machine re-layout is not justified. The physical machine layout is usually the most appropriate application for a new firm where machines are still in the stage of procurement.



**Figure 3: The Use of Automated Handling Systems in a CM Environment**

When parts require processing by a number of machine cells, material handling systems may be acquired. In a CM environment, the commonly used material handling devices include: robot arms, automated guided vehicles (AGV), and gantry robots/slides. The selection criteria for material handling devices include from considerations of: the weight of parts, hazard nature, physical distance, travelling frequency of trips, and cost and benefit factors. Figure 3 presents a sample CM environment where a number of

features of automated handling systems are adopted.

## 1.2 A CM Problem Representation

A CM problem is typically represented by a machine-part incidence matrix  $A=[a_{ij}]$ , of size  $M \times N$  where the values of  $M$  and  $N$  indicate the total number of machines and parts respectively. The machine-part incidence matrix  $[a_{ij}]$  consists of either 0 or 1 values where an entry like 1 or (0) indicates that machine  $M_i$  is used or (not used) to process part  $P_j$ . For example, the machine-part incidence matrix that represents the unsolved CM problem presented in Figure 1 can be depicted as in matrix A1.

$$[a_{ij}] = \begin{array}{c} M_1 \\ M_2 \\ M_3 \\ M_4 \\ M_5 \\ M_6 \end{array} \begin{array}{ccccc} P_1 & P_2 & P_3 & P_4 & P_5 \\ \left[ \begin{array}{ccccc} 1 & & & & \\ 1 & & 1 & & \\ & 1 & & & 1 \\ & 1 & & 1 & 1 \\ & & & 1 & \\ & & 1 & & \end{array} \right] \end{array} \quad (A1)$$

When an initial machine-part incidence matrix  $[a_{ij}]$  is constructed, clusters that contain machine cells and corresponding part families are not visible. All CM models and algorithms existing in the literature manipulate this machine-part incidence matrix so that machine cells and part families are obtained.

### 1.3 Basic CM Assumptions

Greene and Sadowski (1984) reviewed and generated the following list of general assumptions for CM models:

- a. Parts are grouped into families according to their production features.
- b. If there exists a solution to the MSCP, all machines are grouped into cells such that parts are processed within them.
- c. All operations that are required by any part should be completed within one cell.
- d. Cells can share machines but the total number of cells should be kept to a minimum.
- e. Each cell is designed to improve production planning.
- f. Machines that do not belong to any cells must be grouped into a remainder cell.
- g. Some machines cannot be physically grouped into the same cells because of technological constraints (such as paint booths and toxic degreasing equipment).
- h. All operations of a job for a part can be completed by a feasible cell.
- i. Jobs may involve more than one cell.
- j. Jobs should not be assigned to the remainder cell if they can be processed in a specialized cell.
- k. The efficiency of machines performing operations for parts is partially correlated to the job's characteristics.
- l. Most machines have the flexibility to perform multiple operations.



We have further added one additional assumption to the above list. This new assumption is contrasted to the 7<sup>th</sup> assumption listed above (g): where there may exist some machines that one desires to group them together because of personal preference or technological constraints. Our new assumption is stated as follows:

- m. Some machines may be physically grouped into the same cells because of personal preference or technological constraints.

## Chapter II

### LITERATURE SURVEY

In this chapter, existing models, algorithms and expert systems for solving the cellular manufacturing problems are reviewed.

Many survey papers based on the study of CM environments, configurations, and formulations have been published. Edwards (1971) reviewed the concept and advantages of part families formulation, and discussed three types of CM systems that have been implemented in industries. Mosier and Taube (1985) reviewed optimal and heuristic solutions for solving the CM problems that relate to both aspects of cluster formations and scheduling problems. Greene and Sadowski (1984) studied CM formations by reviewing the CM assumptions and advantages. Further justifications of CM advantages in industry are provided by Anonymous (1980a,b), Ballakur (1986), Fazakerlay (1974), Greene and Sadowski (1983), Holtz (1987), Opitz and Wiehdahl (1971), Vos (1979), and Houtzeel and Brown (1984). Durie (1970) presented the first finding of the adoption of CM systems in UK industry. Hyer and Wemmerlov (1989) reported the practices and implementations of CM systems in US industry. Their survey was based on responses to a questionnaire by 53 US users and practitioners. Their findings confirmed the usefulness of CM systems, and identified two major obstacles in practising CM in industry: a) managerial and technical barriers, and b) failure to gain a full understanding

of GT and CM philosophies. The most recent report by Knight and Wall (1989) also presented a real, practical case in designing a CM system for a firm that involved the use of a decision support model as a support function for CM implementation. Shafer and Meredith (1990) compared the performance of nine existing CM algorithms by using three sets of data obtained from manufacturing plants. Conclusions regarding the performance of those nine algorithms have also been drawn in their paper. Wemmerlov and Hyer (1986) surveyed more than 70 CM solutions and discussed them in one of the following forms: identification of part families using a procedural approach, identification of machine grouping using a similarity approach, identification of part families using a part grouping approach, and approach in identifying families and cells simultaneously. Kusiak and Chow (1988) provided a general review of the different methods used to solve CM problems. In their paper, a review of coding classification methods is also presented. Details of the methodologies together with working examples that deal with clustering analysis methods in solving CM problems were also addressed. Readers who are interested in an extensive list of bibliography of CM papers should refer to the paper by Waghodekar and Sahu (1983). Books that specifically contribute to the study and understand of related issues to CM environment include: Ranson (1972), Arn (1975), Burbidge(1975), Hyer (1984), Kusiak (1986a, 1986b, 1987, 1988a, 1988b, 1989, 1990) and Talavage and Hannam (1988).

The remaining portion of this chapter attempts to review some of the most relevant CM literature that are not only related to this research but also provide an

extensive understanding of CM research development. For the purpose of better organization, the literature survey is organized into the following categories: matrix formulations, mathematical programming formulations, graph techniques formulations and expert systems formulation.

## 2.1 Matrix Formulation

### Production Flow Analysis (PFA)

Burbidge (1971) developed the first procedural approach for solving CM problem known as Production Flow Analysis (PFA). The PFA is a qualitative procedure which consists of three levels: factor flow analysis, group analysis and line analysis. Level 1 is an aggregate grouping process which attempts to gather related information to form a machine-part incidence matrix. Based on the outcome of level 1, an attempt to identify machine cells is made in level 2. The procedure involved in level 2 is to rearrange rows and columns of machine-part incidence matrix until clusters involve with cells and families are visibly formed. The generated clusters are then used in the third level to analyze the flow pattern of shop floors, i.e. determine the layout of machines and identify bottleneck machines.

There are two major weaknesses for the PFA. First, the method is not systematic and second, it is difficult for computerization. Although Burbidge (1977) attempted to improve the PFA by presenting his nuclear synthesis technique (which was also discussed

and extended by Dekleva and Menart (1987)), the PFA still remains a manual method. El-Essaway and Torrance (1972) incorporated many features of PFA and developed a computerized Component Flow Analysis (CFA).

#### Component Flow Analysis (CFA)

The CFA is also composed of four steps. In the first step, CFA executes a computer program to identify routing of parts, and then determine the degree of similarity of machines that are required for processing these part types. The second step in CFA adopts a manual approach to form machine cells and part families. The last two steps of CFA are involved with the feed-back system and analytical results of the work load for each cell. However, the second step of CFA also still remains a manual system which makes the CFA impractical for solving a large size of CM problems.

#### Single Linkage Cluster Analysis (SLCA)

McAuley (1972) remedied the first weakness of the PFA by introducing the Single Linkage Cluster Analysis (SLCA). The SLCA is based on similarity coefficient measures  $s_{ij}$  for each pair of machines  $M_i$  and  $M_j$  which are computed as:

$$s_{ij} = \frac{\sum_{k=1, N} d^1(a_{ik}, a_{jk})}{\sum_{k=1, N} d^2(a_{ik}, a_{jk})} \quad (E1)$$

where

$$d^1(a_{ik}, a_{jk}) = \begin{cases} 1 & \text{if } a_{ik} = a_{jk} = 1 \\ 0 & \text{otherwise} \end{cases}$$

$$d^2(a_{ik}, a_{jk}) = \begin{cases} 0 & \text{if } a_{ik} = a_{jk} = 0 \\ 1 & \text{otherwise} \end{cases}$$

To solve a CM problem by using the SLCA, similarity coefficients for all possible pairs of machines are first computed, and these values are used to draw a dendrogram. Machine cells are then obtained by imposing a threshold value onto the dendrogram. The SLCA has two basic flaws: 1) it fails to recognize the machine chaining problem which generated a higher number of intercellular of parts (King and Nakornchai, 1982), and 2) there is no criterion to determine which threshold value should be used.

#### Average Clustering Algorithm (AC)

Seifoddini (1984, 1986, 1989, 1989a) proposed an average linkage clustering algorithm (AC) to superficially solve machine chaining problems. He defined the similarity coefficient between two clusters as an average of the similarity coefficient between all members of two clusters. However, the AC algorithm as he claimed does not always eliminate the machine chaining problems. To date, the machine chaining problem still remains as an unsolved problem in the CM literature.

Seifoddini and Wolfe (1987) have further extended the AC algorithm by proposing a method in selecting the best possible choice for a threshold value. They claimed that a threshold value that contributes to the minimum material handling cost should be chosen. Gupta and Seifoddini (1991) also proposed another version of the extended AC

algorithm - known as CLINK, where the solution is strongly based on the evaluation of grouping efficiency that relies on a production data-base. The mechanism of grouping efficiency function that was applied by the latter paper has been proven and used for a number of performance studies such as Chandrasekharan and Rajagopalan (1986a), and Kumar and Chandrasekharan (1990). Other papers that dealt with the grouping efficiency and comparison results include Harhalakis et al. (1990), Taboun et al. (1991), and Franzier and Gaither (1991).

#### Multi-stage Machines Algorithm

De Witte (1980) designed a clustering algorithm that advocates the concept that some machines may be included in more than one machine cell. He divided all the available machines into 1) primary machines, 2) secondary machines, and 3) tertiary machines. To analyze the relationship between these machines three different similarity coefficients were used: 1) the absolute similarity coefficient  $sa_{ij}$ , 2) a mutually similarity coefficient  $sm_{ij}$ , and 3) a single similarity coefficient  $ss_{ij}$ . He concluded that the clustering approach should start with coefficients of  $sa_{ij}$  and  $sm_{ij}$  and then use  $ss_{ij}$  to allocate the remaining unassigned machines.

#### Rank Order Clustering algorithm (ROC)

The first sorting-based algorithm for CM solution was developed by King (1980) and is known as the Rank Order Clustering (ROC) algorithm. The mechanism of ROC is firstly assigning a weight to each row  $i$  and column  $j$  of a machine-part incidence matrix as

follows:

$$\text{row } i: \quad \sum_{k=1, N} a_{ik} 2^{N-k} \quad (\text{E2})$$

$$\text{column } j: \quad \sum_{k=1, M} a_{kj} 2^{M-k} \quad (\text{E3})$$

where  $M$ ,  $N$  are the total numbers of machines and parts in a machine-part incidence matrix. The sorting procedure for ROC then incorporates the following steps:

- STEP 1      Calculate a decimal equivalent weight for each row
- STEP 2      Sort rows of the decimal equivalent weight values in decreasing order and rearrange the new position of each row according to those sorted values.
- STEP 3      Repeat the above steps for each column.
- STEP 4      Repeat the above steps until the position of each element in each row and column does not change.

The solution for machine cells and part families are identified visibly from the final matrix that is generated by the ROC.

The ROC algorithm was further extended by King and Nakornchai (1982) and Chandrasekharan and Rajagopalan (1986). The main objective of the first paper was to improve the ROC algorithm in terms of computing efficiency and time. In the latter paper, Chandrasekharan and Rajagopalan (1986) modified the ROC algorithm by incorporating i) a "block and slice" method, and ii) a hierarchical clustering method, so that the proposed algorithm is more flexible for general applications.



### Direct Cluster algorithm (DCA)

Chan and Milner (1982) developed a Direct Cluster (DCA) algorithm which consists of the following sorting rules:

- STEP 1 Determine the total number of "1's" in each row and column in the machine-part incidence matrix.
- STEP 2 Rearrange the position of each row (column) according to the value of the total number of "1's" in increasing (decreasing) order.
- STEP 3 Repeat the above steps until the position of each element in each row and column does not change.

The final solution of the DCA algorithm may require the rearrangement of rows and columns by hand before a satisfactory clusters can be visually obtained.

### Bond-Energy Algorithm (BEA)

McCormick et al. (1972) developed another interchanging clustering algorithm called the Bond-Energy Algorithm (BEA). The BEA seeks to form a block-diagonal matrix by maximizing a value called measure of effectiveness (ME), computed as follows:

$$ME = 1/2 \left\{ \sum_{i=1, M} \sum_{j=1, N} a_{ij} [a_{i,j-1} + a_{i,j+1} + a_{i-1,j} + a_{i+1,j}] \right\} \quad (E4)$$

The ME value is used to rearrange the positions of rows and columns in a machine-part incidence matrix until clusters are formed. The procedure involved in using ME values is listed below:

- STEP 1      Set  $i=1$   
                   Select one of the columns arbitrarily.
- STEP 2      Place each of the remaining  $N-i$  columns, one at a time, in each of  $i+1$  positions, and compute each column that gives the largest incremental contribution to the ME value in its best location.
- STEP 3      When all the column have been placed, repeat the above steps for the rows.

#### Further expansion of BEA

Slagle et al. (1975) further developed a CM algorithm that based on the concepts of BEA and the Shortest Spanning Path (SPP) algorithm. Their concept was then later studied by Bhat and Haupt (1976), in which the later paper proposed the deviate measure (DM) between each pair of machines. Bhat and Haupt developed an algorithm in which the matching pair of two machines (i.e. two rows in a machine-part incidence matrix) is measured by a  $c_{ij}$  value as follows:

$$c_{ij} = \sum_{k=1, M} | a_{ik} - a_{jk} | \quad (E5)$$

The algorithm of Bhat and Haupt is quite similar to that of McCormick et al. except that the first one permutes rows and columns of a machine-part incidence matrix  $A$  in a form of matrix  $C=(A*A^T)$ , whereas the latter one permutes rows and calculates matching pair from the original matrix  $A$ . The use of this matching pair concept has also

been further studied by Logendran (1990). The objective of the latter paper is to derive a CM solution that has a minimum total numbers of intercell and intracell movements.

#### Cost-based Method

Askin and Subramanian (1987) developed a clustering algorithm which considers the following manufacturing costs:

- 1) fixed and variable machining cost
- 2) setup cost
- 3) production cycle inventory cost
- 4) work-in-process inventory cost
- 5) material handling cost.

The proposed algorithm consists of three stages. In the first stage, parts are classified by a coding system. Studying the feasibility of possible grouping of parts that based on the manufacturing cost is analyzed and performed in stage two. In the last stage, the actual layout for a group of machine cells is analyzed.

#### "Tick and Check" Procedure

Iri (1968) introduced a "tick and check" procedure to identify if a matrix can be separated into mutually exclusive submatrices. The proposed procedure is outlined as follows:

- STEP 1        Select any row and mark it by a "tick"
- STEP 2        Check and "tick" all columns that have value "1" occur on the "ticked"

row

- STEP 3 Repeat this checking procedure for above steps until all corresponding ticked rows and columns are checked.
- STEP 4 All collection of "ticked" elements form a cluster
- STEP 5 Repeat the above steps for further submatrices identification.

Although the "tick and check" procedure allows to identify the mutually exclusive submatrices from a machine-part incidence matrix, the procedure itself is not systematic and thus cannot be computerized.

#### Extension of the "tick and check" procedure

Kusiak and Chow (1987a) adopts the "tick and check" procedure and further developed and implemented it into a more structured algorithm - known as the Cluster Identification Algorithm (CIA). The CIA will be discussed in more detail in next chapter. It is interesting to note that the CIA concept has also been further expanded by Kusiak and Chow (1987b) where they applied the subcontracting cost that is associated with the parts to derive solutions of the PSCP. The latter work was pursued by Kusiak and Chow (1988) to develop an expert system which was based on a tandem system architecture proposed by Kusiak (1987a,b,c). The proposed expert system architecture was later studied and implemented by Kusiak (1988a, 1988b).

### Linear Cell Clustering algorithm (LCC)

Wei and Kern (1989) defined a most efficient coefficient  $c_{ij}$  to measure the similarity between a pair of machines in a machine-part incidence matrix:

$$c_{ij} = \Gamma(a_{ik}, a_{jk}) \quad (E6)$$

where

$$\Gamma(a_{ik}, a_{jk}) = \begin{cases} (N-1) & , \text{ if } a_{ik} = a_{jk} = 1 \\ 1 & , \text{ if } a_{ik} = a_{jk} = 0 \\ 0 & , \text{ if } a_{ik} \neq a_{jk} \end{cases}$$

The  $c_{ij}$  coefficient is used to develop a "linear cell clustering" algorithm (LCC). The fundamental concept of LCC is to first compute  $c_{ij}$  values for all pair of machines and then group a pair of machines that has the highest  $c_{ij}$  value together. The grouping process is repeated until the specific constraints, such as the total number of machine cells, are met. The computational efficiency of the LCC algorithm was later studied by Chow (1991a).

## 2.2 Mathematical Programming Formulation

Most mathematical programming models developed for solving CM problems are typically based on the study of a distance measure value  $d_{ij}$  between a pair of parts  $P_i$  and  $P_j$ . The distance measure  $d_{ij}$  is a real-valued symmetric function obeying the following axioms (Fu, 1980):

- reflexivity  $d_{ii}$

- symmetry  $d_{ij} = d_{ji}$
- triangle inequality  $d_{iq} = d_{ip} + d_{pq}$ .

The following three distance measures are the most commonly used:

- 1) Minkowski distance measure (Arthanari and Dodge, 1981)

$$d_{ij} = \left\{ \sum_{k=1, N} |a_{ik} - a_{jk}|^r \right\}^{1/r} \quad (\text{E7})$$

where  $r$  is a positive integer value and  $N$  is the total number of parts. Two special cases of the above measure are widely used:

- absolute metric measure (for  $r=1$ )
- Euclidean metric measure (for  $r=2$ )

- 2) Weighted Minkowski distance measure (Arthanari and Dodge, (1981)

$$d_{ij} = \left\{ \sum_{k=1, N} w_k |a_{ik} - a_{jk}|^r \right\}^{1/r} \quad (\text{E8})$$

There are two special cases:  $r=1$  is a weighted absolute metric measure, and  $r=2$  is a weighted Euclidean metric measure.

- 3) Hamming distance measure (Lee, 1981)

$$d_{ij} = \sum_{k=1, N} \delta(a_{ik}, a_{jk}) \quad (\text{E9})$$

where,

$$\delta(a_{ik}, a_{jk}) = \begin{cases} 1, & \text{if } a_{ik} \neq a_{jk} \\ 0, & \text{otherwise.} \end{cases}$$

The above distance measures are also known as dissimilarity measures. These dissimilarity measures may be considered opposite measurement to the similarity measures -like the similarity coefficient stated in Equation E1. Four of the most general representation of mathematical programming models associated with distance measures are presented next: the p-median model, the generalized p-median model, the quadratic programming model, and the fractional programming model.

### The p-Median Model

The p-median model is a linear programming model which is used to derive a CM solution that consists of p total numbers of part families. Mulvey and Crowder (1979) formulated the p-median model as in model (M1):

Define:

N     number of parts

p     total number of desired part families

$d_{ij}$    distance measure between parts  $P_i$  and  $P_j$

$x_{ij}$  =  $\begin{cases} 1, & \text{if part } i \text{ belongs to PF-}j \\ 0, & \text{otherwise.} \end{cases}$

Model (M1)

$$\max \sum_{i=1, N} \sum_{j=1, N} d_{ij} x_{ij} \quad (\text{E10})$$

subject to

$$\sum_{j=1, N} x_{ij} = 1, \quad \forall i=1, N \quad (\text{E11})$$

$$\sum_{j=1,N} x_{ij} = p, \quad (\text{E12})$$

$$x_{ij} \leq x_{jj}, \quad \forall i=1,N \text{ and } j=1,N \quad (\text{E13})$$

$$x_{ij} = 0,1, \quad \forall i=1,N \text{ and } j=1,N \quad (\text{E14})$$

The objective function E10 maximises the total similarity values for all pairs of parts. Constraint E11 ensures that each part belongs to exactly one part family. Constraint E12 specifies the total number of required part families. Constraint E13 ensures that part  $i$  belongs to part family  $j$  only if this part family is formed. The last constraint guarantees integrality. It is clear that the  $p$  value in model (M1) is known a priori. Further study of the extension of the  $p$ -median model for solving clustering problems was pursued by Klastorin (1982).

#### Generalized $p$ -median Model

Kusiak (1987d) further generalized the model (M1) to model (M2) to consider a set of alternative process plans for parts. The objective in model (M2) is to minimize the total sum of the distance measures (i.e. dissimilarity).

Define:

- $F_k$  set of process plans for part  $P_k$ ,  $\forall k=1,N$
- $p$  desired total number of process families
- $d_{ij}$  distance measures between process plans  $i$  and  $j$
- $q$  total number of process plans



Model (M2):

$$\min \sum_{i=1,q} \sum_{i=1,q} d_{ij}x_{ij} \quad (\text{E15})$$

subject to

$$\sum_{i \in F_k} \sum_{j=1,q} x_{ij} = 1, \forall k=1,N \quad (\text{E16})$$

$$\sum_{j=1,q} x_{ij} \leq p, \quad (\text{E17})$$

$$x_{ij} \leq x_{jj}, \forall i=1,q \text{ and } j=1,q \quad (\text{E18})$$

$$x_{ij} = 0,1, \forall i=1,q \text{ and } j=1,q \quad (\text{E19})$$

Constraint E16 is to ensure that only one process plan is chosen for each part. Constraint E17 restrains the upper bound on a total number of process families are allowed. Constraints E18 and E19 correspond to the respective constraints E13 and E14 in model (M1).

### Quadratic Programming Model

Kusiak et al. (1986) formulated a mathematical programming model that allows one to control the output of CM solutions that confine 1) the total number of clusters and 2) the sizes of a cluster. Their proposed formulation is an 0-1 quadratic programming model (M3):

Model (M3):

$$\min \sum_{i=1,N-1} \sum_{j=i+1,N} \sum_{l=1,p} d_{ij}x_{ij}x_{jl} \quad (\text{E20})$$

subject to

$$\sum_{j=1,p} x_{ij} = 1, \quad \forall i=1,N \quad (\text{E21})$$

$$\sum_{i=1,N} x_{ij} = m_j, \quad \forall j=1,p \quad (\text{E22})$$

$$x_{ij} = 0, 1, \quad \forall i=1,N, j=1,p \quad (\text{E23})$$

Constraint E21 ensures each part belongs to exactly one part family. Constraint E22 imposes that part family  $j$  contains exactly  $m_j$  number of parts. Constraint E23 ensures integrality. The (M3) model is solved by using an eigenvector-based algorithm.

#### Fractional Programming Model

Lashkari et al. (1987) modified model (M3) to form model (M4). Model (M4) allows one to control each part family in a CM solution so it contains at least  $L$  number of parts.

Define:

- $d_{ij}$  distance (dissimilarity) between parts  $i$  and  $j$
- $s_{ij}$  similarity measurement between parts  $i$  and  $j$
- $L$  minimum total number of parts in each part family

Model (M4):

$$\min \frac{\sum_{k=1,p} \sum_{i=1,N-1} \sum_{j=i+1,N} d_{ij} X_{ik} X_{jk}}{\sum_{k=1,p} \sum_{i=1,N-1} \sum_{j=i+1,N} s_{ij} X_{ik} X_{jk}} \quad (\text{E24})$$

subject to

$$\sum_{k=1,p} x_{ik} = 1, \quad \forall i=1,N \quad (\text{E25})$$

$$\sum_{i=1,N} x_{ik} \geq L, \quad \forall j=1,p \quad (\text{E26})$$

$$x_{ik} = 0, 1, \quad \forall i=1,N, k=1,p \quad (\text{E27})$$

Constraint E26 ensures each part family consists of at least L number of parts. To solve model (M4), Lashkari et al. applied the transformation function that was introduced by Glover and Woolsey (1974) in which each term of  $x_{ik}x_{jk}$  in model (M4) can be replaced by a variable  $y_{ijk}$  that leads to a new model (M5):

Model (M5):

$$\min \frac{\sum_{k=1,p} \sum_{i=1,N-1} \sum_{j=i+1,N} d_{ij} y_{ijk}}{\sum_{k=1,p} \sum_{i=1,N-1} \sum_{j=i+1,N} s_{ij} y_{ijk}} \quad (\text{E28})$$

subject to

constraints (E25)-(E27)

$$x_{ik} + x_{jk} - y_{ijk} < 1 \quad (\text{E29})$$

$$y_{ijk} < x_{ik} \quad (\text{E30})$$

$$y_{ijk} \leq x_{jk} \quad (\text{E31})$$

$$y_{ijk} = 0, 1, \quad \forall i=1,N; \quad (\text{E32}) \\ j=i+1,N; \\ k=1,p.$$

Lashkari et al. proposed that model (M5) be solved by a parametric search procedure.

Further use of the mathematical programming approach in solving CM problems that consider resource constraints include: Rajamani et al. (1990), Ventura et al. (1990), Stam and Kuula (1991), Gunasingh and Lashkari (1989), and Boctor (1991). A proposed CM model that combines the mathematical programming technique and the extended ROC of King and Nakornchai (1982) was studied by Co and Araar (1988).

### 2.3 Graph Formulations

There are three general types of graph formulations to solve CM problems:

- 1) bipartite graph
- 2) transition graph
- 3) boundary graph

#### Bipartite Graph

The bipartite graph consists of two sets of nodes, with one set representing parts and the other machines. Given that if a machine-part incidence matrix can be mutually separable into submatrices, two or more bipartite graphs can be obtained as a solutions to CM problems. The "close loops" of a sub-tours algorithm proposed by Srinivasan et al. (1990) is an example of the bipartite graph application. However, this approach

is difficult to use for solving the PSCP (Kusiak and Chow, 1988).

### Transition Graph

In a transition graph, parts are represented by nodes, while machines are denoted by an edge between two nodes. The transition graph provides a easy way to identify the bottleneck parts in a CM solution. Chow and Hawaleshka (1989) presented an algorithm that uses the transition graph approach to solve CM problems. Although the proposed solution still remains as an unstructured form, it has great potential for application in industry when colour graphics from CAD/CAM systems are used.

### Boundary Graph

A boundary graph consists of a set of hierarchy of bipartite graphs where each level can represent parts or machines. Determination of the bottleneck parts/machines in this graphical approach is a rather complex task. Several papers have been devoted to this problem. Chow (1991b) presented an algorithm to solve CM problems that involves a boundary graph together with the help of the CIA and the dendrogram. He proposed that parts to be removed as bottleneck parts should be selected and identified from the visual approach in a dendrogram instead from the boundary graph. Lee et al. (1982) presented another heuristic algorithm to detect bottleneck machines/parts. The basic mechanism of their algorithm is to first decide the total number of parts (machines) allowed for each cluster. Their algorithm is to add parts (or machines) into a family (or cell) one at a time. Parts (or machines) are to be removed from that family (or cell) if

inclusion of them violates the stated constraints. Their algorithm is presented below.

Denote:

- G     number of nodes in a graph
- K     maximum number of nodes in a subgraph

STEP 1     Determine the value  $m'$

$$m' = [(G-1)/K] > 1$$

where  $[x]$  is the minimum integer value not smaller than  $x$ .

STEP 2     Set  $m = m'$ .

Choose  $m$  initial nodes, one for each subgraph.

STEP 3     Determine the common node for each subgraph.

STEP 4     Remove the common node to the corresponding subgraph and add the uncommon node to the corresponding subgraph.

STEP 5     Repeat steps 3 and 4 until every node is assigned.

The proposed method assumes that the  $P$  value is known in priori. The algorithm by Lee et al., was then further extended by Vannelli and Kumar (1986) and Kumar and Vannelli (1987). In the latter paper, they imposed a subcontracting cost as a measuring criterion for removing nodes (i.e. parts) that lead to the formation of cells and families for CM solution. Al-Qattan (1990) proposed a branch and bound algorithm which involves the adding of new machines (as in a form of machine duplication) so that the CM solution has a minimum number of bottleneck machines. The proposed model uses

machines as a seed number for branching and parts for the bounding set. Criterion for selection or adding a new machine is dependent on its utilization rate. Vohra et al. (1990) expanded the cut-tree algorithm of Gomoty and Hu (1971) to develop a network model that would yield a minimum interaction between cells. The modified cut-tree algorithm considers processing time of parts represented by the edges (or arcs) of each level of boundary graph. The decomposition (known as the "cut", in his algorithm) of tree is performed by examining a corresponding "multi-terminal minimum-cut" problem first proposed by Ford and Fulkerson (1957).

#### **2.4 Expert Systems Formulation**

The practical application of expert systems for solving CM problems was first reviewed by Buller et al. (1980), whose ideas were later refined by Rayson (1985). Kusiak (1986c) further elaborated the expert system framework by describing the integrated components of the database for such a system. Based on the integration concept, Kusiak (1987a) proposed a more structured framework approach for developing an expert system for solving CM problems that is known as - the tandem system architecture. Kusiak (1987b,d) also showed that the tandem system concept - which consists of an expert system that exchanges information with a set model and algorithms - can be used to solved a complex CM problem within an acceptable computing time. Kusiak and Chow (1988) later proposed three important reasons to support the use of the tandem system

for solving CM problems:

1. there are an abundant existing methods dealing with different aspects or criteria of the CM problems that the tandem system can take advantage of;
2. the tandem system will select an appropriate algorithm/model that would solve a given constrained CM problem with a low computational complexity;
3. CM problems may involve quantitative and qualitative data that the tandem system will gain access to.

In the paper by Kusiak and Chow (1988), they further presented examples of four types of constraints and production rules that can be used for solving practical CM problems in a tandem system environment. The proposed production rules were mainly dealt with a pseudocode that involves "IF-THEN-ELSE" statements. Kusiak (1988b) has further expanded these production rules in details and developed a first hand expert system known as EXGT-S by using the LISP language (Kusiak, 1988a). Although the proposed knowledge-based system perhaps is the first developed expert system for CM problems, the proposed system remains as a rather less structured system because there are no concrete criteria specifically outlined as to how parts and machines are grouped. Therefore, one is not sure of the applicability and validity of the EXGT-S.



## Chapter III

### A HEURISTIC ALGORITHM FOR SOLVING THE MSCP

The mutually separable clustering problem (MSCP) assumes that a machine-part incidence matrix  $A$  which represents a CM problem is composed by a set of exclusively separable submatrices  $A_1, \dots, A_k, \dots, A_K$ . Each submatrix  $A_k$  contains a set of machines and parts that belongs to its respective machine cell  $MC-k$  and part family  $PF-k$ . Since submatrix  $A_k$  represents a sub-solution of a CM problem, the main purpose of the MSCP is to identify these submatrices from matrix  $A$ . Literature relating to the solution for the MSCP clearly satisfy the requirement of CM assumption (b) listed in Section 1.3.

The pioneer work for identifying the solution of the MSCP was perhaps proposed by Iri (1969). However, his algorithm - known as "tick and check" procedure - contains two major flaws. The first flaw is that his algorithm remains non-systematic which makes it not suitable for computerization, whereas the other is that Iri provided no explanation as to how his methodology works. Kusiak and Chow (1987a) proposed a cluster identification algorithm (CIA), in which the working mechanism of CIA is to some extent similar to that of Iri but the latter algorithm remedied the two aforementioned flaws. In this chapter, the logic, algorithm, and computational results of CIA are discussed.

### 3.1 Solution to the MSCP

To present a solution to the MSCP, we first consider a matrix (A1) presented in chapter I. Matrix (A1) is composed by two exclusively separable submatrices but is not notable here mainly because of the position arrangement of machines and parts in that matrix. These two exclusive separable submatrices can be clearly identified if the positions of rows (i.e. represented by machines ) and columns (i.e. represented by parts) of matrix A1 are to be rearranged in the order of  $P_1, P_3, P_2, P_5, P_4$  and  $M_1, M_2, M_6, M_3, M_4, M_5$ . The final result of such rearrangement is shown in matrix A2.

$$\begin{array}{c}
 M_1 \\
 M_2 \\
 M_6 \\
 \dots \\
 M_3 \\
 M_4 \\
 M_5
 \end{array}
 \begin{array}{c}
 P_1 \quad P_3 \quad P_2 \quad P_5 \quad P_4 \\
 \left[ \begin{array}{ccccc}
 \dots & \dots & \dots & \dots & \dots \\
 1 & & : & & \\
 1 & 1 & : & & \\
 & 1 & : & & \\
 \dots & \dots & \dots & \dots & \dots \\
 & & : & 1 & 1 \\
 & & : & 1 & 1 \\
 & & : & & 1 \\
 \dots & \dots & \dots & \dots & \dots
 \end{array} \right]
 \end{array}
 \quad (A2)$$

The solution for the MSCP in matrix (A2) can be read as such:

Cluster 1:

Machine Cell MC-1 :  $M_1, M_2, M_6$

Part Family PF-1 :  $P_1, P_3$

Cluster 2:

Machine Cell MC-2 :  $M_3, M_4, M_5$

Part Family PF-2 :  $P_2, P_4, P_5$ .

In the above solution set, cluster 1 is referred to as the first set of sub-solution for the CM problem and cluster 2 as the second one. It is common practice in the literature to group each element of machines and parts within a cluster to its respective machine cell MC-k and part family PF-k.

To date, literature addressing solution methods for the final layout of matrix A2 required a substantial computational effort (Kusiak and Chow, 1987b). Here, we present a simple logical flow and the most efficient algorithm yet reported - known as Cluster Identification Algorithm (CIA) - for identifying the solution of the MSCP. Justification of this statement is discussed later in this chapter.

### 3.1.1 CIA Logic

By examining the final layout of matrix A2 closely, one may realize that matrix A2 is composed of two diagonal block matrices. The diagonal block structure matrix has the property that each block of elements (in this case they are represented by machines and parts) is independent to the others. To identify these blocks, we first imposed 6 horizontal and vertical lines onto matrix A2 as shown in matrix A3.

$$\begin{array}{c}
 \text{Machine} \\
 \text{Number}
 \end{array}
 \begin{array}{c}
 M_1 \\
 M_2 \\
 M_6 \\
 \hline
 M_3 \\
 M_4 \\
 M_5
 \end{array}
 \begin{array}{c}
 \text{Part Number} \\
 P_1 \quad P_3 \quad P_2 \quad P_5 \quad P_4 \\
 \left[ \begin{array}{ccccc|ccccc}
 \vdots & \vdots & & & & \vdots & \vdots & \vdots & & & \vdots \\
 \cdot 1 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
 \cdot 1 & \cdot & \cdot 1 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
 \cdot & \cdot & \cdot & \cdot 1 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
 \hline
 \cdot & \cdot & \cdot & \cdot & \cdot & \cdot 1 & \cdot & \cdot 1 & \cdot & \cdot & \cdot \\
 \cdot & \cdot & \cdot & \cdot & \cdot & \cdot 1 & \cdot & \cdot 1 & \cdot 1 & \cdot & \cdot \\
 \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & 1 & \cdot \\
 \vdots & \vdots & & & & \vdots & \vdots & \vdots & & & \vdots \\
 h_1 & h_2 & h_3 & h_4 & h_5 & & & & & & 
 \end{array} \right]
 \begin{array}{c}
 \cdot \cdot \cdot \cdot \cdot \\
 \cdot \cdot \cdot \cdot \cdot \\
 \cdot \cdot \cdot \cdot \cdot \\
 \cdot \cdot \cdot \cdot \cdot \\
 \cdot \cdot \cdot \cdot \cdot \\
 \cdot \cdot \cdot \cdot \cdot \\
 \cdot \cdot \cdot \cdot \cdot \\
 \cdot \cdot \cdot \cdot \cdot \\
 \cdot \cdot \cdot \cdot \cdot \\
 \cdot \cdot \cdot \cdot \cdot \\
 \cdot \cdot \cdot \cdot \cdot
 \end{array}
 \begin{array}{c}
 v_1 \\
 v_2 \\
 v_3 \\
 v_4 \\
 v_5 \\
 v_6
 \end{array}
 \end{array}
 \quad (A3)$$

The following observations can be drawn from matrix A3:

1. Each diagonal block consists of its own set of horizontal and vertical lines
2. Each entry value "1" in the matrix is exactly crossed by one vertical and one horizontal lines.

Assume that each block of diagonal matrix represents a cluster, then a set of lines in each diagonal block can be used to identify its respectively elements (i.e. machines and parts). This crucial observation is used to develop the CIA.

### 3.1.2 Cluster Identification Algorithm (CIA)

The basic concept of CIA is to impose a set of vertical and horizontal lines onto a matrix to identify a group of elements that belong to their respective cluster or block. This concept is presented in algorithm 1.

#### ALGORITHM 1 (Kusiak and Chow, 1987a)

- STEP 0      Set iteration number  $k=1$
- STEP 1      Select any row  $i$  of a machine-part incidence matrix  $A^{(k)}$  and draw a horizontal line  $h_i$  through it
- STEP 2      For each column  $j$  that has an entry value "1" on the intersection with the horizontal line  $h_i$ , draw a vertical line  $v_j$
- STEP 3      For each row  $q$  of entry value "1" crossed by a vertical line  $v_j$ , draw a

- horizontal line  $h_q$
- STEP 4 Repeat steps 2 and 3 until all single crossed entry values "1" have been crossed by two lines (i.e. one horizontal and vertical line)
- STEP 5 All corresponding crossed rows and columns form a machine cell MC-k and a part family PF-k
- STEP 6 Transform the machine-part incidence matrix  $A^{(k)}$  into  $A^{(k+1)}$  by removing all crossed rows and columns
- STEP 7 If matrix  $A^{(k+1)} = \phi$ , stop; otherwise set  $k=k+1$  and go to step 1.

The mechanism of CIA is illustrated in the following Example 1.

EXAMPLE 1. Consider the following machine-part incidence matrix A4.

		Part Number									
		$P_1$	$P_2$	$P_3$	$P_4$	$P_5$	$P_6$	$P_7$	$P_8$		
$M_1$	1	1	1			1				Machine Number	(A4)
$M_2$	1						1				
$M_3$					1			1			
$M_4$							1				
$M_5$									1		
$M_6$					1						
$M_7$	1	1	1			1			1		

- STEP 0 Set iteration number  $k=1$
- STEP 1 Row 1 of matrix A4 is selected, and horizontal line  $h_1$  is drawn. The

result is shown in matrix A5.

$$\begin{array}{c}
 A^{(1)} = \\
 M_1 \\
 M_2 \\
 M_3 \\
 M_4 \\
 M_5 \\
 M_6 \\
 M_7
 \end{array}
 \begin{array}{c}
 \text{Part Number} \\
 P_1 \ P_2 \ P_3 \ P_4 \ P_5 \ P_6 \ P_7 \ P_8 \\
 \left[ \begin{array}{cccccccc}
 \cdots & 1 & \cdots & 1 & \cdots & \cdots & 1 & \cdots & \cdots & \cdots \\
 1 & & & & & & 1 & & & \\
 & & & & 1 & & & & 1 & \\
 & & & & & & 1 & & & \\
 & & & & & & & & & 1 \\
 & & & & 1 & & & & & \\
 1 & 1 & & & 1 & & & & & 1
 \end{array} \right] \cdots \cdots h_1 \\
 \text{Machine} \\
 \text{Number}
 \end{array}
 \quad (A5)$$

STEP 2 Three vertical lines  $v_2$ ,  $v_3$ , and  $v_5$  are drawn as in matrix A6.

$$\begin{array}{c}
 A^{(1)} = \\
 M_1 \\
 M_2 \\
 M_3 \\
 M_4 \\
 M_5 \\
 M_6 \\
 M_7
 \end{array}
 \begin{array}{c}
 \text{Part Number} \\
 P_1 \ P_2 \ P_3 \ P_4 \ P_5 \ P_6 \ P_7 \ P_8 \\
 \left[ \begin{array}{cccccccc}
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 \cdots & 1 & \cdots & 1 & \cdots & \cdots & 1 & \cdots & \cdots & \cdots \\
 1 & : & : & : & : & 1 & & & & \\
 : & : & : & 1 & : & : & 1 & & & \\
 : & : & : & : & : & 1 & & & 1 & \\
 : & : & : & 1 & : & : & & & & \\
 1 & 1 & & & 1 & & & & & 1 \\
 : & : & & & : & & & & & \\
 \vdots & \vdots & & & \vdots & & & & & \\
 v_2 & v_3 & & & v_5 & & & & & 
 \end{array} \right] \cdots \cdots h_1 \\
 \text{Machine} \\
 \text{Number}
 \end{array}
 \quad (A6)$$

STEP 3 Horizontal line  $h_7$  is drawn in matrix A7

$$\begin{array}{c}
 \text{Part Number} \\
 P_1 \quad P_2 \quad P_3 \quad P_4 \quad P_5 \quad P_6 \quad P_7 \quad P_8 \\
 \begin{array}{c} M_1 \\ M_2 \\ M_3 \\ M_4 \\ M_5 \\ M_6 \\ M_7 \end{array}
 \left[ \begin{array}{cccccccc}
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 \cdots & 1 & \cdots & 1 & \cdots & \cdots & 1 & \cdots \\
 1 & : & : & : & : & 1 & : & : \\
 : & : & : & 1 & : & : & 1 & : \\
 : & : & : & : & : & : & : & 1 \\
 : & : & : & 1 & : & : & : & : \\
 \cdots & 1 & \cdots & 1 & \cdots & \cdots & 1 & \cdots \\
 : & : & : & : & : & : & : & : \\
 : & : & : & : & : & : & : & : \\
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots
 \end{array} \right]
 \begin{array}{c}
 \cdots \cdots h_1 \\
 \\ \\
 \text{Machine} \\
 \text{Number} \\
 \\ \\
 \cdots \cdots h_7
 \end{array}
 \end{array}
 \quad (A7)$$

$v_2 \quad v_3 \qquad \qquad v_5$

STEP 4 Steps 2 and 3 are repeated for matrix A7 because an entry value "1" of row 7 and column 8 is "single" crossed. Therefore, the final vertical line  $v_8$  is first drawn and the horizontal line  $h_5$  is then imposed as presented in matrix A8.

$$\begin{array}{c}
 \text{Part Number} \\
 P_1 \quad P_2 \quad P_3 \quad P_4 \quad P_5 \quad P_6 \quad P_7 \quad P_8 \\
 \begin{array}{c} M_1 \\ M_2 \\ M_3 \\ M_4 \\ M_5 \\ M_6 \\ M_7 \end{array}
 \left[ \begin{array}{cccccccc}
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 \cdots & 1 & \cdots & 1 & \cdots & \cdots & 1 & \cdots \\
 1 & : & : & : & : & 1 & : & : \\
 : & : & : & 1 & : & : & 1 & : \\
 : & : & : & : & : & : & : & 1 \\
 : & : & : & 1 & : & : & : & : \\
 \cdots & 1 & \cdots & 1 & \cdots & \cdots & 1 & \cdots \\
 : & : & : & : & : & : & : & : \\
 : & : & : & : & : & : & : & : \\
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots
 \end{array} \right]
 \begin{array}{c}
 \cdots \cdots h_1 \\
 \\ \\
 \text{Machine} \\
 \text{Number} \\
 \\ \\
 \cdots \cdots h_5 \\
 \\ \\
 \cdots \cdots h_7
 \end{array}
 \end{array}
 \quad (A8)$$

$v_2 \quad v_3 \qquad \qquad v_5 \qquad \qquad v_8$

STEP 5 Since all entry values "1" that crossed by either vertical or horizontal line are crossed "twice", the first iteration stops here. All elements in this block form a cluster which reads as:

Cluster 1:

$$\text{Machine cell MC-1} = \{M_1, M_5, M_7\}$$

Part family PF-1 = {P<sub>2</sub>, P<sub>3</sub>, P<sub>5</sub>, P<sub>8</sub>}

STEP 6 Matrix A<sup>(1)</sup> is transformed into A<sup>(2)</sup>

$$A^{(2)} = \begin{matrix} & & & & \text{Part Number} \\ & & & & P_1 & P_4 & P_6 & P_7 \\ \begin{matrix} M_2 \\ M_3 \\ M_4 \\ M_6 \end{matrix} & & & & \begin{bmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{bmatrix} & & \text{Machine} \\ & & & & & & & & \text{Number} \end{matrix} \quad (A9)$$

STEP 7 Since matrix A9 ≠ φ, steps 1-4 are repeated on matrix A<sup>(2)</sup>. The second iteration results the layout of matrix A10.

$$A^{(2)} = \begin{matrix} & & & & \text{Part Number} \\ & & & & P_1 & P_4 & P_6 & P_7 \\ \begin{matrix} M_2 \\ M_3 \\ M_4 \\ M_6 \end{matrix} & & & & \begin{bmatrix} \vdots & & & & \vdots \\ \cdot 1 \cdot & \dots & \dots & 1 & \dots & \dots \\ \vdots & & 1 & & & 1 \\ \cdot \cdot \cdot & \dots & \dots & 1 & \dots & \dots \\ \vdots & \dots & 1 & \dots & \vdots & \dots \\ \vdots & & & & \vdots & \dots \\ \vdots & & & & \vdots & \dots \\ v_1 & & & & & v_6 \end{bmatrix} & \dots & \begin{matrix} h_2 \\ h_4 \\ h_6 \end{matrix} \\ & & & & & & & & \text{Machine} \\ & & & & & & & & \text{Number} \end{matrix} \quad (A10)$$

The matrix A10 produces the following solution clusters:

Cluster 2:

Machine cell MC-2: {M<sub>2</sub>, M<sub>4</sub>}

Part family PF-2 : {P<sub>1</sub>, P<sub>6</sub>}



In the third iteration  $k=3$ , matrix A11 is generated.

$$\begin{array}{c}
 \text{Part Number} \\
 P_4 \quad P_7 \\
 \begin{array}{c} \vdots \\ \vdots \end{array} \\
 A^{(3)} = \begin{array}{c} M_3 \\ M_6 \end{array} \begin{array}{c} \left[ \begin{array}{ccc} \cdot & 1 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & 1 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ v_4 & & & & & & & v_7 \end{array} \right] \cdots \cdots \begin{array}{l} h_3 \\ h_4 \end{array} \\
 \end{array} \begin{array}{l} \text{Machine} \\ \text{Number} \end{array} \\
 \end{array} \quad (A11)$$

From this matrix,  $MC-3 = \{M_3, M_6\}$  and  $PF-3 = \{P_4, P_7\}$  are obtained.

The proposed CIA listed in Algorithm 1 decomposed matrix A4 into submatrices which, represented by block of clusters and its corresponding final diagonal block matrices, are shown in matrix A12.

$$\begin{array}{c}
 \text{Part Families} \\
 PF-1 \quad PF-2 \quad PF-3 \\
 \begin{array}{cccc} P_2 & P_3 & P_5 & P_8 \\ P_1 & P_6 & P_4 & P_7 \end{array} \\
 \begin{array}{c} MC-1 \\ MC-2 \\ MC-3 \end{array} \left[ \begin{array}{c} M_1 \\ M_7 \\ M_5 \\ M_2 \\ M_4 \\ M_3 \\ M_6 \end{array} \right] \left[ \begin{array}{cccc} 1 & 1 & 1 & \\ 1 & 1 & 1 & 1 \\ & & & 1 \\ & & 1 & 1 \\ & & & 1 \\ & & 1 & 1 \\ & & 1 & \end{array} \right] \begin{array}{l} \text{Machine} \\ \text{Cells} \end{array} \\
 \end{array} \quad (A12)$$

Therefore, CIA provides the solution for the MSCP.

### 3.2 Computational Complexity and Time for CIA

The computational complexity of CIA can be calculated as follows. Let  $M$ ,  $N$  denote the total number of machines and parts in the matrix  $A$ , respectively. The CIA scans each element of a machine-part incidence matrix  $A$  two times. Since there are total number of  $M \times N$  elements, its computational complexity is thus reported as  $O(2MN)$ , i.e. the number of elementary computer operations is in the order of  $2MN$ .

Table 1 presented some of the most efficient heuristic algorithms for solving the MSCP problems in the existing literature. This table shows that our proposed CIA has the lowest computational complexity. To offer an impression about the importance of computational difficulties in solving CM problems, it is enough to state that solving a CM problem is equivalent to solving two travelling salesman problems (Lawler et al., 1985).

TABLE 1

## Comparison of Computational Complexity for Various Algorithms

Algorithm	Computational Complexity
McCormick et al. (1972)	$O(NM^2 + N^2M)$
Slagle et al. (1975)	$O(NM^2 + N^2M)$
Bhat and Haupt (1979)	$O(NM^2 + N^2M)$
King (1980)	$O(NM^2 + N^2M)$
Kusiak (1985)	$O(NM^2 + N^2M)$
Seifoddini (1989a)	$O(NM \log M) + O(M(M^2/2) \log(M^2/2))$
Wei and Kern (1989)	$O(NM \log M) + O((M^2/2) \log(M^2/2))$
The proposed CIA	$O(2MN)$

To test the performance of the proposed CIA, a FORTRAN code was developed and a number of problems of different sizes have been solved on an AMDAHL 580 computer. The data for these problems was generated based on a uniform random number generator. The computational results are summarized in Table 2.

TABLE 2

**Computational Results Using CIA (AMDAHL 580, Operating System MVS-TSO)**

Incidence Matrix		Number of Clusters	CPU [secs]
Number of machines, M	Number of Parts, N		
10	10	1	0.00
20	40	1	0.01
60	80	4	0.06
80	100	1	0.11
100	200	6	0.25

The computational experience showed that the CIA is very efficient. As expected, the CPU time is proportional to the product of  $M \times N$ . In order to compare the computing performance between the proposed CIA and other existing algorithms, we selected the LCC algorithm presented by Wei and Kern (1989). The preference in selecting the LCC algorithm over others for comparison is not only because of its lower computational complexity reported in Table 1, but also because the determination of its MSCP solution requires no human interaction (as, say, those reported in Average Linkage Clustering by Seifoddini (1989a)). Table 3 gives the comparison results. The testing was done on a VAX 785A computer and is based on a PASCAL code. Again, results in Table 3 show that the proposed CIA outperformed the LCC algorithm.

TABLE 3

**Computational Results Using CIA and LCC (VAX 785A,  
Operating System VMS)**

Incidence Matrix		CPU	
Num. of Machine, M	Num. of Parts, N	Proposed CIA [secs]	LCC Algorithm [secs]
10	10	0.02	0.39
20	40	0.03	2.15
60	80	0.15	54.03
80	100	0.25	165.41
100	200	0.52	395.40

### 3.3 Conclusions

In this chapter, we presented a new and most efficient algorithm to solve the MSCP yet reported in literature at the time when our results were published. The proposed model is known as the Cluster Identification Algorithm (CIA). We have compared its efficiency in terms of computational complexity and computer times to those in the literature. The computational time of CIA is linearly proportional to the product of value M and N. A low computational time for solving the MSCP is highly desired in practice because the planning of CM solution begins as early as during the development of the Master Production Plan (instead of starting at the scheduling level). An example illustrating the working mechanism of the CIA was also presented.

## CHAPTER IV

### AN EXTENSION OF CIA FOR THE PSCA

The CIA presented in Chapter III efficiently solves the MSCP. However, the CIA cannot be directly applied to solve CM problems that relate to the PSCP since the latter type of problems do not consist of a set of exclusively separable matrices. To solve PSCP by using CIA, modification of the proposed algorithm is required. In this chapter, we are presenting a modified version of CIA - known as Cost Analysis Algorithm (CAA) - to obtain a solution of PSCP.

#### 4.1 Cost Analysis Algorithm (CAA)

The PSCP assumes that a machine-part incidence matrix  $A$  is not composed of a set of exclusively separable matrices. The general approach in solving the PSCP in the literature is to incorporate a set of constraints with an algorithm. The purpose for imposing these constraints is to determine which components (i.e. parts) should be removed from matrix  $A$  so that matrix  $A$  will transform into a diagonal block matrix (i.e. contains a set of exclusively separable matrices) so that clusters of solutions for a CM problem are obtained. Samples of those constraints that are being imposed in PSCP solution methods may range from the maximum number of machines allowed within a cell, a maximum flow capacity of material handling systems to specifying the total

number of machine cells, etc.. In general, parts are considered as components to be removed in forming a PSCP's solution and not machines because the latter items are valuable and permanent assets for a company, not appropriate for solution identification. The proposed CAA is also confined in terms of this general assumption.

#### 4.1.1 CAA Logic

We assume that the rows and columns in a matrix  $A$  represent its respective machines and parts. The basic mechanism of CAA is to first associate a cost factor  $c_j$  with each part  $P_j$  in a matrix  $A$ . The use of cost  $c_j$  for the CM solution derivation will be explained in the next section.

Costs  $c_j$  may derive from one of the following criteria:

- i) subcontracting cost
- ii) production cost
- iii) part flow rate.

The first two costs are applied to determine a lower cost for the total number of parts to be removed when a solution for PSCP is formed. Parts that are being identified for removal or to be manufactured by outsiders such as subcontractors. The last concept - part flow rate - is useful to reduce an excessive utilization rate of material handling systems so that removed parts are manufactured within a functional workstation.

#### 4.1.2 Cost Analysis Algorithm (CAA)

The proposed CAA itself confines to the following assumptions:

- 1) only a maximum number of  $L$  machines are permitted in each machine cell;
- 2) when the condition 1 is violated then parts associated with lower subcontracting costs are to be removed from matrix  $A$ .

Assumption 2 warrants a minimum subcontracting cost when a solution for PSCP is obtained. The CAA is presented below.

##### Algorithm 2 (Kusiak and Chow, 1987b)

- STEP 0      Set iteration number  $k=1$  and the upper limit on the number of machines in each cell to  $L$ .
- STEP 1      From matrix  $A^{(k)}$  select the column  $j$  which involves at most  $L$  machines and has maximum cost. Draw a vertical line  $v_j$  through the selected column.
- STEP 2      For each row  $i$  corresponding to the entry value "1" on the intersection with the vertical line  $v_j$ , draw horizontal lines  $h_i$ . Machines corresponding to these lines will be included in machine cell MC- $k$ .
- STEP 3      Let  $V^{(k)}$  be the set of all columns crossed exactly once by any of the horizontal lines  $h_i$ . From the set  $V^{(k)}$ , select a column with the maximum



cost (one at a time) and apply the CIA. If this column does not increase the number of machines in MC-k over the imposed upper limit  $L$ , draw a vertical line through it; otherwise add this part to the set of parts to be removed from  $A^{(k)}$  and select the column with the next maximum cost. Repeat this process until all the element of  $V^{(k)}$  have been scanned.

- STEP 4 All corresponding crossed rows and columns form a machine cell MC-k and part family PF-k.
- STEP 5 Transform the machine-part incidence matrix  $A^{(k)}$  into  $A^{(k+1)}$  by removing all crossed rows and columns.
- STEP 6 If matrix  $A^{(k+1)} = \phi$ , stop; otherwise set  $k=k+1$  and go to step 1.

The cost analysis algorithm is illustrated on Example 2.

Example 2.

Given a machine-part incident matrix (A13) and a production cost  $c_j$  for each of the eleven parts, determine a solution of PSCP that yields a minimum subcontracting cost. It is further assumed that the total number of machines allowed within each machine cell is not more than  $L=4$ .

		Part Number												
		P <sub>1</sub>	P <sub>2</sub>	P <sub>3</sub>	P <sub>4</sub>	P <sub>5</sub>	P <sub>6</sub>	P <sub>7</sub>	P <sub>8</sub>	P <sub>9</sub>	P <sub>10</sub>	P <sub>11</sub>		
M <sub>1</sub>	]		1	1				1					Machine Number	(A13)
M <sub>2</sub>		1				1						1		
M <sub>3</sub>											1	1		
M <sub>4</sub>		1		1			1							
M <sub>5</sub>						1			1					
M <sub>6</sub>		1			1				1	1	1			
M <sub>7</sub>				1	1		1	1		1				

cost = [2.5 8.0 70.0 6.0 15 5.0 10.0 7.0 2.0 30.0 4.0] = c<sub>j</sub>

The mechanism of Algorithm 2 on Example 2 is presented below.

STEP 0      Set k=1, and L=4

STEP 1      Part P<sub>3</sub> with the maximum production cost c<sub>3</sub>=10.0 has been selected and line v<sub>3</sub> is drawn. The results of steps 1 and 2 are shown in matrix (A14).

		Part Number															
		P <sub>1</sub>	P <sub>2</sub>	P <sub>3</sub>	P <sub>4</sub>	P <sub>5</sub>	P <sub>6</sub>	P <sub>7</sub>	P <sub>8</sub>	P <sub>9</sub>	P <sub>10</sub>	P <sub>11</sub>					
M <sub>1</sub>	]	.....	1	.....	.....	.....	.....	1	.....	.....	.....	.....	.....	.....	h <sub>1</sub>		
M <sub>2</sub>		1		:		1							1			Machine Number	
M <sub>3</sub>				:								1	1				
M <sub>4</sub>		.....	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....		h <sub>4</sub>
M <sub>5</sub>				:		1			1								
M <sub>6</sub>		1		:	1				1	1	1						
M <sub>7</sub>		.....	1	.....	1	.....	1	.....	1	.....	1	.....	.....	.....	.....		h <sub>7</sub>

cost = [2.5 8.0 70.0 6.0 15 5.0 10.0 7.0 2.0 30.0 4.0] = c<sub>j</sub>

: v<sub>3</sub>

STEP 2      Since machines M<sub>1</sub>, M<sub>4</sub>, and M<sub>7</sub> are required to process part 3, horizontal lines h<sub>1</sub>, h<sub>4</sub> and h<sub>7</sub> are drawn. Corresponding machines M<sub>1</sub>, M<sub>4</sub>, and M<sub>7</sub> are included in machine cell MC-1.

STEP 3 The set  $V^{(1)} = \{P_1, P_2, P_4, P_6, P_7, P_9\}$ . From  $V^{(1)}$ , columns 7, 2 and 6 corresponding costs  $c_7 = 10.0$ ,  $c_2 = 8.0$ , and  $c_6 = 5.0$  are selected and vertical lines  $v_7$ ,  $v_2$ , and  $v_6$  are drawn and its result is shown in matrix A15. Parts  $P_1$ ,  $P_4$ , and  $P_9$  with respective subcontracting cost  $c_1=2.5$ ,  $c_4=6.0$ , and  $c_9 = 4.0$  are to be subcontracted. Including the latter parts in part family PF-1 would violate the constraint restriction of the total number of machine  $L=4$  for each machine cell.

		Part Number														
		P <sub>1</sub>	P <sub>2</sub>	P <sub>3</sub>	P <sub>4</sub>	P <sub>5</sub>	P <sub>6</sub>	P <sub>7</sub>	P <sub>8</sub>	P <sub>9</sub>	P <sub>10</sub>	P <sub>11</sub>				
M <sub>1</sub>	[	.....	1	.....	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	h <sub>1</sub>	
M <sub>2</sub>		1	.....	.....	.....	.....	1	.....	.....	.....	.....	.....	.....	.....	.....	.....
M <sub>3</sub>		.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
M <sub>4</sub>		.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
M <sub>5</sub>		.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
M <sub>6</sub>		.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
M <sub>7</sub>		.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	h <sub>7</sub>
cost=		[2.5	8.0	70.0	6.0	15	5.0	10.0	7.0	2.0	30.0	4.0]				
		.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....				
		.....	v <sub>2</sub>	.....	v <sub>3</sub>	.....	.....	v <sub>6</sub>	.....	v <sub>7</sub>	.....	.....				

Machine Number (A15)

STEP 4 From matrix A14, the following first cluster is obtained;

Cluster 1:

Machine Cell MC-1 = {M<sub>1</sub>, M<sub>4</sub>, M<sub>7</sub>}

Part Family PF-1 = {P<sub>2</sub>, P<sub>3</sub>, P<sub>6</sub>, P<sub>7</sub>}.

STEP 5 Matrix A14 is transformed into matrix A15.

$$\begin{array}{c}
 \text{Part Number} \\
 P_6 \quad P_8 \quad P_{10} \quad P_{11} \\
 \begin{array}{l} M_2 \\ M_3 \\ M_5 \\ M_6 \end{array} \left[ \begin{array}{cccc} 1 & & & 1 \\ & & 1 & 1 \\ 1 & & & \\ & 1 & 1 & \end{array} \right] \begin{array}{l} \text{Machine} \\ \text{Number} \end{array} \\
 \text{cost} = [ 15 \quad 7.0 \quad 30.0 \quad 4.0 ] = c_j
 \end{array} \quad (A16)$$

STEP 6 Set  $k=k+1=2$  and go to step 1.

The final result of the second iteration ( $k=2$ ) is shown in matrix A16 and the following cluster is obtained:

Cluster 2:

Machine cell MC-2 =  $\{M_2, M_3, M_5, M_6\}$

Part Family PF-2 =  $\{P_5, P_8, P_{10}, P_{11}\}$ .

$$\begin{array}{c}
 \text{Part Number} \\
 P_5 \quad P_8 \quad P_{10} \quad P_{11} \\
 \begin{array}{l} M_2 \\ M_3 \\ M_5 \\ M_6 \end{array} \left[ \begin{array}{cccc} \vdots & \vdots & \vdots & \vdots \\ \cdot 1 \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot 1 \cdot & & & \\ \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot 1 \cdot \cdot \cdot \cdot 1 \cdot & & & \\ \cdot 1 \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot & & & \\ \cdot \cdot \cdot \cdot 1 \cdot \cdot \cdot \cdot 1 \cdot \cdot \cdot \cdot \cdot \cdot \cdot & & & \\ \vdots & \vdots & \vdots & \vdots \end{array} \right] \begin{array}{l} \cdot \cdot \cdot v_2 \\ \cdot \cdot \cdot v_3 \\ \cdot \cdot \cdot v_5 \\ \cdot \cdot \cdot v_6 \end{array} \begin{array}{l} \text{Machine} \\ \text{Number} \end{array} \\
 \text{cost} = [ \begin{array}{cccc} 15 & 7.0 & 30.0 & 4.0 \\ \vdots & \vdots & \vdots & \vdots \\ v_5 & v_8 & v_{10} & v_{11} \end{array} ] = c_j
 \end{array} \quad (A17)$$

The final layout to a solution of PSCP generated by the CAA for a CM problem presented in matrix A13 is shown in matrix A18 below.

Part Number

(A18)

		PF-1				PF-2						
		P <sub>2</sub>	P <sub>3</sub>	P <sub>7</sub>	P <sub>6</sub>	P <sub>11</sub>	P <sub>5</sub>	P <sub>8</sub>	P <sub>10</sub>	P <sub>1</sub>	P <sub>4</sub>	P <sub>9</sub>
MC-1	M <sub>1</sub>	1	1	1								
	M <sub>7</sub>		1	1	1						1	1
	M <sub>4</sub>		1		1					1		
MC-2	M <sub>2</sub>					1	1			1		
	M <sub>5</sub>						1	1				
	M <sub>3</sub>					1			1			
	M <sub>6</sub>							1	1	1	1	1

$c_j = [8.0 \ 70 \ 10.0 \ 50.0 \ 4.0 \ 15.0 \ 7.0 \ 30.0 \ 2.5 \ 6.0 \ 2.0 ]$

#### 4.2 Computational time for CAA

The CAA was coded in FORTRAN V and a number of generated CM problems based on the uniform number generator were tested. The computational results are presented in Table 4 (Kusiak and Chow, 1987b).

TABLE 4

**Computational Results Using CAA (AMDAHL 580, Operating System MVS-TSO)**

Incidence Matrix		Number of Clusters Obtained	Number of Parts Deleted	CPU [secs]
Number of Machine, M	Number of Parts, N			
10	10	3	0	0.01
20	40	10	1	0.03
60	80	23	5	0.96
80	100	27	8	1.91
100	200	45	16	17.41

Density of Incidence Matrix 20%-30%  
 Range of Cost Coefficients [5,150]  
 Maximum Number of Machines in a Cluster L=5

The CPU time requirements for the proposed CAA are modest. The CAA consumes more computing time than that of CIA mainly due to the search procedure in steps 1 and 3 in CAA. However, CAA allows us to solve large scale and practical industrial CM problems. The computational complexity of CAA is reported as  $O(2MN) + O(N\log N)$ , where the last term refers to N columns of cost which need to be searched and is equivalent to sorting the list of N elements.

### 4.3 Discussion

The proposed CAA can be implemented in two modes:

- (i) Fully automated, i.e. the user provides the data required and CAA generates a final CM solution;
- (ii) Interactive, i.e. the user not only provides the input data but also participates in the formation of cells and parts processes.

The second mode seems to be more appropriate if CAD/CAM systems together with colour graphics are used. It takes advantage of the user's expertise while machine cells and part families are forming. Other examples of interactive rules being developed for the proposed CAA model were discussed by Kusiak and Chow (1988) and Kusiak (1988a, 1989).

#### 4.4 Conclusions

In this chapter, we presented an extension version of the CIA model - known as Cost Analysis Algorithm (CAA) - to solve CM problems that relate to PSCP. Due to the dynamics of our proposed CAA model, this concept has been further pursued in other literature discussed in previous section. Although the proposed CAA is a practical approach in solving PSCP, it has the following deficiencies:

- 1) when selecting the parts to be removed in the STEP 3 of the proposed CAA, the set covering problem is not considered;
- 2) the proposed model remains imperfect when the unit cost for each part is identical;

- 3) it does not consider the machine chaining problem that was discussed in Chapter II.

Of course, it is understood that the first flaw can be overcome by including the set covering formulation into the proposed algorithm. This approach is not recommended for two reasons. The first one is that the set covering problem is an optimization approach and remains too time consuming to obtain a feasible CM solution for PSCP. The other reason is that it is not appropriate for one to interact a proposed algorithm with other existing algorithms; otherwise evaluation of the performance of the former algorithm cannot be studied. It is, however, still questionable if the set covering formulation should be included in any proposed expert system because of the first stated reason.

Although the proposed CAA is still valid when all parts have a unity cost (i.e. same unit cost for all parts), the CAA does not consider the flow rate of inter- and intra-cellular movements of parts which would contribute to the third point that was being raised. We did not intend to present a perfect model to overcome all these flaws as CAA is only an extension version of CIA, mainly used for solving the MSCP. Since we strongly feel that a model to solve the PSCP that would overcome the aforementioned problems should be a stand alone model, we are proposing an alternative solution method in the next chapter.



## CHAPTER V

### MACHINE GROUPING APPROACH - A SOLUTION METHOD FOR THE PSCP

Literature relating to a solution method for PSCP can be generally categorized into three approaches: machine-part grouping, part grouping and machine grouping. Machine-part grouping is a solution technique which studies the rows and columns of a machine-part matrix  $A$  such that a solution for PSCP of machine cells and part families are obtained simultaneously. The CIA and CAA presented in previous chapters are samples of such a grouping approach. Part grouping is based on the manipulation of a matrix  $B (=A^T * A)$  to first identify the components of part families. Its corresponding components of machine cells are then read from the original matrix  $A$ . The entry values in matrix  $B$  may be computed in terms of similarity scores that are discussed in previous chapter. In contrast to the part grouping approach, machine grouping is based on studying a matrix  $C (=A * A^T)$ , whose entries represent pairwise measurement of similarity scores between two machines  $M_i$  and  $M_j$ . The mechanism of the latter approach is to first obtain the solution of machine cells and then retrieve its corresponding components of part families from matrix  $A$ .

In a CM environment, it is general understanding that the total number of parts

involved in a matrix  $A$  is much greater than the total number of machines. Since the value of these total numbers would have a direct impact on the computational efforts of a CM solution, we are more interested to deal with a smaller size of a CM problem representation. The machine grouping approach uses the smallest matrix size  $C$  to solve a CM problem requiring a minimum computational time (Gunasingh and Lashkari, 1989). It is thus the favoured approach, especially when CM belongs to a type of NP complete problem (Lawler et al., 1985). The solution method to be presented here for PSCP will also be based on the machine grouping approach. However, its use results in the so-called machine chaining problem, from the improper grouping of machines generating a higher number of exceptional parts in a CM solution (King and Nakornchai, 1982). Exceptional parts are parts that require the processes of more than one machine cell. Therefore, prior to presenting an algorithm for PSCP, we will first develop a solution method to overcome the machine chaining problem. The machine chaining problem concept will be further explained in next section. Seifodinni (1984) has superficially addressed this problem by replacing the Single Linkage Clustering Algorithm with an Average Cluster algorithm which, he claimed, does not always eliminate the machine chaining problem.

In this chapter, we present an efficient method for solving the machine chaining problem that forms a base for the development of an algorithm for solving PSCP. We first discuss the principle that underlie a machine chaining problem and then proceed to the solution algorithm.

### 5.1 Basic Concept of the Machine Chaining Problem

A machine chaining problem is encountered when two machine cells (or a machine and a machine cell) are joined together merely because they share the highest similarity coefficient. This can result in a higher total number of exceptional parts (also known as intercellular movement of parts) in a CM solution (McAuley, 1972 and Seifoddini, 1984). Consider an example depicted in matrix A19:

$$\begin{array}{c}
 M_1 \\
 M_2 \\
 M_3 \\
 M_4 \\
 M_5
 \end{array}
 \begin{bmatrix}
 P_1 & P_2 & P_3 & P_4 & P_5 & P_6 & P_7 & P_8 & P_9 & P_{10} & P_{11} & P_{12} & P_{13} \\
 1 & 1 & 1 & 1 & & 1 & & & & & & & \\
 1 & 1 & 1 & & 1 & & 1 & & & & & & \\
 & & & 1 & 1 & 1 & 1 & 1 & 1 & 1 & & & \\
 & & & & & & & 1 & 1 & 1 & 1 & 1 & 1 \\
 & & & & & & & & 1 & 1 & 1 & 1 & 1
 \end{bmatrix}
 \quad (A19)$$

Assume that the final result of a CM solution is to group these five machines into two machine cells. Let us assume that matrix A20 is a solution to such a problem which interpret as follows. There are two machine cells  $MC-1 = \{M_1, M_2\}$  and  $MC-2 = \{M_3, M_4, M_5\}$ , two part families  $PF-1 = \{P_1, P_2, P_3\}$  and  $PF-2 = \{P_8, P_9, P_{10}, P_{11}, P_{12}, P_{13}\}$ , and four exceptional parts  $EP = \{P_4, P_5, P_6, P_7\}$ . The exceptional parts are marked as "\*" in matrix A20.

$$\begin{array}{c}
 \begin{array}{c}
 \text{MC-1} \\
 \text{MC-2}
 \end{array}
 \begin{array}{c}
 \left. \begin{array}{l} M_1 \\ M_2 \end{array} \right\} \\
 \left. \begin{array}{l} M_3 \\ M_4 \\ M_5 \end{array} \right\}
 \end{array}
 \left[ \begin{array}{cccccccccccccc}
 & \overbrace{\text{PF-1}} & & & \overbrace{\text{EP}} & & & & \overbrace{\text{PF-2}} & & & & & \\
 & P_1 & P_2 & P_3 & P_4 & P_5 & P_6 & P_7 & P_8 & P_9 & P_{10} & P_{11} & P_{12} & P_{13} \\
 \begin{array}{l} 1 \\ 1 \end{array} & 1 & 1 & 1 & 1 & & 1 & & & & & & & \\
 \begin{array}{l} 1 \\ 1 \end{array} & 1 & 1 & 1 & & 1 & & 1 & & & & & & \\
 & & & & * & * & * & * & 1 & 1 & 1 & & & \\
 & & & & & & & & 1 & 1 & 1 & 1 & 1 & 1 \\
 & & & & & & & & & 1 & 1 & 1 & 1 & 1
 \end{array} \right] \quad (\text{A20})
 \end{array}$$

From matrix A20, one can see that the total number of exceptional parts in this matrix can be reduced to 3 if machine  $M_3$  is grouped with machine cell MC-1 instead of machine cell MC-2. The latter solution is shown in matrix A21 giving: (i) two machine cells MC-1 =  $\{M_1, M_2, M_3\}$  and MC-2 =  $\{M_4, M_5\}$ , (ii) two part families PF-1 =  $\{P_1, P_2, P_3, P_4, P_5, P_6, P_7\}$  and PF-2 =  $\{P_{11}, P_{12}, P_{13}\}$ , and (iii) three exceptional parts EP =  $\{P_8, P_9, P_{10}\}$ . The matrix A21 solution is regarded as being better than matrix A20 because the former has a lesser number of intercellular movement of parts. The "inappropriateness" of the machine grouping shown in matrix A20 whereby a higher intercellular movement of parts is generated, is known as the machine chaining problem.

$$\begin{array}{c}
 \begin{array}{c}
 \text{MC-1} \\
 \text{MC-2}
 \end{array}
 \begin{array}{c}
 \left. \begin{array}{l} M_1 \\ M_2 \\ M_3 \end{array} \right\} \\
 \left. \begin{array}{l} M_4 \\ M_5 \end{array} \right\}
 \end{array}
 \left[ \begin{array}{cccccccccccccc}
 & \overbrace{\text{PF-1}} & & & \overbrace{\text{EP}} & & & & \overbrace{\text{PF-2}} & & & & & \\
 & P_1 & P_2 & P_3 & P_4 & P_5 & P_6 & P_7 & P_8 & P_9 & P_{10} & P_{11} & P_{12} & P_{13} \\
 \begin{array}{l} 1 \\ 1 \end{array} & 1 & 1 & 1 & 1 & & 1 & & & & & & & \\
 \begin{array}{l} 1 \\ 1 \end{array} & 1 & 1 & 1 & & 1 & & 1 & & & & & & \\
 & & & & 1 & 1 & 1 & 1 & * & * & * & & & \\
 & & & & & & & & 1 & 1 & 1 & 1 & 1 & 1 \\
 & & & & & & & & & 1 & 1 & 1 & 1 & 1
 \end{array} \right] \quad (\text{A21})
 \end{array}$$

The basic flaw in the grouping process presented in matrix A20 lies in the fact that existing CM algorithms fail to identify similarity coefficients between machine cells

because algorithms consider machines in a machine cell as individual machines instead of as a group. We propose a solution to this problem.

## 5.2 Solution Method for Machine Chaining Problems

Our proposed method to solve machine chaining problems involves two stages. First, we consider individual machine cells as a group of machines by converting each cell to a new machine unit. Second, we identify an efficient machine grouping algorithm that includes the first concept. Details follow next.

### 5.2.1 Machine Cell Conversion (Chow and Hawaleshka, 1992a)

The basic idea of machine cell conversion is to ensure that machines in each cell are considered as a unit and not as individual machine. Our proposed method first represents a machine cell by a symbol, and computes its corresponding entry values as the member of its part family. In doing so, let us assume that a machine cell is formed by grouping machine  $M_i$  and  $M_j$  together, then the new machine unit  $M_{i,j}$  is defined as:

$$M_{i,j} = M_i \cup M_j = U(M_i, M_j) \quad (E33)$$

Consider the following example in which a machine consists of five parts where

$M_i=(1,0,0,1,0)$  and  $M_j=(1,0,0,1,1)$ , then

$$\begin{aligned} M_{i,j} &= (1,0,0,1,0) \cup (1,0,0,1,1) \\ &= (1,0,0,1,1) \end{aligned}$$

In the machine conversion process, we assume that two machines are to be grouped together only if they share the highest similarity between all pairwise of machines. The following definitions describe the new machine unit concept.

Definition 1

A new machine unit representing a machine cell which consists of machines  $M_i$  and  $M_j$  is defined as follows:

$$M_{i,j} = U(M_i, M_j)$$

Definition 2

In the machine grouping approach, two machines  $M_i$  and  $M_j$  are grouped together if they share the highest similarity of parts.

Definition 3

$M_i$  is a subset of  $M_j$ , i.e.  $M_i \subseteq M_j$ , implying that if  $M_{i[k]}=1$  then  $M_{j[k]}=1$ , but not vice versa; for  $k=1, \dots, P$ .

Following from Definition 3, Lemma 1 can be developed which would leads to the conclusive statements of Lemmas 2 and 3.

Lemma 1

$$M_i \subseteq M_j \text{ then } \Phi(M_i) \leq \Phi(M_j) \quad (\text{E34})$$

Proof:

If  $\Phi(M_i) > \Phi(M_j)$  implies that the total number of numerals of 1s in  $M_i$  is more than those in  $M_j$ , then  $M_i \not\subseteq M_j$  (see Definition 3). On the other hand, if  $M_i \subseteq M_j$  then the total number of numerals of 1s in  $M_j$  must not be less than those in  $M_i$  (Definition 3), therefore  $\Phi(M_i) \leq \Phi(M_j)$ .

Lemma 2

$$\Phi(M_{i,j}) \geq \Phi(M_i) \text{ and } \Phi(M_{i,j}) \geq \Phi(M_j) \quad (\text{E35})$$

Proof:

The proof of Lemma 2 is rather straightforward.  $M_{i,j} = U(M_i, M_j)$  (from Definition 1) implies that  $M_i \subseteq M_{(i,j)}$  and  $M_j \subseteq M_{(i,j)}$ . And from Lemma 1, we have  $\Phi(M_{(i,j)}) \geq \Phi(M_i)$  and  $\Phi(M_{(i,j)}) \geq \Phi(M_j)$ .

Lemma 3

The new machine unit concept detects a higher number of common parts between

two machine cells MC-k and MC-l.

Proof:

For simplicity, let us consider that

$$\text{MC-k} = (M_1, M_2, \dots, M_{q-1}, M_q)$$

$$\text{and MC-l} = (M_{q+1})$$

Then, the new machine unit for MC-k is

$$\text{MC-k} = M_{1,2,\dots,q} = U(M_1, M_2, \dots, M_{q-1}, M_q),$$

and the total number of common parts between machine cells MC-k and MC-l is

$$\Phi(\text{MC-k} \cap \text{MC-l}) = \Phi(M_{1,2,\dots,q} \cap M_{q+1}).$$

Let us consider another representation of MC-k that does not follow the new machine unit concept as  $\text{MC-r} = (M_1, M_2, \dots, M_{q-1}) \subseteq \text{MC-k}$ , and  $\Phi(\text{MC-r} \cap \text{MC-l}) = \Phi(U(M_1, M_2, \dots, M_{q-1}) \cap M_{q+1})$ .

We know that  $\Phi(U(M_1, M_2, \dots, M_{q-1})) \not\geq \Phi(M_{1,\dots,q-1,q})$  because  $\text{MC-r} \subseteq \text{MC-k}$  (by Lemma 2), therefore  $\Phi(\text{MC-k} \cap \text{MC-l}) \geq \Phi(\text{MC-r} \cap \text{MC-l})$ , which implies that the new machine unit concept detects a higher number of common parts between two machine cells.

Let us assume that a set of machines are grouped into a series of machine cells, and further we wish to group, say, an  $(n+2)$  total number of machine cells into an  $(n+1)$  total number of machine cells, then the following theory is valid.



Theorem 1 (Chow and Hawaleshka, 1991a)

Grouping a pairwise machine cells from  $(n+2)$  total number of machine cells into  $(n+1)$  total number of machine cells that has the highest number of similarity parts and according to the new machine unit concept would eliminate the machine chaining problem.

Proof:

Without loss of generality, consider the following three machine cells:

$$MC-i = M_{1,\dots,k-1} = U(M_1, \dots, M_{k-2}, M_{k-1})$$

$$MC-k = (M_k)$$

$$MC-j = M_{k+1,\dots,k+p} = U(M_{k+1}, \dots, M_{k+p})$$

and a machine cell that does not follow the new machine unit concept

$$MC-q = (M_1, \dots, M_{k-2}) \subset MC-i$$

Let us further assume that

$$\Phi(MC-i \cap MC-k) = x \geq \Phi(MC-j \cap MC-k) = y,$$

then grouping MC-i with MC-k would create a minimum number of intercellular movement of parts,  $y$ .

Now consider a group of machine cell MC-q:

$$\Phi(MC-q \cap MC-k) = z \leq x \text{ (see Lemma 2).}$$

Case 1: value of  $z = x$

$$\text{Then } \Phi(MC-i \cap MC-k) = z \geq \Phi(MC-j \cap MC-k) = y,$$

grouping machine cell MC-k with MC-i, which has y number of exceptional parts.

Case 2: value of  $z < x$

Then  $\Phi(\text{MC-i} \cap \text{MC-k}) = z < \Phi(\text{MC-j} \cap \text{MC-k}) = y$ , and machine cell MC-k is grouped with MC-j which results in an x total number of intercellular movement of parts (i.e. total number of parts in machine cell MC-i). But  $x \geq y$  (by assumption), therefore this grouping generates an improper machine assignment problem.

In summary, the new machine unit concept operated by means of the following steps:

STEP 1. Convert machine cell  $\text{MC-k} = \{M_1, \dots, M_q\}$  to a new machine unit  $M_{(1, \dots, q)}$ , by computing its corresponding entry values of row  $i=(1, \dots, q)$  and column  $j$  as follows:

$$M_{(1, \dots, q), j} = \begin{cases} 1 & \text{if part } P_i \text{ is a member of} \\ & \text{part family PF-k, } j=1, N. \\ 0 & \text{otherwise.} \end{cases} \quad (\text{E36})$$

where N is the total number of parts in a machine-part matrix A.

STEP 2. Replace machines  $M_1, \dots, M_q$  by a new machine unit  $M_{(1, \dots, q)}$  in machine-part matrix A.

So far, we have demonstrated that the grouping of machines according to the new machine unit concept and according to the highest number of common parts would solve the machine chaining problem. In the next section, we will develop an algorithm for PSCP that incorporates the above concept.

### 5.3 The New Machine Grouping Algorithm (MGA)

To develop a machine grouping algorithm (MGA) that incorporates our new machine unit concept, we first join together a pair of machines that has the highest similarity score in the matrix  $C(=A \cdot A^T)$ . This procedure is repeated until the desired constraints, such as a specific number of machine cells, are met. There are two basic problems involved in selecting the pair of machines to be grouped: a) determining an efficient way for computing and selecting similarity scores, and b) determining an efficient criterion to select a pair of machines if there is more than one highest score. Most CM papers (eg: Seifoddini (1984), Wei and Kern (1989)) do not consider the principles of these two steps in their algorithms but attempt to solve these problems in a single step, thereby making themselves inefficient.

We propose to solve the first problem by using two score measurements:  $S_{ij}$  and  $D_{ij}$ .

$S_{ij}$  scores measure the total number of parts (i.e. total number of value "1" in a row of matrix A) that needs to be processed by both machines  $M_i$  and  $M_j$ , while  $D_{ij}$  scores identify the total number of parts that do not need to be processed by both machines  $M_i$  and  $M_j$ . To solve the machine grouping and the second problem, a pair of machines  $M_i$  and  $M_j$  that has the highest score of  $S_{ij}$  is grouped together and the highest value of  $D_{ij}$  is used to prioritize the tie scores of  $S_{ij}$ . The justification for such a grouping technique is that the values of  $S_{ij}$  and  $D_{ij}$  indicate the highest similarity between two machines. If these values are small, it indicates that both machines are highly dissimilar and it is undesirable that they be grouped together first. It should be clear also that  $S_{ij}$  values are more important than  $D_{ij}$  values as the former represent the actual total number of parts that are to be processed by both machines  $M_i$  and  $M_j$ .

The direct approach in implementing the above proposed method is to generate a list of pairwise machines by first positioning  $S_{ij}$  values in descending order, using  $D_{ij}$  value to prioritize the tie scores, and then grouping machines according to their sorting. This grouping approach involves greater computational time because it requires a separate listing of  $S_{ij}$  and  $D_{ij}$ . An efficient way to circumvent this is via a  $C_{ij}$  value computed as shown in equation E37.

$$C_{ij} = K * S_{ij} + D_{ij} \quad (E37)$$

The constant  $K$  in  $C_{ij}$  is a very large value used to emphasize the importance of  $S_{ij}$  over  $D_{ij}$ . Clearly the grouping of machines according to the sorted  $C_{ij}$  list is the same as in the previous sorting procedures that involve values of  $S_{ij}$  and  $D_{ij}$ . The values of  $C_{ij}$  can

be directly computed from a machine-part matrix A as follows:

$$C_{ij} = \sum_{k=1, N} \Gamma(M_{i[k]}, M_{j[k]}) \quad (\text{E38})$$

where

$$\Gamma(M_{i[k]}, M_{j[k]}) = \begin{cases} K & , \text{ if } M_{i[k]} = M_{j[k]} = 1 \\ 1 & , \text{ if } M_{i[k]} = M_{j[k]} = 0 \\ 0 & , \text{ if } M_{i[k]} \neq M_{j[k]} \end{cases}$$

Wei and Kern (1989) used the exact measurement of  $C_{ij}$  as defined above except that they represented  $K$  by  $(N-1)$ . To equate our approach to theirs, we could relate our  $K$  value to their  $(N-1)$  value as  $N$ . The value of  $N$  is considered as a large value in a machine grouping problem because the value of  $D_{ij}$  cannot have a value of  $N$ ; otherwise none of the parts would need to be processed by any machines and thus either machine  $M_i$  or  $M_j$  would appear on a machine-part matrix A. Therefore, the commonality scores presented by Wei and Kern can be further generalized as follows.

### Theorem 2

The commonality score detect the highest similar score between two machines  $M_i$  and  $M_j$ , and is defined as follows (Wei and Kern, 1989):

$$C_{i,j} = (N) * \Phi(M_i \cap M_j) + \Phi((M_i \cup M_j)) \quad (\text{E39})$$

The proof of Theorem 2 is omitted because it has been discussed by Wei and Kern (1989).

### 5.3.1 The Proposed Model

The proposed MGA model will first compute the similarity scores  $C_{ij}$  in a form of a matrix  $C(=A \cdot A^T)$ . The first machine cell will be formed by grouping a pair of machines that has the highest similarity value of  $C_{ij}$ . The next step converts a machine cell in a form of new machine unit as described in the above section. This procedure is then repeated until the desired constraints, such as the total number of machine cells, are met. In the grouping process, we incorporate the Linear Cell Clustering (LCC) algorithm of Wei and Kern since ungrouped machines are given first priority for grouping with other machines (or machine cells). The priority concept rules out the possibility of all machines being grouping into one cell when implementing this proposed model. Our MGA model is presented in Algorithm 3.

Algorithm 3 (Chow and Hawaleshka, 1991a).

STEP 1. Compute similarity scores  $C_{ij}$  for machines  $M_i$  and  $M_j$  in a machine-part matrix A as:

$$C_{ij} = \sum_{k=1, N} \Gamma(M_{i[k]}, M_{j[k]})$$

where

$$\Gamma(M_{i[k]}, M_{j[k]}) = \begin{cases} N & , \text{ if } M_{i[k]} = M_{j[k]} = 1 \\ 1 & , \text{ if } M_{i[k]} = M_{j[k]} = 0 \\ 0 & , \text{ if } M_{i[k]} \neq M_{j[k]} \end{cases}$$

N is the total number of parts in matrix A.

STEP 2. Select the highest similarity score of  $C_{ij}$  with at least one machine  $M_i$  or  $M_j$

that has not yet been considered in the grouping process, and form a machine cell. If all machines are in a machine cell, go to step 3; otherwise go to step 4.

STEP 3. Join machine cells with the highest value of  $C_{ij}$  into one cell.

STEP 4. Designate a newly-grouped machine cell  $M_{(i,j)}$  and compute its entry value:

$$M_{(i,j),k} = \begin{cases} 1 & \text{if at least one of} \\ & M_{i[k]} \text{ and } M_{j[k]} = 1, \text{ for } k=1, N. \\ 0 & \text{otherwise} \end{cases}$$

STEP 5. Formulate a new machine-part matrix A by replacing machines  $M_i$  and  $M_j$  with  $M_{(i,j)}$ . When all machines are grouped into a cell (or meet specified constraints) then STOP; otherwise go to step 1.

We will demonstrate the layout of Algorithm 3 - MGA -by using an example of a matrix A as depicted in matrix A19.

STEP 1. The following  $C_{ij}$  values are computed as:

$$C_{ij} = \begin{matrix} & M_1 & M_2 & M_3 & M_4 & M_5 \\ \begin{matrix} M_1 \\ M_2 \\ M_3 \\ M_4 \\ M_5 \end{matrix} & \begin{bmatrix} - & 45 & 29 & 2 & 3 \\ & - & 29 & 2 & 3 \\ & & - & 42 & 29 \\ & & & - & 68 \\ & & & & - \end{bmatrix} \end{matrix}$$

STEP 2. Since  $C_{45}$  is the highest value, machines  $M_4$  and  $M_5$  are grouped together to

form a machine cell MC-1; proceed to step 4.

STEP 4. The entry value for the new machine  $M_{(4,5)}$  unit is:

$$M_{(4,5)} = (0,0,0,0,0,0,0,1,1,1,1,1,1)$$

STEP 5. The new matrix A is:

$$M_{(4,5)} \begin{bmatrix} P_1 & P_2 & P_3 & P_4 & P_5 & P_6 & P_7 & P_8 & P_9 & P_{10} & P_{11} & P_{12} & P_{13} \\ M_1 & 1 & 1 & 1 & 1 & & 1 & & & & & & \\ M_2 & 1 & 1 & 1 & & 1 & & 1 & & & & & \\ M_3 & & & & 1 & 1 & 1 & 1 & 1 & 1 & & & \\ M_{(4,5)} & & & & & & & & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \quad (A22)$$

Repeating step 1, machines  $M_1$  and  $M_2$  are grouped since  $C_{12}=45$  is the highest score. The result is shown in matrix A23.

$$\begin{matrix} M_{(1,2)} \\ M_3 \\ M_{(4,5)} \end{matrix} \begin{bmatrix} P_1 & P_2 & P_3 & P_4 & P_5 & P_6 & P_7 & P_8 & P_9 & P_{10} & P_{11} & P_{12} & P_{13} \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & & & & & & \\ & & & 1 & 1 & 1 & 1 & 1 & 1 & 1 & & & \\ & & & & & & & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \quad (A23)$$

Machine  $M_3$  is grouped with machine cell  $M_{(1,2)}$  as  $C_{ij} = C_{(1,2),3} = 55$  which is the highest score in matrix A23.

If the final solution is to have two machine cells, then STOP here; otherwise activate step 4 of the procedure.

STEP 4. Machines  $M_{(1,2,3)}$  and  $M_{(4,5)}$  are the last to be merged into a cell.



It is interesting to know that if the final result is to have two machine cells then the result is the same as those presented in matrix A21 as: MC-1 =  $M_{(4,5)} = (M_4, M_5)$  and MC-2 =  $M_{(1,2,3)} = (M_1, M_2, M_3)$ , and exceptional parts  $EP = \{P_8, P_9, P_{10}\}$ .

#### 5.4 Discussions

One conclusive remark that can be derived from studying the results of the machine grouping algorithms in this chapter is that the total number of exceptional parts or intercellular movement of parts in say  $(n+1)$  total number of machine cells is always less than or equal to  $(n)$  total number of machine cells in any grouping algorithm. This observation is rather important for practitioners who wish to consider the number of exceptional parts as a partial decision making process. Lemma 4 states and proves such a result.

Lemma 4 (Chow and Hawaleshka, 1991a)

In a machine grouping algorithm, the total number of exceptional parts generated by  $(n+1)$  total number of machine cells is always greater or equal to those by  $(n)$  total number of machine cells.

Proof:

Let us define the  $(n+1)$  total number of machine cells as follows:

$$(n+1) \text{ cells} = (MC-1, MC-2, \dots, MC-(n-1), MC-n, MC-(n+1)).$$

It is clear that  $n$  number of machine cells are obtained by grouping any two of  $(n+1)$  number of machine cells together. Let us further assume that the  $n$  total number of machine cells are formed by grouping  $MC-n$  and  $MC-(n+1)$  together, i.e.:

$$n \text{ cells} = (MC-1, MC-2, \dots, MC-(n-1), (MC-n \cup MC-(n+1))).$$

By Definition 1, we know that  $(MC-n \cup MC-(n+1))$  is a new machine unit which implies that every part that is involved in  $MC-n$  and  $MC-(n+1)$  are in  $(MC-n \cup MC-(n+1))$  - because  $MC-n$  and  $MC-(n+1) \subseteq (MC-n \cup MC-(n+1))$ . However, the total number of exceptional parts between  $MC-1, MC-2, \dots, MC-(n-1)$  is independent from  $(MC-n, MC-(n+1))$  and  $(MC-n \cup MC-(n+1))$ .

The exceptional parts for machine cells  $MC-n$  and  $MC-(n+1)$  are:

$$\Phi(MC-n \cap MC-(n+1)) = r \geq 0$$

Value  $r = 0$  if the part numbers in  $MC-n$  is an exclude set of  $MC-(n+1)$ ; otherwise  $r$

$> 0$ .

However,  $\Phi(\cap (MC-n \cup MC-(n+1))) = s = 0$  because it is a new machine unit.

Since  $\Phi(MC-n \cap MC-(n+1)) = r \geq s = \Phi(\cap (MC-n \cup MC-(n+1)))$ , therefore the total number of exceptional parts generated by  $n$  total number of machine cells is not more than  $(n+1)$  total number of machine cells.

## 5.5 Conclusion

In this chapter, we presented an efficient method to solve machine chaining problems. The proposed new machine unit concept is proven to guarantee an optimal solution to machine chaining problems for grouping  $(n+2)$  total number of machine cells into  $(n+1)$  total number of machine cells. The proposed model is then incorporated with similarity scores that were proposed by Wei and Kern to develop an algorithm. The computational experience for the proposed algorithm will be examined and presented in Chapter VI.

## CHAPTER VI

### COMPUTATIONAL EXPERIENCE FOR THE PROPOSED MGA

We selected two algorithms - the Average Clustering (AC) algorithm and the Linear Cell Clustering (LCC) algorithm - from literature to compare with our proposed MGA. These two algorithms were selected mainly because they are not only reported as efficient algorithms in literature, but also deal with the machine grouping approach.

#### 6.1 Computational Experience (Chow and Hawaleshka, 1992b)

The first data set to be selected for comparison is derived from the paper by Kumar and Vannelli (1987). This particular data is singled out for test mainly because Wei and Kern were also using it to test the performance of the LCC algorithm. Since our proposed machine grouping algorithm is to some extent similar to that of LCC algorithm, it is interesting to compare our results to theirs. The data is presented in matrix A24 which shows in Figure 4.

Table 5 shows the results of our proposed method, with those of the LCC and AC algorithms. In this table, we compare the results of each algorithm by identifying solutions that have been derived from five different machine cells. It can be seen that our proposed algorithm generates fewer exceptional parts than the solutions by the other

two algorithms. The corresponding machine cells, part families and exceptional part numbers are also listed in the table. The empirical comparison of exceptional parts for the data provided in Table 5 is better illustrated in Figure 4.1. There is however no guarantee that our proposed model will always outperform the others in all cases. The justification for this observation is that our proposed model provides an optimal grouping of any stage from  $(n+i)$  total number of machine cells into  $(n+i-1)$  total number of machine cells, but the optimality concept is only confined to a local rather than global solution. Justification of this statement will be discussed later. For further comparison we tested these three models for a number of data sets. The two data sets which best describe the general behaviour of the findings are from the data set obtained from Gupta and Seifoddini (1990) and King (1980). These data sets are provided in Figures 5 and 6 (i.e. matrices A25 and A26), and the comparative results are shown in Figures 7 and 8 respectively. The concluding findings will be discussed in the next section.

Machine Number	Part number																															
	111111111111								222222222222								333333333333								44							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30		
1						1																			111		1	1				
2						11		1																	11		1	1				
3						1							1										11			11		1	1			
4					1			1																		11		1	1			
5					1																						1	1				
6					1																							1	1			
7																												1	1			
8	1					11		1																			1					
9	1					1																										
10	1					1																								1		
11																												1		1		
12																														11		
13																														1		
14						11																								1		
15																														1		
16																														1		
17																														1		
18																														1		
19	1	1																														
20	1	1																														
21																														1		
22																														11		
23	1																													1		
24																														1		
25						1																										
26																																
27																																
28																																
29	1	1																														
30	1	1																														

(A24)

Figure 4: Machine-part matrix in Kumar and Vannelli's problem (1987).

Table 5: Comparison of solutions for variable size machine cells

Total number of machine cells	Total number of exceptional parts and its part numbers	Machine cells	Part Families
PROPOSED ALGORITHM			
6	10 EP={P <sub>1</sub> , P <sub>7</sub> , P <sub>9</sub> , P <sub>14</sub> , P <sub>18</sub> , P <sub>19</sub> , P <sub>24</sub> , P <sub>25</sub> , P <sub>26</sub> , P <sub>28</sub> }	MC-1={M <sub>1</sub> , M <sub>2</sub> , M <sub>3</sub> , M <sub>10</sub> , M <sub>11</sub> , M <sub>12</sub> , M <sub>21</sub> , M <sub>22</sub> , M <sub>23</sub> } MC-2={M <sub>4</sub> , M <sub>5</sub> , M <sub>6</sub> , M <sub>27</sub> , M <sub>28</sub> } MC-3={M <sub>13</sub> , M <sub>24</sub> } MC-4={M <sub>9</sub> , M <sub>19</sub> , M <sub>20</sub> , M <sub>29</sub> , M <sub>30</sub> } MC-5={M <sub>7</sub> , M <sub>14</sub> , M <sub>15</sub> , M <sub>17</sub> , M <sub>18</sub> , M <sub>25</sub> , M <sub>26</sub> } MC-6={M <sub>8</sub> , M <sub>16</sub> }	PF-1={P <sub>2</sub> , P <sub>10</sub> , P <sub>11</sub> , P <sub>12</sub> , P <sub>20</sub> , P <sub>23</sub> , P <sub>31</sub> , P <sub>32</sub> , P <sub>33</sub> , P <sub>39</sub> , P <sub>40</sub> , P <sub>41</sub> } PF-2={P <sub>8</sub> , P <sub>15</sub> , P <sub>29</sub> , P <sub>35</sub> } PF-3={P <sub>38</sub> } PF-4={P <sub>3</sub> , P <sub>13</sub> , P <sub>21</sub> , P <sub>22</sub> , P <sub>30</sub> } PF-5={P <sub>4</sub> , P <sub>5</sub> , P <sub>16</sub> , P <sub>17</sub> , P <sub>27</sub> , P <sub>34</sub> , P <sub>36</sub> , P <sub>37</sub> } PF-6={P <sub>6</sub> }
5	8 EP={P <sub>7</sub> , P <sub>9</sub> , P <sub>14</sub> , P <sub>18</sub> , P <sub>19</sub> , P <sub>24</sub> , P <sub>25</sub> , P <sub>26</sub> , P <sub>28</sub> }	MC-1={M <sub>1</sub> , M <sub>2</sub> , M <sub>3</sub> , M <sub>10</sub> , M <sub>11</sub> , M <sub>12</sub> , M <sub>21</sub> , M <sub>22</sub> , M <sub>23</sub> } MC-2={M <sub>4</sub> , M <sub>5</sub> , M <sub>6</sub> , M <sub>9</sub> , M <sub>19</sub> , M <sub>20</sub> , M <sub>27</sub> , M <sub>28</sub> , M <sub>29</sub> , M <sub>30</sub> } MC-3={M <sub>13</sub> , M <sub>24</sub> } MC-4={M <sub>8</sub> , M <sub>16</sub> } MC-5={M <sub>7</sub> , M <sub>14</sub> , M <sub>15</sub> , M <sub>17</sub> , M <sub>18</sub> , M <sub>25</sub> , M <sub>26</sub> }	PF-1={P <sub>2</sub> , P <sub>10</sub> , P <sub>11</sub> , P <sub>12</sub> , P <sub>20</sub> , P <sub>23</sub> , P <sub>31</sub> , P <sub>32</sub> , P <sub>33</sub> , P <sub>39</sub> , P <sub>40</sub> , P <sub>41</sub> } PF-2={P <sub>1</sub> , P <sub>3</sub> , P <sub>8</sub> , P <sub>9</sub> , P <sub>13</sub> , P <sub>15</sub> , P <sub>21</sub> , P <sub>22</sub> , P <sub>29</sub> , P <sub>30</sub> , P <sub>35</sub> } PF-3={P <sub>22</sub> } PF-4={P <sub>38</sub> } PF-5={P <sub>4</sub> , P <sub>5</sub> , P <sub>16</sub> , P <sub>17</sub> , P <sub>27</sub> , P <sub>34</sub> , P <sub>36</sub> , P <sub>37</sub> }
4	6 EP={P <sub>18</sub> , P <sub>19</sub> , P <sub>24</sub> , P <sub>25</sub> , P <sub>26</sub> , P <sub>28</sub> }	MC-1={M <sub>1</sub> , M <sub>2</sub> , M <sub>3</sub> , M <sub>10</sub> , M <sub>11</sub> , M <sub>12</sub> , M <sub>21</sub> , M <sub>22</sub> , M <sub>23</sub> } MC-2={M <sub>4</sub> , M <sub>5</sub> , M <sub>6</sub> , M <sub>7</sub> , M <sub>8</sub> , M <sub>9</sub> , M <sub>14</sub> , M <sub>15</sub> , M <sub>17</sub> , M <sub>18</sub> , M <sub>19</sub> , M <sub>20</sub> , M <sub>25</sub> , M <sub>26</sub> , M <sub>27</sub> , M <sub>28</sub> , M <sub>29</sub> , M <sub>30</sub> } MC-3={M <sub>13</sub> , M <sub>24</sub> } MC-4={M <sub>6</sub> , M <sub>16</sub> }	PF-1={P <sub>2</sub> , P <sub>10</sub> , P <sub>11</sub> , P <sub>12</sub> , P <sub>20</sub> , P <sub>23</sub> , P <sub>31</sub> , P <sub>32</sub> , P <sub>33</sub> , P <sub>39</sub> , P <sub>40</sub> , P <sub>41</sub> } PF-2={P <sub>1</sub> , P <sub>3</sub> , P <sub>4</sub> , P <sub>5</sub> , P <sub>8</sub> , P <sub>9</sub> , P <sub>13</sub> , P <sub>14</sub> , P <sub>15</sub> , P <sub>16</sub> , P <sub>17</sub> , P <sub>21</sub> , P <sub>22</sub> , P <sub>27</sub> , P <sub>29</sub> , P <sub>30</sub> , P <sub>34</sub> , P <sub>35</sub> , P <sub>36</sub> , P <sub>37</sub> } PF-3={P <sub>29</sub> } PF-2={P <sub>38</sub> }
3	4 EP={P <sub>18</sub> , P <sub>19</sub> , P <sub>24</sub> , P <sub>25</sub> }	MC-1={M <sub>1</sub> , M <sub>2</sub> , M <sub>3</sub> , M <sub>10</sub> , M <sub>11</sub> , M <sub>12</sub> , M <sub>21</sub> , M <sub>22</sub> , M <sub>23</sub> } MC-2={M <sub>4</sub> , M <sub>5</sub> , M <sub>6</sub> , M <sub>7</sub> , M <sub>8</sub> , M <sub>9</sub> , M <sub>14</sub> , M <sub>15</sub> , M <sub>17</sub> , M <sub>18</sub> , M <sub>16</sub> , M <sub>18</sub> , M <sub>19</sub> , M <sub>20</sub> , M <sub>25</sub> , M <sub>26</sub> , M <sub>27</sub> } MC-3={M <sub>13</sub> , M <sub>24</sub> } MC-4={M <sub>28</sub> , M <sub>29</sub> , M <sub>30</sub> }	PF-1={P <sub>2</sub> , P <sub>10</sub> , P <sub>11</sub> , P <sub>12</sub> , P <sub>20</sub> , P <sub>23</sub> , P <sub>31</sub> , P <sub>32</sub> , P <sub>33</sub> , P <sub>39</sub> , P <sub>40</sub> , P <sub>41</sub> } PF-2={P <sub>1</sub> , P <sub>3</sub> , P <sub>4</sub> , P <sub>5</sub> , P <sub>6</sub> , P <sub>7</sub> , P <sub>8</sub> , P <sub>9</sub> , P <sub>13</sub> , P <sub>14</sub> , P <sub>15</sub> , P <sub>16</sub> , P <sub>17</sub> , P <sub>21</sub> , P <sub>22</sub> , P <sub>26</sub> , P <sub>27</sub> , P <sub>28</sub> , P <sub>29</sub> , P <sub>30</sub> , P <sub>34</sub> , P <sub>35</sub> , P <sub>36</sub> , P <sub>37</sub> } PF-3={P <sub>38</sub> }
2	2 EP={P <sub>19</sub> , P <sub>25</sub> }	MC-1={M <sub>1</sub> , M <sub>2</sub> , M <sub>3</sub> , M <sub>4</sub> , M <sub>5</sub> , M <sub>6</sub> , M <sub>7</sub> , M <sub>8</sub> , M <sub>9</sub> , M <sub>10</sub> , M <sub>11</sub> , M <sub>12</sub> , M <sub>14</sub> , M <sub>15</sub> , M <sub>16</sub> , M <sub>17</sub> , M <sub>18</sub> , M <sub>19</sub> , M <sub>20</sub> , M <sub>21</sub> , M <sub>22</sub> , M <sub>23</sub> , M <sub>25</sub> , M <sub>26</sub> , M <sub>27</sub> , M <sub>28</sub> , M <sub>29</sub> , M <sub>30</sub> } MC-2={M <sub>13</sub> , M <sub>24</sub> }	PF-1={P <sub>1</sub> to P <sub>18</sub> , P <sub>20</sub> to P <sub>26</sub> , P <sub>26</sub> to P <sub>37</sub> , P <sub>39</sub> , P <sub>40</sub> , P <sub>41</sub> } PF-2={P <sub>38</sub> }

Table 5: Comparison of solutions for variable size machine cells (Cont'd)

LINEAR CELL CLUSTERING ALGORITHM	
6	<p>11</p> <p>EP={P<sub>5</sub>, P<sub>7</sub>, P<sub>14</sub>, P<sub>15</sub>, P<sub>18</sub>, P<sub>19</sub>, P<sub>24</sub>, P<sub>25</sub>, P<sub>26</sub>, P<sub>35</sub>, P<sub>37</sub>}</p> <p>MC-1=CM<sub>8</sub>, M<sub>9</sub>, M<sub>19</sub>, M<sub>20</sub>, M<sub>27</sub>, M<sub>28</sub>, M<sub>29</sub>, M<sub>30</sub>}                      MC-2=CM<sub>14</sub>, M<sub>25</sub>}                      MC-3=CM<sub>13</sub>, M<sub>24</sub>}                      MC-4=CM<sub>5</sub>, M<sub>7</sub>, M<sub>15</sub>, M<sub>17</sub>, M<sub>18</sub>, M<sub>26</sub>}                      MC-5=CM<sub>4</sub>, M<sub>6</sub>, M<sub>16</sub>}                      MC-6=CM<sub>1</sub>, M<sub>2</sub>, M<sub>3</sub>, M<sub>10</sub>, M<sub>11</sub>, M<sub>12</sub>, M<sub>21</sub>, M<sub>22</sub>, M<sub>23</sub>}</p> <p>PF-1={P<sub>1</sub>, P<sub>3</sub>, P<sub>8</sub>, P<sub>9</sub>, P<sub>13</sub>, P<sub>21</sub>, P<sub>22</sub>, P<sub>29</sub>, P<sub>30</sub>}                      PF-2={P<sub>4</sub>}                      PF-3={P<sub>38</sub>}                      PF-4={P<sub>16</sub>, P<sub>17</sub>, P<sub>27</sub>, P<sub>34</sub>, P<sub>36</sub>}                      PF-5={P<sub>6</sub>, P<sub>28</sub>}                      PF-6={P<sub>2</sub>, P<sub>10</sub>, P<sub>11</sub>, P<sub>12</sub>, P<sub>20</sub>, P<sub>23</sub>, P<sub>31</sub>, P<sub>32</sub>, P<sub>33</sub>, P<sub>39</sub>, P<sub>40</sub>, P<sub>41</sub>}</p>
5	<p>10</p> <p>EP={P<sub>5</sub>, P<sub>7</sub>, P<sub>14</sub>, P<sub>15</sub>, P<sub>18</sub>, P<sub>19</sub>, P<sub>24</sub>, P<sub>25</sub>, P<sub>35</sub>}</p> <p>MC-1=CM<sub>8</sub>, M<sub>9</sub>, M<sub>19</sub>, M<sub>20</sub>, M<sub>27</sub>, M<sub>28</sub>, M<sub>29</sub>, M<sub>30</sub>}                      MC-2=CM<sub>13</sub>, M<sub>24</sub>}                      MC-3=CM<sub>5</sub>, M<sub>7</sub>, M<sub>15</sub>, M<sub>17</sub>, M<sub>18</sub>, M<sub>26</sub>}                      MC-4=CM<sub>4</sub>, M<sub>6</sub>, M<sub>16</sub>, M<sub>25</sub>}                      MC-5=CM<sub>1</sub>, M<sub>2</sub>, M<sub>3</sub>, M<sub>10</sub>, M<sub>11</sub>, M<sub>12</sub>, M<sub>21</sub>, M<sub>22</sub>, M<sub>23</sub>}</p> <p>PF-1={P<sub>1</sub>, P<sub>3</sub>, P<sub>8</sub>, P<sub>9</sub>, P<sub>13</sub>, P<sub>21</sub>, P<sub>22</sub>, P<sub>29</sub>, P<sub>30</sub>}                      PF-2={P<sub>38</sub>}                      PF-3={P<sub>16</sub>, P<sub>17</sub>, P<sub>27</sub>, P<sub>34</sub>, P<sub>36</sub>}                      PF-4={P<sub>4</sub>, P<sub>6</sub>, P<sub>28</sub>}                      PF-5={P<sub>2</sub>, P<sub>10</sub>, P<sub>11</sub>, P<sub>12</sub>, P<sub>20</sub>, P<sub>23</sub>, P<sub>31</sub>, P<sub>32</sub>, P<sub>33</sub>, P<sub>39</sub>, P<sub>40</sub>, P<sub>41</sub>}</p>
4	<p>7</p> <p>EP={P<sub>14</sub>, P<sub>15</sub>, P<sub>18</sub>, P<sub>19</sub>, P<sub>24</sub>, P<sub>25</sub>, P<sub>35</sub>}</p> <p>MC-1=CM<sub>8</sub>, M<sub>9</sub>, M<sub>19</sub>, M<sub>20</sub>, M<sub>27</sub>, M<sub>28</sub>, M<sub>29</sub>, M<sub>30</sub>}                      MC-2=CM<sub>13</sub>, M<sub>24</sub>}                      MC-3=CM<sub>4</sub>, M<sub>5</sub>, M<sub>6</sub>, M<sub>7</sub>, M<sub>14</sub>, M<sub>15</sub>, M<sub>16</sub>, M<sub>17</sub>, M<sub>18</sub>, M<sub>25</sub>, M<sub>26</sub>}                      MC-4=CM<sub>1</sub>, M<sub>2</sub>, M<sub>3</sub>, M<sub>10</sub>, M<sub>11</sub>, M<sub>12</sub>, M<sub>21</sub>, M<sub>22</sub>, M<sub>23</sub>}</p> <p>PF-1={P<sub>1</sub>, P<sub>3</sub>, P<sub>8</sub>, P<sub>9</sub>, P<sub>13</sub>, P<sub>21</sub>, P<sub>22</sub>, P<sub>29</sub>, P<sub>30</sub>}                      PF-2={P<sub>38</sub>}                      PF-3={P<sub>4</sub>, P<sub>5</sub>, P<sub>6</sub>, P<sub>7</sub>, P<sub>16</sub>, P<sub>17</sub>, P<sub>26</sub>, P<sub>27</sub>, P<sub>28</sub>, P<sub>34</sub>, P<sub>36</sub>, P<sub>37</sub>}                      PF-4={P<sub>2</sub>, P<sub>10</sub>, P<sub>11</sub>, P<sub>12</sub>, P<sub>20</sub>, P<sub>23</sub>, P<sub>31</sub>, P<sub>32</sub>, P<sub>33</sub>, P<sub>39</sub>, P<sub>40</sub>, P<sub>41</sub>}</p>
3	<p>4</p> <p>EP={P<sub>18</sub>, P<sub>19</sub>, P<sub>24</sub>, P<sub>25</sub>}</p> <p>MC-1=CM<sub>13</sub>, M<sub>24</sub>}                      MC-2=CM<sub>4</sub>, M<sub>5</sub>, M<sub>6</sub>, M<sub>7</sub>, M<sub>8</sub>, M<sub>9</sub>, M<sub>14</sub>, M<sub>15</sub>, M<sub>16</sub>, M<sub>17</sub>, M<sub>18</sub>, M<sub>19</sub>, M<sub>20</sub>, M<sub>25</sub>, M<sub>26</sub>, M<sub>27</sub>, M<sub>28</sub>, M<sub>29</sub>, M<sub>30</sub>}                      MC-3=CM<sub>1</sub>, M<sub>2</sub>, M<sub>3</sub>, M<sub>10</sub>, M<sub>11</sub>, M<sub>12</sub>, M<sub>21</sub>, M<sub>22</sub>, M<sub>23</sub>}</p> <p>PF-1={P<sub>38</sub>}                      PF-2={P<sub>1</sub>, P<sub>3</sub> to P<sub>9</sub>, P<sub>13</sub> to P<sub>17</sub>, P<sub>21</sub>, P<sub>22</sub>, P<sub>25</sub> to P<sub>30</sub>, P<sub>34</sub> to P<sub>37</sub>}                      PF-3={P<sub>2</sub>, P<sub>10</sub>, P<sub>11</sub>, P<sub>12</sub>, P<sub>20</sub>, P<sub>23</sub>, P<sub>31</sub>, P<sub>32</sub>, P<sub>33</sub>, P<sub>39</sub>, P<sub>40</sub>, P<sub>41</sub>}</p>
2	<p>3</p> <p>EP={P<sub>19</sub>, P<sub>25</sub>, P<sub>24</sub>}</p> <p>MC-1=CM<sub>4</sub>, M<sub>5</sub>, M<sub>6</sub>, M<sub>7</sub>, M<sub>8</sub>, M<sub>9</sub>, M<sub>13</sub>, M<sub>14</sub>, M<sub>15</sub>, M<sub>16</sub>, M<sub>17</sub>, M<sub>18</sub>, M<sub>19</sub>, M<sub>20</sub>, M<sub>24</sub>, M<sub>25</sub>, M<sub>26</sub>, M<sub>27</sub>, M<sub>28</sub>, M<sub>29</sub>, M<sub>30</sub>}                      MC-2=CM<sub>1</sub>, M<sub>2</sub>, M<sub>3</sub>, M<sub>10</sub>, M<sub>11</sub>, M<sub>12</sub>, M<sub>21</sub>, M<sub>22</sub>, M<sub>23</sub>}</p> <p>PF-1={P<sub>3</sub> to P<sub>9</sub>, P<sub>13</sub> to P<sub>17</sub>, P<sub>21</sub>, P<sub>22</sub>, P<sub>25</sub> to P<sub>30</sub>, P<sub>34</sub> to P<sub>38</sub>}                      PF-2={P<sub>2</sub>, P<sub>10</sub>, P<sub>11</sub>, P<sub>12</sub>, P<sub>20</sub>, P<sub>23</sub>, P<sub>31</sub>, P<sub>32</sub>, P<sub>33</sub>, P<sub>39</sub>, P<sub>40</sub>, P<sub>41</sub>}</p>



Table 5: Comparison of solutions for variable size machine cells (Cont'd)

AVERAGE CLUSTERING ALGORITHM			
6	10 EP={P <sub>5</sub> , P <sub>7</sub> , P <sub>14</sub> , P <sub>17</sub> , P <sub>18</sub> , P <sub>19</sub> , P <sub>24</sub> , P <sub>25</sub> , P <sub>26</sub> , P <sub>28</sub> }	MC-1={M <sub>1</sub> , M <sub>2</sub> , M <sub>3</sub> , M <sub>10</sub> , M <sub>11</sub> , M <sub>12</sub> , M <sub>21</sub> , M <sub>22</sub> , M <sub>23</sub> } MC-2={M <sub>4</sub> , M <sub>16</sub> } MC-3={M <sub>1</sub> , M <sub>15</sub> , M <sub>25</sub> } MC-4={M <sub>5</sub> , M <sub>7</sub> , M <sub>17</sub> , M <sub>18</sub> , M <sub>26</sub> } MC-5={M <sub>13</sub> , M <sub>24</sub> } MC-6={M <sub>4</sub> , M <sub>8</sub> , M <sub>9</sub> , M <sub>19</sub> , M <sub>20</sub> , M <sub>27</sub> , M <sub>28</sub> , M <sub>29</sub> , M <sub>30</sub> }	PF-1={P <sub>2</sub> , P <sub>10</sub> , P <sub>11</sub> , P <sub>12</sub> , P <sub>20</sub> , P <sub>23</sub> , P <sub>21</sub> , P <sub>32</sub> , P <sub>33</sub> , P <sub>39</sub> , P <sub>40</sub> , P <sub>41</sub> } PF-2={P <sub>6</sub> , P <sub>37</sub> } PF-3={P <sub>4</sub> , P <sub>16</sub> , P <sub>27</sub> , P <sub>34</sub> , P <sub>36</sub> } PF-4={P <sub>38</sub> } PF-5={P <sub>1</sub> , P <sub>3</sub> , P <sub>8</sub> , P <sub>9</sub> , P <sub>13</sub> , P <sub>15</sub> , P <sub>21</sub> , P <sub>22</sub> , P <sub>29</sub> , P <sub>30</sub> , P <sub>35</sub> }
5	9 EP={P <sub>5</sub> , P <sub>7</sub> , P <sub>14</sub> , P <sub>17</sub> , P <sub>18</sub> , P <sub>19</sub> , P <sub>24</sub> , P <sub>25</sub> , P <sub>28</sub> }	MC-1={M <sub>1</sub> , M <sub>2</sub> , M <sub>3</sub> , M <sub>10</sub> , M <sub>11</sub> , M <sub>12</sub> , M <sub>21</sub> , M <sub>22</sub> , M <sub>23</sub> } MC-2={M <sub>4</sub> , M <sub>14</sub> , M <sub>15</sub> , M <sub>16</sub> , M <sub>25</sub> } MC-3={M <sub>5</sub> , M <sub>7</sub> , M <sub>17</sub> , M <sub>18</sub> , M <sub>26</sub> } MC-4={M <sub>13</sub> , M <sub>24</sub> } MC-5={M <sub>1</sub> , M <sub>5</sub> , M <sub>19</sub> , M <sub>20</sub> , M <sub>27</sub> , M <sub>28</sub> , M <sub>29</sub> , M <sub>30</sub> }	PF-1={P <sub>2</sub> , P <sub>10</sub> , P <sub>11</sub> , P <sub>12</sub> , P <sub>20</sub> , P <sub>23</sub> , P <sub>31</sub> , P <sub>32</sub> , P <sub>33</sub> , P <sub>39</sub> , P <sub>40</sub> , P <sub>41</sub> } PF-2={P <sub>4</sub> , P <sub>16</sub> , P <sub>27</sub> , P <sub>34</sub> , P <sub>36</sub> } PF-3={P <sub>38</sub> } PF-4={P <sub>1</sub> , P <sub>3</sub> , P <sub>8</sub> , P <sub>9</sub> , P <sub>13</sub> , P <sub>15</sub> , P <sub>21</sub> , P <sub>22</sub> , P <sub>29</sub> , P <sub>30</sub> , P <sub>35</sub> }
4	7 EP={P <sub>7</sub> , P <sub>14</sub> , P <sub>18</sub> , P <sub>19</sub> , P <sub>24</sub> , P <sub>25</sub> , P <sub>28</sub> }	MC-1={M <sub>1</sub> , M <sub>2</sub> , M <sub>3</sub> , M <sub>10</sub> , M <sub>11</sub> , M <sub>12</sub> , M <sub>21</sub> , M <sub>22</sub> , M <sub>23</sub> } MC-2={M <sub>5</sub> , M <sub>6</sub> , M <sub>7</sub> , M <sub>14</sub> , M <sub>15</sub> , M <sub>16</sub> , M <sub>17</sub> , M <sub>18</sub> , M <sub>25</sub> , M <sub>26</sub> } MC-3={M <sub>13</sub> , M <sub>24</sub> } MC-4={M <sub>4</sub> , M <sub>8</sub> , M <sub>9</sub> , M <sub>19</sub> , M <sub>20</sub> , M <sub>27</sub> , M <sub>28</sub> , M <sub>29</sub> , M <sub>30</sub> }	PF-1={P <sub>2</sub> , P <sub>10</sub> , P <sub>11</sub> , P <sub>12</sub> , P <sub>20</sub> , P <sub>23</sub> , P <sub>31</sub> , P <sub>32</sub> , P <sub>33</sub> , P <sub>39</sub> , P <sub>40</sub> , P <sub>41</sub> } PF-2={P <sub>4</sub> , P <sub>6</sub> , P <sub>16</sub> , P <sub>17</sub> , P <sub>26</sub> , P <sub>27</sub> , P <sub>34</sub> , P <sub>36</sub> , P <sub>37</sub> } PF-3={P <sub>38</sub> } PF-4={P <sub>1</sub> , P <sub>3</sub> , P <sub>8</sub> , P <sub>9</sub> , P <sub>13</sub> , P <sub>15</sub> , P <sub>21</sub> , P <sub>22</sub> , P <sub>29</sub> , P <sub>30</sub> , P <sub>35</sub> }
3	6 EP={P <sub>7</sub> , P <sub>14</sub> , P <sub>18</sub> , P <sub>19</sub> , P <sub>24</sub> , P <sub>28</sub> }	MC-1={M <sub>1</sub> , M <sub>2</sub> , M <sub>3</sub> , M <sub>10</sub> , M <sub>11</sub> , M <sub>12</sub> , M <sub>21</sub> , M <sub>22</sub> , M <sub>23</sub> } MC-2={M <sub>5</sub> , M <sub>6</sub> , M <sub>7</sub> , M <sub>13</sub> , M <sub>14</sub> , M <sub>15</sub> , M <sub>16</sub> , M <sub>17</sub> , M <sub>18</sub> , M <sub>24</sub> , M <sub>25</sub> , M <sub>26</sub> } MC-3={M <sub>4</sub> , M <sub>8</sub> , M <sub>9</sub> , M <sub>19</sub> , M <sub>20</sub> , M <sub>27</sub> , M <sub>28</sub> , M <sub>29</sub> , M <sub>30</sub> }	PF-1={P <sub>2</sub> , P <sub>10</sub> , P <sub>11</sub> , P <sub>12</sub> , P <sub>20</sub> , P <sub>23</sub> , P <sub>31</sub> , P <sub>32</sub> , P <sub>33</sub> , P <sub>39</sub> , P <sub>40</sub> , P <sub>41</sub> } PF-2={P <sub>4</sub> , P <sub>6</sub> , P <sub>16</sub> , P <sub>17</sub> , P <sub>26</sub> , P <sub>27</sub> , P <sub>34</sub> , P <sub>36</sub> , P <sub>37</sub> } PF-3={P <sub>1</sub> , P <sub>3</sub> , P <sub>8</sub> , P <sub>9</sub> , P <sub>13</sub> , P <sub>15</sub> , P <sub>21</sub> , P <sub>22</sub> , P <sub>25</sub> , P <sub>29</sub> , P <sub>30</sub> , P <sub>35</sub> , P <sub>38</sub> }
2	3 EP={P <sub>18</sub> , P <sub>19</sub> , P <sub>24</sub> }	MC-1={M <sub>1</sub> , M <sub>2</sub> , M <sub>3</sub> , M <sub>10</sub> , M <sub>11</sub> , M <sub>12</sub> , M <sub>21</sub> , M <sub>22</sub> , M <sub>23</sub> } MC-2={M <sub>4</sub> , M <sub>5</sub> , M <sub>6</sub> , M <sub>7</sub> , M <sub>8</sub> , M <sub>9</sub> , M <sub>13</sub> , M <sub>14</sub> , M <sub>15</sub> , M <sub>16</sub> , M <sub>17</sub> , M <sub>18</sub> , M <sub>19</sub> , M <sub>20</sub> , M <sub>24</sub> , M <sub>25</sub> , M <sub>26</sub> , M <sub>27</sub> , M <sub>28</sub> , M <sub>29</sub> , M <sub>30</sub> }	PF-1={P <sub>2</sub> , P <sub>10</sub> , P <sub>11</sub> , P <sub>12</sub> , P <sub>20</sub> , P <sub>23</sub> , P <sub>31</sub> , P <sub>32</sub> , P <sub>33</sub> , P <sub>39</sub> , P <sub>40</sub> , P <sub>41</sub> } PF-2={P <sub>1</sub> , P <sub>3</sub> , P <sub>4</sub> , P <sub>5</sub> , P <sub>6</sub> , P <sub>7</sub> , P <sub>8</sub> , P <sub>9</sub> , P <sub>13</sub> , P <sub>14</sub> , P <sub>15</sub> , P <sub>16</sub> , P <sub>17</sub> , P <sub>21</sub> , P <sub>22</sub> , P <sub>25</sub> , P <sub>26</sub> , P <sub>27</sub> , P <sub>28</sub> , P <sub>29</sub> , P <sub>30</sub> , P <sub>34</sub> , P <sub>38</sub> }

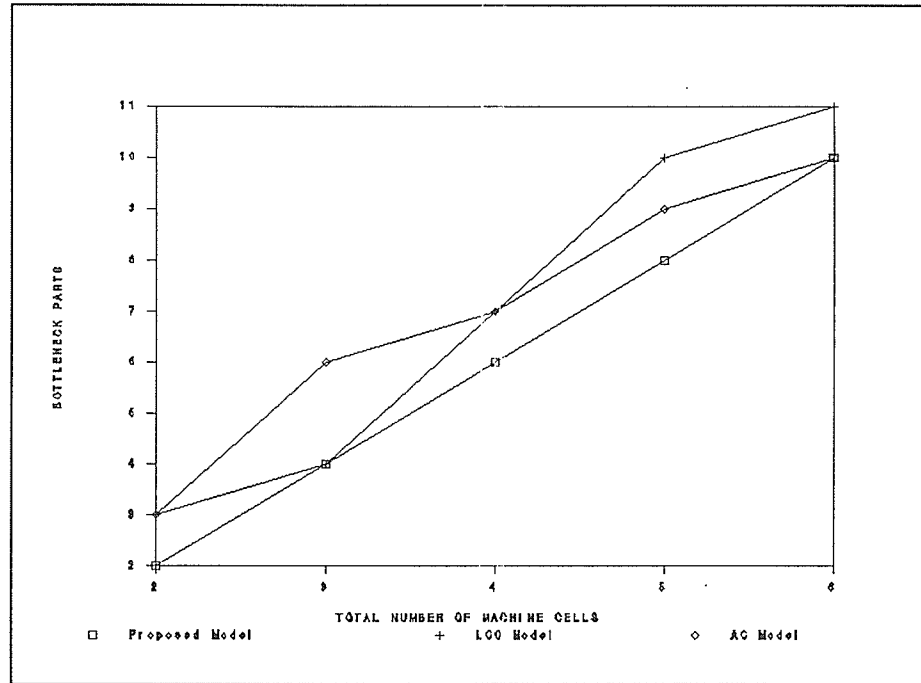


Figure 4.1: Empirical comparison of three models by using Kumar and Vannelli's data (1987)

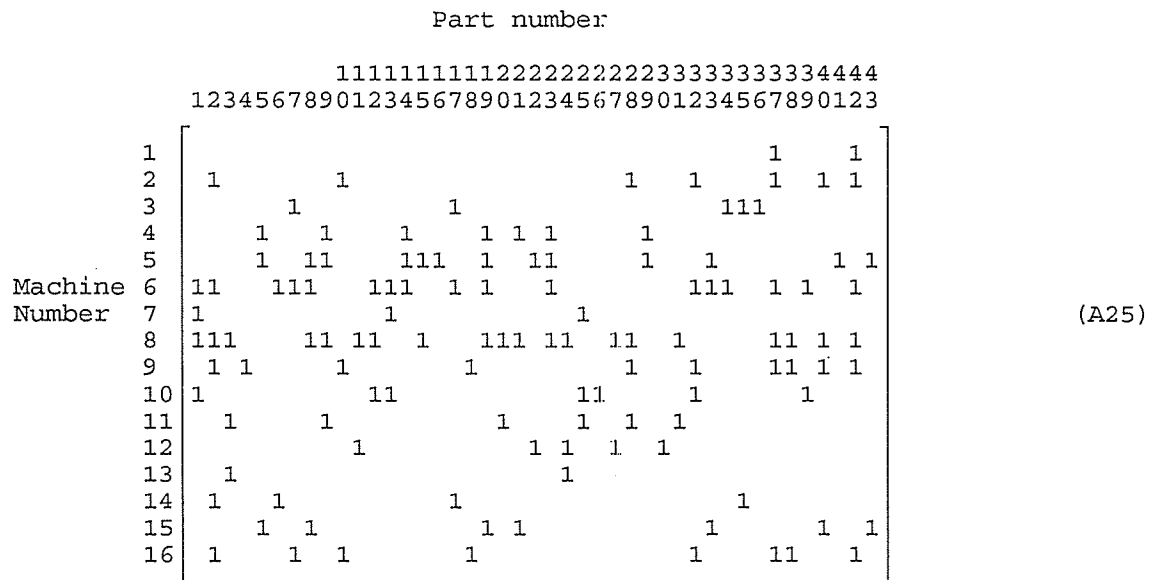


Figure 5: Machine-part matrix in Gupta and Seifoddini's problem (1990).

Part Number

1111111111222222222  
123456789012345678901234567

Machine Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	11	1111																									
2	11	111																									
3			111111																								
4	1111			11																							
5	1	1	111111																								
6	111	1111111																									
7	111	11111																									
8																											
9																											
10																											
11																											
12	11	1	1																								
13																											
14																											
15	1																										
16																											
17	11	11																									
18																											
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Figure 6 Machine-part matrix in King's problem (1980).

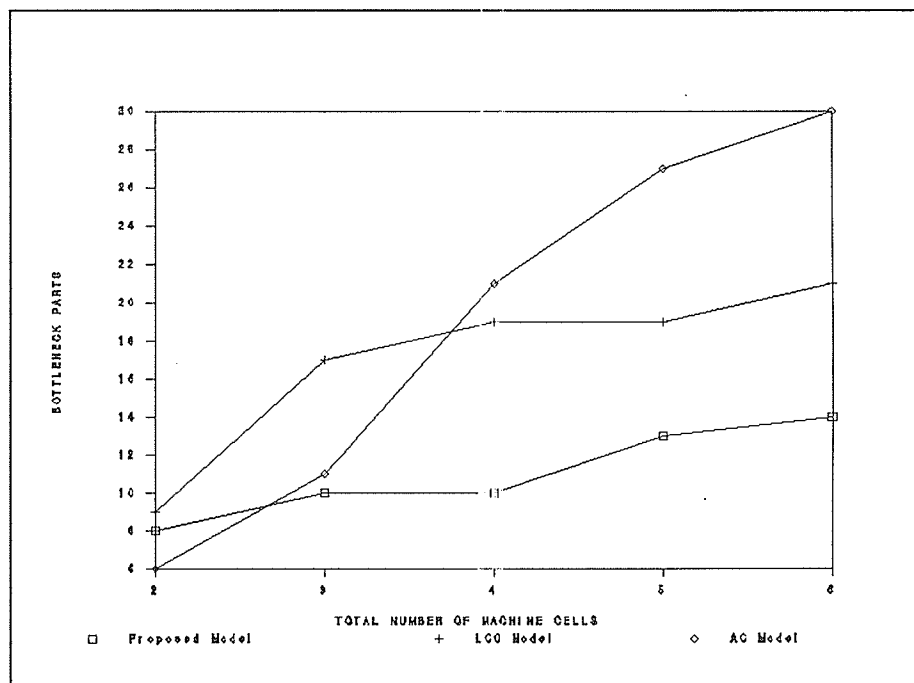


Figure 7: Empirical comparison of three models by using Gupta and Seifoddini's data (1990)

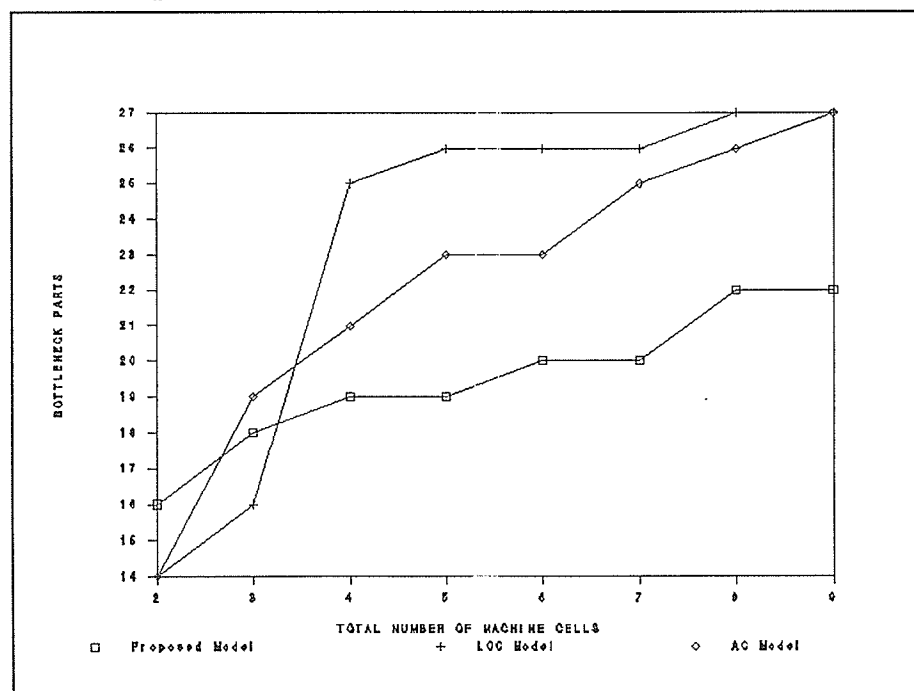


Figure 8: Empirical comparison of three models by using King's data (1980)

## 6.2 Discussions

Our model does not always outperform the other two algorithms when the total number of required machine cells (i.e. TMC) is small. For example, the AC model generates a smaller total number of exceptional parts when  $TMC = 2$  as shown in Figure 5. In Figure 6, LCC and AC outperformed our model when TMC are 2 and 3. This behaviour is mainly because the total number of machines in those final machine cells is rather small. For instance, one of the machine cells in Figure 5 of AC model consists of only two machines when  $TMC = 2$ , whereas our model contains four and the LCC model contains three. Additional data analysis strongly indicated that our proposed model outperforms the other two models when TMC is greater than 4 in a set of selected data. Our model is thus more useful for machine grouping since there is hardly any real, practical case where the requirement of TMC is less than 4.

Although we have proven that our new machine unit concept does in fact provide a local minimization of machine grouping (i.e. within any stage of the machine grouping process), it does not guarantee global minimization. This phenomenon is due to a) our proposed model being a heuristic algorithm, and b) the CM problem being an NP complete problem.

### 6.3 Conclusion

In this chapter, the results show that our proposed MGA outperformed others in a selected set of data when the total number of required machine cells for a CM solution is greater or equal to 4. The practical implementation of the proposed model is perhaps to incorporate a number of realistic constraints into the grouping process which are of concern to practitioners. The final product of the latter approach is known as an expert CM system. An expert system for CM is designed to interface a set of additional constraints with a proposed model. In the next chapter, we will present and develop such an expert CM system. The expert system components together with some realistic constraints will also be discussed.

## CHAPTER VII

### KNOWLEDGE-BASED SYSTEM FOR SOLVING CELLULAR MANUFACTURING

In previous chapters, we have proposed two new algorithms - the CIA and the MGA - which allow users to solve well structured CM problems. However, CM problems encountered in the real life mainly deal with rather semi- or ill-structured type of problems such as when two machines cannot be grouped into a cell. These ill-structured CM problems - whose solutions require the assistance from a knowledge-based approach - have not been addressed in the previous algorithms . In this chapter, a knowledge-based system (KBS) - known as the CELLular Manufacturing Information Systems (CEMIS) - designed for solving CM problems is presented. The problem type, data requirement and input format required by the proposed CEMIS is first discussed in next section. This is followed by the discussions of the KBS concept and models of CEMIS. A numerical example and its results are illustrated in subsequent sections.

## 7.1 Problem Specification

The proposed CEMIS solves both well- and ill-structured type of CM problems. The call for the need of CEMIS is mainly because a solution for ill-structured CM problem does not directly derive from a CM model or algorithm, but needs to interact with a set of rules that requires expert knowledge from CM experts (Prerau, 1990). The specific types of ill-structured CM problems may simply be due to the constraints faced on the shop-floor or from the experience of that managers. Table 6 shows some of the practical constraints that are being considered in CM literature in developing a KBS. The proposed CEMIS - whose elements will be discussed in the next section - considers the following set of practical constraints:

1. Maximum capacity of machine cells;
2. Total number of required machine cells;
3. Technological constraints;
4. Selection of material handling systems.

Details of each component and the required data are provided below.



**Table 6: Typical constraints imposed in CM problems**

	Total number of cells	The Size of each cell	Technological Constraints	Other Constraints
Wei and Kern (1989)	x	x		
Kusiak and Chow (1987 & 1988)	x		x	x
Kusiak (1988)	x	x	x	x
Kumar and Vannelli (1987)	x	x		x
Ventura et al. (1990)	x	x		

Maximum capacity of machine cells. The maximum capacity of machine cells refers to the total number of machines that are allowed in a machine cell when a CM solution is formed. This constraint plays an important role in designing a CM layout as managers may possess a good feeling on the direct impact of machine cells on the shop floor layout. In using the proposed CEMIS, users are required to represent this requirement as a numerical value. The input format will be discussed in a later section.

Total number of machine cells. The total number of machine cells refer to a CM solution in which only a specific number of machine cells is generated. Formation of specific machine cells may make it easier to manage the material flows within a shop floor. The entry data of such a requirement is indicated by a numerical value.

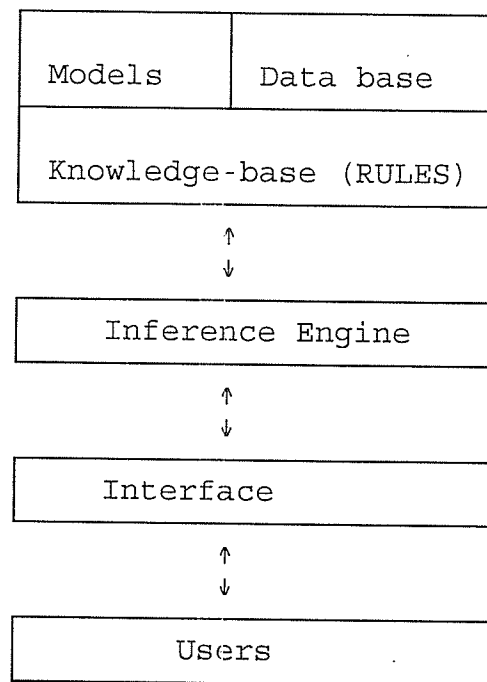
Technological constraints. The technological constraints refer to specifically to

a set of machines that must or must not be included in a single cell. For example, there may exist a situation where a furnace and a painting machine should not be included in the same cell. In contrast, it may be desired that a drilling machine and a cooling machine be in the same cell. The data for each case is arranged in a  $1 \times m$  array, where  $m$  is the total number of machines that match the specific requirement. The detailed format for each case will also be discussed later.

Selection of material handling systems. The selection of material handling systems refers to the specific devices needed to handle parts within a cell. In the proposed CEMIS, we only consider three specific types of material handling systems: robot arms, gantry arms and automated guided vehicles represented respectively by codes R, G and A. A relationship chart for parts that are required for these special arrangements will be asked for by the system.

## 7.2 KBS Concept and Model of CEMIS

The general concept of a KBS for CM involves manipulating a set of CM models/algorithms and human experts to develop a system which can be used by a wide range of users for solving ill-structured types of CM problems. Figure 9 presents a general structure of KBS. Each component of the proposed KBS framework is discussed here.



**Figure 9: General structure of the knowledge-based system**

Users. Users represent the end-users of such a KBS who interact with the interface device to produce CM solutions.

Interface. Interface is an electronic device (such as a Personal Computer PC) which enables users to communicate with the KBS.

Models. Models refer to CM models/algorithms that allow KBS to produce a specific set of CM solutions. In our CEMIS, two models are used - the CIA and the MGA. These two models apply in turn to interface with the knowledge base (which will be discussed later) in deriving a specific CM solution.

Knowledge base. The knowledge base stores the facts of CM problems. It also includes expert knowledge on how and when to use these facts to generate CM solutions. The knowledge base presentational paradigms used most often in KBS are production rules - which are in the form of IF-THEN-ELSE format (Giarratono and Riley, 1989). In our proposed CEMIS, there are five classes of production rules:

- a) CLASS 1 rules relate to CM problems whose solution has a specific number of machine cells
- b) CLASS 2 rules relate to CM problems where each cell holds not more than a specific number of machines
- c) CLASS 3 rules relate to CM problems that satisfy technical constraints such as a set of machines that must or must not be included in a single cell
- d) CLASS 4 rules relate to CM problems that satisfy selection of material handling systems such as AGV, robot arms, and gantry slides
- e) CLASS 5 rules read in the related data sets, such as a machine-part matrix A and values M and N
- f) CLASS 6 rules interact the above parameters with our MODEL to derive a solution.

To present samples of these production rules, consider the following CM problem: Determine a CM solution in which each machine cell contains not more than 5 machines, and where machines  $M_1$  and  $M_4$  must be included in the same machine cell. Two sample

rules of CEMIS which examine these constraints are as follows.

Rule A

```
{IF    machines  $M_1$  and  $M_4$  need to be together

      THEN  replace these machines by a new machine unit
            AND
            compute its associated entry value  $a_{ij}$ 
            AND go to CLASS 5 rules }
```

Rule B

```
{IF    including a pair of machines that has the highest
      value of  $C_{ij}$  in machine cell MC-k exceeds
      maximum number of machines in each cell = 5 (i.e. > 5)

      THEN  ignore this value of  $C_{ij}$ 

      ELSE  group machines  $M_i$  and  $M_j$  together }
```

Rule 5 is a CLASS 3 rules which allows the proposed CEMIS to convert all data read from CLASS 4 rules by incorporating it with our proposed "new machine unit" concept. Whereas Rule 16 checks if CLASS 1 rules are violated. The response to the latter rule would lead the CEMIS to activate other rules so that a feasible CM solution is generated. However, readers may be interested to know that violation of CLASS 6 rules would result in terminating the CEMIS and a final result is produced. A specific production rule for CLASS 6 is listed below.

```
{IF    (remaining regular machines + new machine units) or
      (total number of new machine units) = specific number
      of maximum machine cells

      THEN  form the remaining regular machines as individual
            machine cells
            AND
            print the CM solution
```

ELSE proceed to the normal grouping procedure }

The knowledge base in the proposed CEMIS consists of 69 rules. New rules can be added when required. A completed list of the knowledge base is shown in Appendix A.

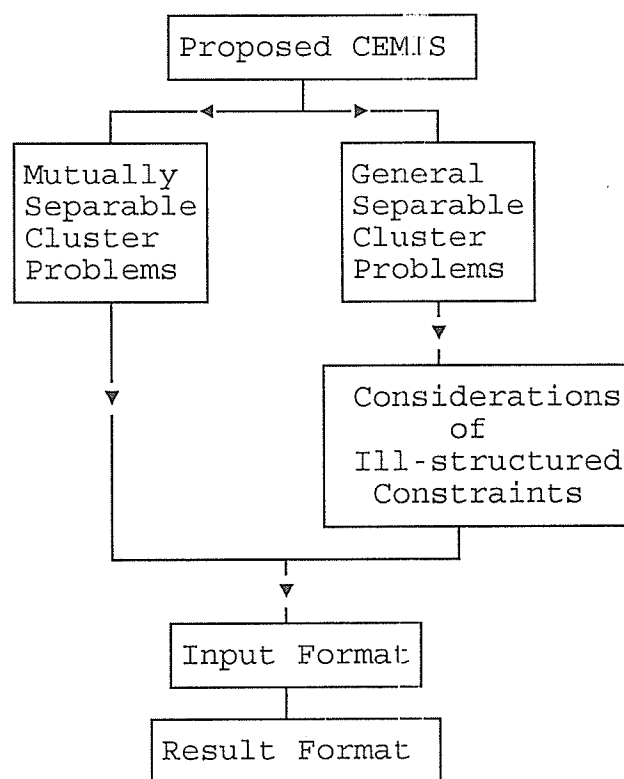
Inference engine. An inference engine is a set of strategies which match the data provided by the database with the information contained in the knowledge base. The proposed CEMIS uses the forward-chaining strategy in which the system works from an initial set of conditions and proceeds forward to the next rule if a specific condition is met. This forward-chaining strategy is clearly illustrated in the above stated production rules.

Database. The database contains the relevant facts or data describing a CM problem. The database will be used to interact with models and constraints specified in the knowledge base. Users are required to supply this data in a format that is being developed in our proposed CEMIS.

The proposed CEMIS, coded in PASCAL, mainly consists of a series of sample production rules and thus use of 4GL is not needed. Readers may be interested to note that Doukidis and Paul (1990) reported that a high-level language such as PASCAL is commonly used to implement a KBS. Readers who are interested in details of each KBS

component may refer to Neale (1990), Giarratano and Riley (1989), and Rozendblit et al. (1990)). In the following section, we would illustrate the inputting format of our proposed CEMIS.

### 7.3 The Proposed CEMIS



**Figure 10: The basic structure of the proposed CEMIS**

Our proposed CEMIS allows users to solve both well- and semi- structured CM problems. The basic structure of the proposed CEMIS is depicted in Figure 10 (Chow, 1990).

Figure 11 illustrates the initial query format when our proposed CEMIS is activated. Users are required to select either option 1 or 2 by typing a numerical value. The mutually separable cluster problem of option 1 refers to the use of the proposed CIA, whereas the general separable cluster problem of option 2 alludes to the machine chaining problem (where the proposed MGA will be used for solution findings). The definitions of these terms can be checked by typing in option 3 which is a help command and is illustrated through the following examples and figures.

```
CELLULAR MANUFACTURING INFORMATION SYSTEMS
(CEMIS)

Welcome to the CEMIS

Please select the type of CM problem to be solved:

1. Mutually Separable Cluster Problem (MSCP)
2. Partially Separable Cluster Problem (PSCP)

OR

3. HELP command

Selection: _
```

**Figure 11: Initial query format for the proposed CEMIS**

It should be clear to the users that option 1 in Figure 11 is used to evaluate if a given CM problem can be physically decomposed into a set of mutually separable clusters. Given if a cluster solution is simply too large to be handled by the management then its submatrix should then be treated as the input data to the option 2, where the use of practical constraints that was described in section 7.1 can be considered. Therefore, it is assumed that option 1 does not consider the practical constraints at all. The format of Figure 12 will be activated from the proposed CEMIS when option 2 is chosen from



Figure 11.

In selecting any option in Figures 11 and 12, the proposed system allows users two ways to input the data of a CM problem (See Figure 13).

```
CELLULAR MANUFACTURING INFORMATION SYSTEMS
(CEMIS)

You have now selected option 2 (i.e. the PSCP).

Do you wish to consider the resource constraints:

1. Yes
2. No

Selection: _
```

**Figure 12: Resource format of CEMIS**

```
CELLULAR MANUFACTURING INFORMATION SYSTEMS
(CEMIS)

Please select the input format:

1. Manual Input
2. File Input

Selection: _
```

**Figure 13: Input format of CEMIS**

As an example of manual data inputting for mutually separable cluster problems, let us consider a CM problem as depicted in matrix (A1) in Chapter 1. Its data inputting format is shown in Figure 14. Those values typed in bold face are input data from users.

Alternatively, selecting option 2 in Figure 13 would result in Figures 15 and 16. The code '1' appears in the first line of Figure 16 indicates that the CIA model is selected.

```

CELLULAR MANUFACTURING INFORMATION SYSTEMS
(CEMIS)

You are now solving a Mutual Separable Cluster Problem.
Please specify the following information:

    Total number of machines (rows) = 6
    Total number of parts (columns) = 5

Attention:
    Please enter data in a matrix form.

Begin inputting data:

                Parts
Machine 1: 10000
Machine 2: 10100
Machine 3: 01001
Machine 4: 01011
Machine 5: 00010
Machine 6: 00100

End of data inputting

```

Figure 14: Manual data inputting Mode

```

CELLULAR MANUFACTURING INFORMATION SYSTEMS
(CEMIS)

Please specify the input file name.

(Attention:
    The first line consists of two values; m representing
    the total number of machines; and n the total of
    parts. The remaining values are either 0 or 1.

    File Name: EXAMPLE

Press RETURN key after typing the file name

```

Figure 15: File Name Input of Figure 14

```

1
6 5
10000
10100
01001
01011
00010
00100

```

Figure 16: The data format for the file "Example" of matrix (A1)

In addition to the above input format, four bits of information relating to the practical constraints of general separable clustering problems for option 1 in Figure 12 are required. These values are asked individually if the manual inputting format is chosen. The general format of file inputting for the use of practical constraints is shown in Table 7.

**Table 7: General file input format for general separable clustering problems**

A	----	A=1 indicates the use of CIA, and A=2 is the MGA
M N	----	specific problem size
[a <sub>ij</sub> ]	----	matrix of numerical data of a CM problem
C	----	numeral value for maximum capacity of each machine cell
D	----	numeral value for total number of machine cells
K	----	number of groups of grouped machines
k group l	--	k = serial number Group l, k = 1, ..., K Group l = paired machines to be grouped together
U	----	number of groups of ungrouped machines
u group j	--	u = serial number in Group j, u = 1, ..., U Group j = paired machines not to be grouped together
H	----	number of parts need for special material handling systems
h group i	--	h = serial number in Group i, h = 1, ..., H Group i = pair of part number and its required material handling system s, S=V,G,R (where code A represents automated guided Vehicles, G - Gantry arms, and R - Robot arms)

In order to illustrate the input format of Table 7, let us consider the following

example.

**EXAMPLE 2:** Illustrate the input format of Table 7 for the following CM problem.

1. Solve the CM problem by using the MGA model
2. A CM problem which consists of 100 machines and 200 parts;
3. Each machine cell contains not more than 7 machines;
4. The total desired number of machine cells is 20;
5. The following machines need to be grouped into the same cells:  $M_1$  with  $M_{11}$ ,  $M_{15}$  with  $M_{20}$ , and  $M_{22}$  with  $M_{59}$  and  $M_{68}$ ;
6. There is no machine that cannot be physically grouped together with others into a machine cell;
7. Parts  $P_{12}$ ,  $P_{46}$ ,  $P_{100}$  need to be handled by robot arms;
8. Parts  $P_{22}$  and  $P_{60}$  require a gantry arm for transportation.

The input format for Example 2 is shown in Table 8.

**Table 8: General file input format for EXAMPLE 2**

```

2
100 200
[ai]
7
20
3
1 1 11
2 15 20
3 22 59 68
0
2
1 12 46 100 R
2 22 60 G

```

In the above table, the value on the first line (ie. value 2) instructs the CEMIS to apply the MGA model. The next two lines indicate the problem size and its  $a_{ij}$  values, which is an  $M \times N$  matrix consisting of 0 and 1 values. (It should be clear that the matrix of  $a_{ij}$  would consist of  $100 \times 200$  elements of a matrix which should be replaced here). The fourth and fifth line shows the respective maximum allowance of each machine cell capacity and the total desired number of machine cells in the CM solution. The sixth line informs the proposed CEMIS that there are three groups of machines needed to be grouped together. These groups of data are illustrated in the sequence data shown in the following three lines where the first code of these lines is the indication of respective group of data. The value "0" appearing in the tenth line signifies that there are no machines that cannot be grouped into cells; therefore the term of "u group j" shown in Table 7 is omitted as data input in Table 8. (Given that if the latter constraints applied, then the input format is similar to those of grouped machines like from lines 5 to 8). The eleventh line tells the proposed system that there are two groups of parts requiring the special care of handling devices. The twelfth line indicates the first group of parts which requires robot arms handling **R**; whereas the last line in the table shows the second group of parts requiring the gantry arm **G**. Although the proposed CEMIS allows us to manipulate the file facility for data inputting, users are warned to be cautious regarding the accuracy of its format. Any deviation from the specified input format would lead to either inaccurate result or cause the termination of the CEMIS.

The proposed CEMIS has the capability to detect some input data errors when

using the manual input format. For example, it checks whether the entered values of  $M$  and  $N$  are non-zero values and whether each entry of the machine-part incidence matrix is of numeral values "0" or "1".

To illustrate the output format of CEMIS, let us further consider a CM problem listed in Example 3.

Example 3.

Determine a CM solution of machine cells, part families and exceptional parts that meets the following constraints:

1. A machine-part matrix as shown in matrix (A24) of Chapter 6;
2. The maximum number of machines in each cell is 15.
3. The maximum number of machine cells is 4 and;
4. Machines  $M_3$  and  $M_{22}$  cannot be included in the same machine cell;
5. Machines  $M_5$  and  $M_{15}$  must be included in the same machine cell;
6. Part  $P_8$  requires handling by a gantry arm.

The proposed CEMIS examines each of the constraints specified above and generates the output format as shown in Figure 17 (Chow and Hawaleshka 1991b). In the report format, the CEMIS will first show the inputting data received from users, including the machine-part incidence matrix  $a_{ij}$ . This information forms an important

element allowing users to gain full understanding of the exact type of CM problem to be solved by the proposed CEMIS (Senn, 1990). The proposed CEMIS presents the resulting findings in two parts. The first part illustrates the members of each cluster (ie. machine cell and part family), and those parts that belong to bottleneck and non-bottleneck parts (ie. excluded parts) together with their related percentages. The percentage of bottleneck parts in the report is computed from the ratio of total number units of bottleneck parts divided by the total number of parts involved in that cluster. This item makes it easier for users to analyze if joining two clusters into one is desirable when most parts involved in that clusters are bottleneck parts. The second part of the report presentation shows the information on intercellular parts movements between clusters. This information allows managers to gain a fuller picture regarding the CM solution so that better planning and design of the CM environment is achieved. Information regarding special handling of parts is provided at the end of this report.

```

CELLULAR MANUFACTURING INFORMATION SYSTEMS
(CEMIS)

***** SOLUTION FINDINGS *****

The original size of the CM problem is:

    Total number of machines (rows) = 30
    Total number of parts (columns) = 41

The input machine-part matrix is:

                Part number
                11111111112222222222333333333344
                12345678901234567890123456789012345678901
Machine
Number 1 |           1           111       1 1
        2 |           11          1       11       1 1
        3 |           1           1           1       11       11
        4 |           1           1           11  1       1
        5 |           1           1           1           1 1
        6 |           1           1           1           1 1
        7 |           1           1           1           1 1
        8 | 1           11          1           1           1
        9 | 1           1           1           1           1
       10 | 1           1           1  1           1
       11 |           1           1           1           1 1
       12 |           11          11  11           11
       13 |           1           1           1           1
       14 | 11           1           1           1           1
       15 |           1           1           1           1
       16 |           1           1           1           1

ENTER RETURN FOR MORE INFORMATION ..... (Cont'd) ...

```

Figure 17: Output format of the proposed CEMIS (see continuation)



CELLULAR MANUFACTURING INFORMATION SYSTEMS (CEMIS)						
***** SOLUTION FINDINGS *****						
						(Cont'd)
17		1		1		1
18			1 1		1	1
19	1 1			11		1
20	1 1			11		
21		1 1			111	1
22		1 1		1	11	11
23	1		1	1	1	1
24						1
25	1					
26			1		1	1 1
27		1	1			
28		1			1	1
29	1 1	1	1	1	1	
30	1 1			11		

Constraints:

- (1) Maximum number of machine cells allowed: 4
- (2) Maximum number of machines in a cell : 15
- (3) Machines that cannot be included in a cell:  
M3 and M22
- (4) Machines that must be included in a cell:  
M5 and M15
- (5) Parts requiring AGV handling : N/A
- (6) Parts requiring robot arms handling : N/A
- (7) Parts requiring gantry arms handling : P8

ENTER RETURN FOR MORE INFORMATION ..... (Cont'd) ...

Figure 17: Output format of the proposed CEMIS

```

CELLULAR MANUFACTURING INFORMATION SYSTEMS
(CEMIS)

***** SOLUTION FINDINGS *****
                                                    (Cont'd)

***** Result Analysis *****

Cluster 1:

MC-1={M1, M2, M11, M12, M13, M21, M22, M24}
PF-1={P10, P11, P12, P18, P19, P20, P23, P24, P25, P31, P32
      P38, P39, P40, P41}

Analysis:
=====

Excluded parts: {P10, P11, P19, P33, P38, P41}
Bottleneck parts: {P12, P18, P20, P23, P24, P25, P31, P32,
                   P39, P40}

                Machines  Parts  Bottleneck Parts
                =====  =====  =====
Total units:    8         16         10
Percentage :   27%      39%      62.5%

Cluster 2:

MC-2={M4, M8, M9, M19, M20, M27, M28, M29, M30}
PF-2={P1, P3, P7, P8, P9, P13, P14, P15, P21, P22, P24, P25,
      P28, P29, P30, P35}

Analysis:
=====

Excluded parts: {P1, P3, P8, P9, P13, P15, P21, P22,
                 P29, P30, P35}
Bottleneck parts: {P7, P14, P24, P25, P28}

                Machines  Parts  Bottleneck Parts
                =====  =====  =====
Total units:    9         16         5
Percentage :   30%      39%      31.3%

ENTER RETURN FOR MORE INFORMATION ..... (Cont'd) ...

```

Figure 17: Output format of the proposed CEMIS

```

CELLULAR MANUFACTURING INFORMATION SYSTEMS
(CEMIS)

***** SOLUTION FINDINGS *****
                                                                    (Cont'd)

Cluster 3:

MC-3={M3,M10,M23}
PF-3={P2,P12,P20,P23,P31,P32,P39,P40}

Analysis:
=====

Excluded parts:  {P2}
Bottleneck parts: {P12,P20,P23,P31,P32,P39,P40}

                Machines  Parts  Bottleneck Parts
                =====  =====  =====
Total units:    3          8          7
Percentage :   10%       19.5%     87.5%
                                                                    (Cont'd)

Cluster 4:

MC-4={M5,M6,M7,M14,M15,M16,M17,M18,M25,M26}
PF-4={P4,P5,P6,P7,P14,P16,P17,P18,P26,P27,P28,P34,
      P36,P37}

Analysis:
=====

Excluded parts:  {P4,P5,P6,P16,P17,P26,P27,P34,
                  P36,P37}
Bottleneck parts: {P7,P14,P18,P28}

                Machines  Parts  Bottleneck Parts
                =====  =====  =====
Total units:    10         14          4
Percentage :   33%       34.1%     28.6%

ENTER RETURN FOR MORE INFORMATION ..... (Cont'd) ...

```

Figure 17: Output format of the proposed CEMIS

CELLULAR MANUFACTURING INFORMATION SYSTEMS  
(CEMIS)

\*\*\*\*\* SOLUTION FINDINGS \*\*\*\*\*

(Cont'd)

Intercellular Movement of Parts Analysis:

Total number of bottleneck parts : 13  
Percentage of Parts involved: 31.7%

Part numbers : {P7, P12, P14, P18, P20, P23, P24, P25, P28,  
P31, P32, P39, P40}.

Movement of parts:

P7 involved in machine cells: MC-2, MC-4  
P12 involved in machine cells: MC-1, MC-3  
P14 involved in machine cells: MC-2, MC-4  
P18 involved in machine cells: MC-1, MC-4  
P20 involved in machine cells: MC-1, MC-3  
P23 involved in machine cells: MC-1, MC-3  
P24 involved in machine cells: MC-1, MC-2  
P25 involved in machine cells: MC-1, MC-2  
P28 involved in machine cells: MC-2, MC-4  
P31 involved in machine cells: MC-1, MC-3  
P32 involved in machine cells: MC-1, MC-3  
P39 involved in machine cells: MC-1, MC-3  
P40 involved in machine cells: MC-1, MC-3

\*\*\*\* P8 requiring Gantry robot arm handling  
Bottleneck part : No  
Cluster involved : Cluster 2

END OF ANALYSIS

Figure 17: Output format of the proposed CEMIS

## 7.4 Conclusion

This chapter proposes a KBS for CM known as the CEMIS. The proposed CEMIS allows users to consider both well- and semi-structured types of CM problems. The models applied in the CEMIS are the two models (ie. the CIA and the MGA) that have been proposed in the previous chapters. In our proposed CEMIS, the CIA model is referred to as the mutually separable cluster problems (MSCP) and does not consider any real, practical constraints. The MGA solves the partially separable cluster problem (PSCP) with or without considerations of a set of practical constraints. Our proposed CEMIS may be used in the following ways. First, a CM problem is solved by the MSCP. Second, any unsatisfied solution form MSCP is then treated as the input data to the PSCP for further analysis. Users may wish to consider the practical constraints in the PSCP in turns so that a full picture of the CM solution is obtained. The general logic flow of the suggested method is illustrated in Figure 18. The proposed CEMIS provides two modes of data inputting - i.e. file and manual inputting. Users who are not clear regarding the file inputting format may consider the manual inputting mode where step-by-step instructions are provided. The use of CEMIS is illustrated in this chapter by examples.

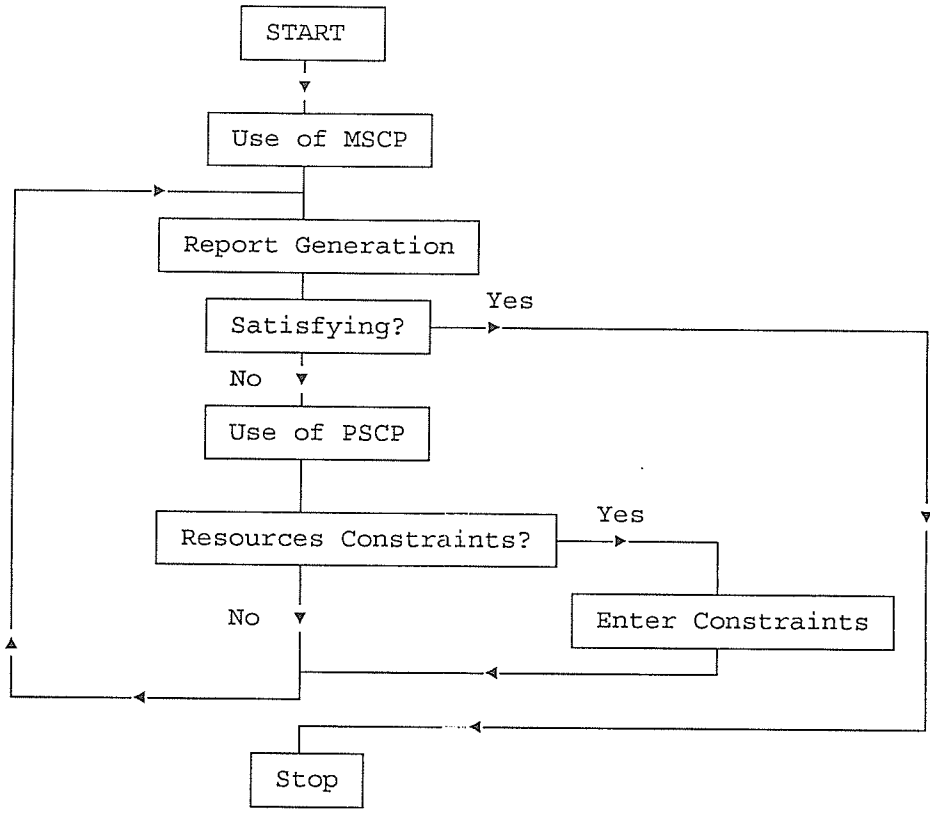


Figure 18: Logical flow chart for the use of CEMIS

## Chapter VIII

### CONCLUSIONS

In this thesis, cellular manufacturing (CM) problems have been addressed. The classification of CM problems into two types of separable clustering problems - i.e. a mutually separable clustering problem (MSCP) and a partially separable clustering problem (PSCP) - was identified. Two new algorithms have been proposed. The first one known as the Cluster Identification Algorithm (CIA) is used to solve CM problems that are related to the MSCPs. The proposed Machine Grouping Algorithm (MGA) makes use of the concepts of "new machine unit" and machine grouping techniques to solve the PSCPs. The models developed have the following advantages:

1. the CIA
  - provides the most efficient computational time yet given in the literature to determine the optimal solutions of MSCPs;
  - has the flexibility to consider additional constraints - such as cost factors.
2. the MGA
  - solves the machine chaining problem that was reported in literature;
  - incorporates the "new machine unit" concept which provides the optimal solution for grouping  $(n+2)$  total number of machine cells into  $(n+1)$  total number of machine cells;
  - shows the behaviour of the total number of intercellular parts in relation to the sizes of machine cells;

- has the flexibility to consider additional constraints.

Computational experience has shown that the CIA is very efficient. This result reduces the unnecessary computational effort in checking the existence of MSCP and their numbers. Since its computational time is  $O(2MN)$ , it can be used prior to solving PSCP.

The computational results shown for the machine chaining problems indicate that our proposed MGA produces a better quality solution compared to other two in the CM literature when the desired total number of machine cells is greater than three. This result is most useful in practice since practitioners are more likely to be involved with real CM solutions which contain the formation of more than three machine cells. It should be noted that obtaining a global optimal algorithm for CM problems that belongs to the PSCP is not feasible because CM is an NP complete problem.

Much of the existing CM literature attempts to dilute the complexity of CM problems by imposing a set of constraints into their algorithms/models. However a complete analysis of solution for a CM problem cannot be accomplished mainly due to the lack of understanding of the individual proposed methods. One of the possible resolutions to this problem is to borrow the concept of knowledge-based systems. Our proposed CEMIS - which makes use of the models developed by us - allows users to



perform a complete analysis of CM problems in the following way by:

1. identifying if a large CM problem can be decomposed into a set of mutually separable clusters;
2. analyzing those unsatisfied clusters sizes listed in point 1 by identifying their corresponding partially separable clusters;
3. further examining the clusters of CM solutions listed in point 2 by incorporating a set of practical constraints - such as the maximum capacity of machine cells, the total number of required machine cells, technological constraints, and the selection of material handling systems for parts.

The advantages of CEMIS are as follows:

- it enables users to solve both well- and ill-structured types of CM problems;
- it uses efficient algorithms to solve the CM problems;
- it allows users to consider any combination of a set of four practical constraints for a CM problem;
- it allows two modes of data inputting: file and manual inputting format;
- it can be used in both PC and mini/main-frame computers.

We believe that the two algorithms and the CEMIS we have proposed are a significant contribution to the field of analysis and design of cellular manufacturing systems.

**W.S.CHOW**

## REFERENCES

1. I. Al-Qattan (1990), "Designing flexible manufacturing cells using a branch and bound method", International Journal of Production Research, Vol. 28, No. 2, pp. 325-336.
2. Anonymous (1980a), "How to predict the benefit of group technology", Production Engineer, Feb., pp. 51-54.
3. Anonymous (1980b), "Product-based group technology pay off", Mechanical and Production Engineering, Vol. 3, pp. 37-39.
4. E.A. Arn (1975), Group Technology: An Integrated Planning and Implementation Concept for Small and Medium Batch Production, Springer-Verlag.
5. T.S. Arthanari and Y. Dodge (1981), Mathematical Programming in Statistics, Wiley, New York.
6. R. Askin and S. Subramanian (1987), "A cost-based heuristic for group technology configuration", International Journal of Production Research, Vol. 25, No. 1, pp. 101-114.
7. A. Ballakur (1986), "Streamlining material flows for just-in-time application", in Proceedings of 1986 Fall IIE Conference, Boston, MA., pp. 51-56.
8. M.V. Bhat and A. Haupt (1976), "An efficient clustering algorithm", IEEE Transactions on Systems, Man and Cybernetics, Vol. SMC-6, No. 1, pp. 61-64.
9. F.F. Boctor (1991), "A linear formulation of the machine-part cell formation problem", International Journal of Production Research, Vol. 29, No. 2, pp. 343-356.
10. W.I. Bullers, S.Y. Nof and A.B. Whiston (1980), "Artificial intelligence in manufacturing planning and control", AIEE Transactions, Dec., pp. 351-363.
11. J.L. Burbidge (1971), "Production Flow Analysis", The Production Engineer, April/May, pp. 139-152.
12. J.L. Burbidge (1975), The Introduction of Group Technology, London: Heinemann.

13. J.L. Burbidge (1977), "A manual method of Production Flow Analysis", Production Engineer, Vol. 56, pp. 34-38.
14. H.M. Chan and D.A. Milner (1982), "Direct clustering algorithm for group formation in cellular manufacturing", Journal of Manufacturing Systems, Vol. 1, No. 1, pp.65-74.
15. M.P. Chandrasekharan and R. Rajagopalan (1986), "MODROC: An extension of rank order clustering for group technology", International Journal of Production Research, Vol. 24, No. 5, pp. 1221-1233.
16. M.P. Chandrasekharan and R. Rajagopalan (1987), "ZODIAC - An algorithm for concurrent formation of part families and machine cells", International Journal of Production Research, Vol. 25, No. 6, pp. 835-850.
17. W.S. Chow (1990), "Computer-Aided Production Analysis System (CAPAS)", The Impact of Information Technology on Systems Management, (Edited by C. Yau), in Proceedings of the International Conference on Systems Management'90, 11-13 June 1990, Chinese University of Hong Kong, Hong Kong, pp. 338-342.
18. W.S. Chow (1991a), "A note on a linear cell clustering algorithm", International Journal of Production Research, Vol. 29, No. 1, pp. 215-218.
19. W.S. Chow (1991b), "The generalization of cluster identification problems", Proceedings of The Fourth International Conference on Comparative Management, June 2-4, National Sun Yet-sen University, Kaohsiung, Taiwan, pp. 265-269.
20. W.S. Chow and O. Hawaleshka (1989), "The dendogram approach in machine grouping problems", Autotech Asia'89, Industrial Automation Technology Conference Proceedings, Oct. 5-6, Hong Kong Productivity Council, Hong Kong, pp. 80-96.
21. W.S. Chow and O. Hawaleshka (1991a), "Minimizing intercellular part movements in manufacturing cell formation", submitted to International Journal of Production Research (forthcoming).
22. W.S. Chow and O. Hawaleshka (1991b), "Expert support system for designing cellular manufacturing", (Edited by D.F. Kocaoglu & K. Niwa), Proceedings of the Portland International Conference on Management of Engineering and Technology (PICMET'91), Portland University, Oregon, USA, Oct. 27-31, pp. 440-443.
23. W.S. Chow and O. Hawaleshka (1992a), "An efficient algorithm for solving the

- machine chaining problem in Cellular Manufacturing", Computers and Industrial Engineering, Vol. 22, No. 1, pp. 95-100.
24. W.S. Chow and O. Hawaleshka (1992b), "A novel machine grouping and knowledge-based approach for cellular manufacturing", European Journal of Operational Research (forthcoming).
  25. H.C. Co and A. Araar (1988), "Configuring cellular manufacturing systems", International Journal of Production Research, Vol. 26, No. 9, pp. 1511-1522.
  26. J. De Witte (1980), "The use of similarity coefficients in production flow analysis", International Journal of Production Research, Vol. 18, No. 4, pp. 503-514.
  27. J. Dekleva and D. Menart (1987), "Extensions of Production Flow Analysis", Journal of Manufacturing Systems, Vol. 6, No. 3, pp. 93-105.
  28. G.I. Doukidis and R.J. Paul (1990), "A survey of the application of artificial intelligent techniques within OR society", Journal of Operational Research Society, Vol. 41, No. 5, pp. 363-375.
  29. F.R.E. Durie (1970), "A survey of group technology and its potential for user application in the UK", Production Engineer, Feb., pp. 51-61.
  30. G.A. B. Edwards (1971), "The family grouping philosophy", International Journal of Production Research, Vol. 9, No. 3, pp. 337-352.
  31. I.G.K. El-Essaway and J. Torrance (1972), "Component Flow Analysis - An effective approach to production systems design", Production Engineer, Vol. 51, pp. 165- 170.
  32. G.M. Fazakerlay (1974), "Group technology: Social benefits and social problems", Production Engineer, Oct., pp. 383-386.
  33. L.R. Ford and D.R. Fulkerson (1957), "A simple algorithm for finding maximal network flows and an application to the hitchcock problem", Canadian Journal of Mathematics, Vol. 9, pp. 210-218.
  34. G.V. Frazier and N. Gaithier (1991), "Seed selection procedures for cell formation heuristics", International Journal of Production Research, Vol. 29, No. 11, pp. 2227-2237.
  35. K.S. Fu (1980), "Recent developments in pattern recognition", IEEE Transactions on Computers, Vol. C-29, No. 10, pp. 845-854.

36. J. Giarratano and G. Riley (1989), Expert Systems: Principles and Programming, Boston: PWS-Kent Publishing Company.
37. F. Glover and E. Woolsey (1974), "Converting the 0-1 polynomial problem to a 0-1 linear programming", Operations Research, Vol. 22, pp. 180-182.
38. T.J. Greene and R.P. Sadowski (1983), "Cellular manufacturing control", Journal of Manufacturing Systems, Vol. 2, No. 2., pp. 137-145.
39. T.J. Greene and R.P. Sadowski (1984), "A review of cellular manufacturing assumptions, advantages and design techniques", Journal of Operations Management, Vol. 4, No. 2, pp. 84-97.
40. K.R. Gunasingh and R.S. Lashkari (1989), "Machine grouping problem in cellular manufacturing systems - An integer programming approach", International Journal of Production Research, Vol. 27, No. 9, pp. 1465-1473.
41. T. Gupta and H. Seifoddini (1991), "Production data based similarity coefficient for machine-component grouping decisions in the design of a cellular manufacturing systems", International Journal of Production Research, Vol. 28, No. 7, pp. 1247-1269.
42. G. Harhalakis, R. Nagi and J.M. Proth (1990), "An efficient heuristic in manufacturing cell formation for group technology application", International Journal of Production Research, Vol. 28, No. 1, pp. 185-198.
43. S.S. Heragu (1988), Machine Layout: An Optimization and Knowledge-based Approach, Unpublished Ph.D. Dissertation, University of Manitoba, Canada.
44. R.D. Holtz (1987), "GT and CAPP cut work-in-process time 80%: Part I and Part II", Assembly Engineer, Vol. 21, No. 6, pp. 24-27, and Vol. 21, No. 7, pp.16-19.
45. A. Houtzeel and C.S. Brown (1984), "A management overview of group technology" in N.L. Hyer and R.E. King (Ed.), Group Technology at Work, Society of Manufacturing Engineers, Michigan, pp. 3-16.
46. N.L. Hyer (Ed.) (1984), Group Technology at Work, Society of Manufacturing Engineers, Michigan.
47. N.L. Hyer and U. Wemmerlov (1989), "Group technology in the US manufacturing industry: A survey of current practices", International Journal of Production Research, Vol. 27, No. 8, pp. 1287-1304.

48. M. Iri (1968), "On the synthesis of the loop cut set matrices and the related problem", in K. Kondo (Ed.), RAAG Memoirs, Vol. 4, pp. 376-410.
49. J.R. King (1980), "Machine-component group formulation in production flow analysis: An approach using a rank order clustering algorithm", International Journal of Production Research, Vol. 18, No. 2, pp. 213-232.
50. J.R. King and V. Nakornchai (1982), "Machine-component group formation in group technology: Review and extension", International Journal of Production Research, Vol. 20, No. 2, pp. 117-133.
51. T.D. Klastorin (1982), "The p-median problem for cluster analysis: A comparison test using the mixture model approach", Management Science, Vol. 31, No. 1, pp. 1134-1146.
52. D.O. Knight and M.L. Wall (1989), "Using group technology for improving communication and coordination among teams of workers in manufacturing cells", Industrial Engineering, January, pp. 28-34.
53. C.S. Kumar and M.P. Chandrasekharan (1990), "Grouping efficiency: A quantitative criterion for goodness of block diagonal forms to binary matrices in group technology", International Journal of Production Research, Vol. 28, No. 2, pp. 233-243.
54. K.R. Kumar and A. Vanneli (1987), "Strategic subcontracting for efficient disaggregated manufacturing", International Journal of Production Research, Vol. 25, No. 12, pp. 1715-1728.
55. A. Kusiak (Ed.) (1986a), Modelling and Design of Flexible Manufacturing Systems, Elsevier.
56. A. Kusiak (Ed.) (1986b), Flexible Manufacturing Systems: Methods and Studies, North Holland.
57. A. Kusiak (1986c), "Design and management of computer integrated manufacturing systems", in Proceedings of the 1986 Fall IIE Conference, Dec., Boston, MA.
58. A. Kusiak (Ed.) (1987), Modern Production Management Systems, North Holland.
59. A. Kusiak (1987a), "Artificial intelligence and operation research in flexible manufacturing systems", Information Systems and Operational Research (INFOR), Vol. 25, No. 1, pp. 2-12.

60. A. Kusiak (1987b), "Design of expert systems for scheduling automated manufacturing systems", Industrial Engineering, Vol. 19, No. 7, pp. 42-46.
61. A. Kusiak (1987c), "An expert system for group technology", Industrial Engineering, Vol 19, No. 10., pp.56-61.
62. A. Kusiak (1987d), "The generalized group technology concept", International Journal of Production Research, Vol 25, No. 4, pp. 561-569.
63. A. Kusiak (Ed) (1988a), Expert Systems: Strategies and Solutions in Manufacturing Design and Planning, Society of Manufacturing Engineer.
64. A. Kusiak (1988b), "EXGT-S: A knowledge based system for group technology", International Journal of Production Research, Vol. 26, No.5, pp. 887-904.
65. A. Kusiak (Ed.) (1989), Knowledge Based Systems in Manufacturing, Taylor and Francis.
66. A. Kusiak (Ed.) (1990), Intelligent Manufacturing Systems, Prentice Hall.
67. A. Kusiak and W.S. Chow (1987a), "An algorithm for cluster identification", IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-17, No. 4, pp. 696-699.
68. A. Kusiak and W.S. Chow (1987b), "Efficient solving of the group technology problem", Journal of Manufacturing Systems, Vol. 6, No. 2, pp. 117-124.
69. A. Kusiak and W.S. Chow (1988), "Decomposition of Manufacturing Systems", IEEE Journal of Robotics and Automation, Vol. 4, No. 5, Oct., pp. 457-471.
70. A. Kusiak, A. Vannelli and K.R. Kumar (1986), "Clustering analysis: Models and algorithms", Control and Cybernetics, Vol. 15, No. 2, pp. 139-154.
71. R.S. Lashkari, S.P. Dutta, and G. Nadoli (1987), "Part family formation in flexible manufacturing systems - An integer programming approach", in A. Kusiak (Ed.), Modern Production Management Systems, North Holland, pp. 627-635.
72. E.L. Lawler, J.K. Lenstra, A.H.G.R. Kan and D.B. Shmoy (Eds) (1985), The Travelling Salesman Problem: A Guided Tour of Combination Optimization, Wiley, New York.
73. J.L. Lee, W.G. Vogt, and M.H. Mickle (1982), "Calculation of shortest paths y optimal decomposition", IEEE Transaction on Systems, Man and Cybernetics,

- Vol. SMC-12, pp. 410-415.
74. R.C.T. Lee (1981), "Clustering analysis and its application", in J.T. Tou (Ed.), Advances in Information Systems Science, Plenum, New York.
  75. R. Logendran (1990), "A workload based model for minimizing total intercell and intracell moves in cellular manufacturing", International Journal of Production Research, Vol. 28, No. 5, pp. 913-925.
  76. J. McAuley (1972), "Machine grouping for efficient production", Production Engineer, Feb., pp. 53-57.
  77. W.T. McCormick, P.J. Schweitzer, and T.W. White (1972), "Problem decomposition and data reorganization by cluster technique", Operations Research, Vol. 20, No. 5, pp. 993-1009.
  78. C. Mosier and L. Taube (1985), "The facets of group technology and their impacts on implementation - A-state-of-art survey", International Journal of Management Science, Vol. 13, No. 5, pp. 381-391.
  79. J.M. Mulvey and H.P. Crowder (1979), "Clustering analysis: An application of lagrangian relaxation", Management Science, Vol. 25, No. 4, pp. 329-340.
  80. I.M. Neale (1990), "Modelling expertise for KBS development", Journal of Operational Research Society, Vol. 41, No. 5, pp. 447-458.
  81. H. Opitz and H.P. Wiendahl (1971), "Group technology and manufacturing system for small and medium quantity production", International Journal of Production Research, Vol. 9, No. 1, pp. 181-203.
  82. D.S. Prerau (1990), Developing and Managing Expert Systems: Proven Techniques for Business and Industry, Addison-Wesley Publishing Company, New York.
  83. D. Rajamani, N. Singh and Y.P. Aneja (1990), "Integrated design of cellular manufacturing systems in the presence of alternative process plans", International Journal of Production Research, Vol. 28, No. 8, pp. 1541-1554.
  84. G.M. Ranson (1972), Group Technology: A Foundation for Better Company Operation, McGill-Hill, New York.
  85. P.T. Rayson (1985), "A review of expert systems principles and their role in manufacturing systems", Robotica, Vol. 3, No. 4, pp. 279-287.



86. J.W. Rozendblit, J. Hu, T.G. Kim and B.P. Zeigler (1990), "Knowledge-based design and simulation environment (KBDSE): Foundation concepts and implementation", Journal of Operational Research Society, Vol. 41, No. 6, pp. 475-489.
87. H. Seifoddini (1984), Cost Based Machine-Component Grouping model: In Group Technology, Unpublished Ph.D. Dissertation, Oklahoma State University, U.S.A..
88. H. Seifoddini (1986), "Improper machine assignment in machine-component grouping in grouping technology", IIE 1986 Fall Industrial Engineering Conference Proceedings, pp. 406-409.
89. H. Seifoddini (1989), "A note on the similarity coefficient method and the problem of improper machine assignment in GT applications", International Journal of Production Research, Vol. 27, No. 7, pp.1161-1165.
90. H. Seifoddini (1989a), "Single linkage versus average linkage clustering in machine cells formation applications", Computers and Industrial Engineering, Vol. 16, No. 3, pp. 419-426.
91. H. Seifoddini and P.M. Wolfe (1986), "Application of the similarity coefficient method in group technology", IIE transactions, Sep., pp. 271-277.
92. H. Seifoddini and P.M. Wolfe (1987), "Selection of a threshold value based on material handling cost in machine-component grouping", IIE Transactions, Vol. 19, No. 3, pp. 266-270.
93. J.N. Senn (1990), Information Systems in Management, 4th Edition, Wadsworth Publishing Co, Belmont, California.
94. S.M. Shafer and J.R. Merdith (1990), "A comparison of selected manufacturing cell formation techniques", International Journal of Production Research, Vol. 28, No. 4, 661-673.
95. A. Shtub (1989), "Modelling group technology cell formation as a generalized assignment problem", International Journal of Production Research, Vol. 27, pp. 775-782.
96. J.L. Slagle, C.L. Chang, and S.R. Heller (1975), "A clustering and data recognition algorithm", IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-5, pp. 125-128.
97. R.R. Sokel and P.H.A. Sneath (1968), Principles of Numerical Taxonomy, Freeman and Co..

98. G. Srinivasan, T.T. Narendran and B. Mahadevan (1990), "An assignment model for the part-families problem in group technology", International Journal of Production Research, Vol. 28, No. 1, pp. 145-152.
99. A. Stam and M. Kuula (1991), "Selecting a flexible manufacturing system using multiple criteria analysis", International Journal of Production Research, Vol. 29, No. 4, pp. 803-820.
100. S.M. Taboun, S. Sankaran and S. Bhole (1991), "Comparison and evaluation of similarity measures in group technology", Computers and Industrial Engineering, Vol. 20, No. 3, pp. 343-353.
101. M.T. Tabucanon and R. Ojha (1987), "ICMA - A heuristic approach for intercell flow reduction in cellular manufacturing systems", Material Flow, Vol. 4, pp. 189-197.
102. J. Talavage and R.G. Hannam (1988), Flexible manufacturing Systems in Practice: Applications, Design and Simulation, Marcel Dekker, Inc., New York.
103. S.H. Teng and J.T. Black (1989), "An expert system for manufacturing cell control", Computers and Industrial Engineering, Vol. 17, No. 1-4, pp. 1039-1056.
104. A. Vannelli and K.R. Kumar (1986), "A method for finding minimal bottleneck cells for grouping part-machine families", International Journal of Production Research, Vol. 24, No. 2, pp. 387-400.
105. J.A. Ventura, F.F. Chen and C. Wu (1990), "Grouping parts and tools in flexible manufacturing systems production planning", International Journal of Production Research, Vol. 28, No. 6, pp. 1039-1056.
106. T. Vohra, D. Chen, J.C. Chang and H. Chen (1990), "A network approach to cell formation in cellular manufacturing", International Journal of Production Research, Vol. 28, No. 11, pp. 2075-2084.
107. W.J. Vos (1979), "Group technology, what can it do for you?", in Vth International Conference on Production Research, August 12-16, Amsterdam, The Netherlands.
108. P.H. Waghodekar and S. Sahu (1983), "Group technology: A research bibliography", OPSEARCH, Vol. 20, No. 4, pp. 225-249.
109. J.C. Wei and G.M. Kern (1989), "Commonality analysis: A linear cell clustering algorithm for group technology", International Journal of Production Research,

Vol. 27, No. 12, pp. 2053-2063.

110. U. Wemmerlov and N.L. Hyer (1986), "Procedures for the part family/machine group identification problem in cellular manufacturing", Journal of Operations Management, Vol. 6, No. 2, pp.125-147.

## APPENDIX A

### PRODUCTION RULES FOR THE CEMIS

#### CLASS I RULES

##### RULE 1.

IF maximum number of machines in each cell is applied  
THEN get the input data = C

##### RULE 2.

IF value C is not a numeric data  
THEN print error message

##### RULE 3.

IF value C is a numeric data  
AND not equal to 0  
THEN set MAXMACH = C  
ELSE print error message

#### CLASS II RULES

##### RULE 4.

IF maximum number of machine cells is applied  
THEN get input value = D

##### RULE 5.

IF value D is not a numeric data  
THEN print error message

RULE 6.

IF value D is a numeric value  
AND not equal to 0  
THEN set MAXMCELL = D  
ELSE print error message

CLASS III RULESRULE 7.

IF technological constraint of machines that need to be grouped  
together is applied  
THEN get input value = K

RULE 8.

IF value K is not a numeric value  
THEN print error message

RULE 9.

IF value K is a numeric value  
THEN collect K groups of arrays of data

RULE 10.

IF total number of arrays is less than K groups  
THEN print error message

RULE 11.

IF any array of the K groups contains less than two machines  
THEN print error message

RULE 12.

IF technological constraint of machines that cannot be grouped  
together is applied  
THEN get input value = U

RULE 13.

IF value U is not a numeric value  
THEN print error message

RULE 14.

IF value U is a numeric value  
THEN collect U groups of arrays of data

RULE 15.

IF total number of arrays is less than U groups  
THEN print error message

RULE 16.

IF any array of the U groups contains less than two machines  
THEN print error message

RULE 17.

IF value K=0  
THEN there is no machine needed to be grouped together

RULE 18.

IF value K=0  
AND the next line consists of an array entry  
THEN print error message

RULE 19.

IF value U=0  
THEN there is no machine cannot be grouped together

RULE 20.

IF value U=0  
AND the next line consists of an array entry  
THEN print error message

CLASS IV RULESRULE 21.

IF parts that require special care of MHS  
THEN get input value = H

RULE 22.

IF value H is not a numeric data  
THEN print error message

RULE 23.

IF value H is a numeric data  
THEN collect H groups of arrays of data

RULE 24.

IF total number of arrays is less than H groups  
THEN print error message

RULE 25.

IF each array contains no part number  
THEN print error message

RULE 26.

IF any MHS is not coded in any code of A, R, G  
THEN print error message

RULE 27.

IF no code of any of A, R, G at the end of each array  
THEN print error message

RULE 28.

IF value H=0  
THEN there is no special material handling system is requested

RULE 29.

IF value  $H=0$   
AND there is any new entry value in the next line  
THEN print error message

CLASS V RULESRULE 30.

IF value of M and N is not numeric data  
THEN print error message

RULE 31.

IF the second line consists not a pair of values M and N  
THEN print error message

RULE 32.

IF entry values of  $a_{ij}$  are not either 1s or 0s  
THEN print error message

RULE 33.

IF  $a_{ij}$  has less than M number of rows of data  
THEN print error message

RULE 34.

IF each row  $a_{ij}$  consists of less than N column  
THEN print error message



CLASS VI RULESRULE 35.

IF machines need to be grouped together  
 THEN convert them into a new machine unit  
 AND replace the new data in the  $a_{ij}$

RULE 36.

IF a group of machines cannot be physically grouped together  
 THEN keep them into a ungrouped machine list UNMACHINE

RULE 37.

IF a pair of machines is not listed in UNMACHINE  
 THEN apply Theorem 2 to compute all  $c_{ij}$  scores

RULE 38.

IF  $c_{ij}$  scores are newly computed  
 THEN sort  $c_{ij}$  scores in descending order

RULE 39.

IF  $c_{ij}$  scores ties in the sorting procedure  
 THEN pairs of machines are to be ranked in a random order within the respective groups

RULE 40.

IF value of  $c_{ij}$  is the highest score  
 AND machines  $M_i$  and  $M_j$  are not in UNMACHINE  
 AND including them into a cell do not exceed MAXMACH  
 THEN consider machines  $M_i$  and  $M_j$  to be grouped together  
 ELSE ignore it and search for next highest  $c_{ij}$  scores

RULE 41.

IF a pair of machines is considered to be grouped together  
 THEN check if any pair of machines consists of at least a regular machine  
 AND prepare the latter pair which has the highest  $c_{ij}$  to be the most preference pair to be grouped together

RULE 42.

IF machines have been newly grouped together  
THEN convert machines into a new machine units  
AND compute its new  $c_{ij}$  score and replace it in scores table

RULE 43.

IF (remaining regular machines + new machine units) = MAXCELL  
THEN form the remaining regular machines as individual cell  
AND print CM solution

RULE 44.

IF remaining machines are belonging to UNMACHINE  
AND grouping process is not completed  
THEN print error message

RULE 45.

IF all regular machines have been grouped  
THEN start grouping all new machine units

RULE 46.

IF a pair of machines is the most preference and is satisfy with all  
resource constraints  
THEN set the pair of machines as the final pair of machines to be  
grouped together

RULE 47.

IF each machine cell contains parts require special care of MHS that  
code as A  
THEN print related parts requires to be handled by Automated Guided  
Vehicles

RULE 48.

IF each machine cell contains parts require special care of MHS that  
code as R  
THEN print related parts requires to be handled by robot arms

RULE 49.

IF each machine cell contains parts require special care of MHS that  
code as G  
THEN print related parts requires to be handled by gantry slides

RULE 50.

IF printing the parts related to the use of material handling systems  
THEN also identify the involved machine cell  
AND identify if it is a bottleneck parts

RULE 51.

IF bottleneck parts are to be handled by robot arms  
THEN inform users of infeasibility because of distance constraints

RULE 52.

IF parts that require to be processed by more than one machine cells  
THEN print related parts as bottleneck parts

RULE 53.

IF parts are bottleneck parts  
THEN print machine cells that were being involved

RULE 54.

IF only the mutual separable solution is interested  
THEN select CIA model

RULE 55.

IF the partial separable cluster solution is interested  
THEN select the MGA model

RULE 56.

IF the consideration of resources constraints is required  
THEN select the MGA model

RULE 57.

IF the CIA model is selected  
AND also consider resource constraints  
THEN print error message

RULE 58.

IF printing the final CM report  
THEN parts that are only involved in one cell is known as Excluded parts  
AND others are defined as bottleneck parts

RULE 59.

IF computing the percentage of bottleneck parts in the final CM report  
THEN percentage is computed as the ratio of total number units of bottleneck parts divided by the total number of parts involved in that cell

RULE 60.

IF computing the percentage of parts involved in a cluster in the final CM report  
THEN percentage is computed as the ratio of total number of parts in that cell divided by the value N

RULE 61.

IF computing the percentage of intercellular movement of part analysis  
THEN percentage is computed as total number of bottleneck parts for all cells divided by the value N

RULE 62.

IF printing the movement of parts in the final CM report  
THEN bottleneck parts are to be printed together with its associated machine cells

RULE 63.

IF file input format is selected by users  
THEN request an ASCII coded file name

RULE 64.

IF code A = 1  
THEN the CIA model is applied

RULE 65.

IF code A = 2  
THEN the MGA model is used

RULE 66.

IF code A is neither a value of 1 or 2  
THEN print error message

RULE 67.

IF manual input format is selected by users  
THEN activate the manual format file

RULE 68.

IF the PSCP is selected as the manual input format  
THEN request if users wish to consider the resource constraints

RULE 69.

IF computing the percentage of machines in each cell  
THEN percentage is computed as the total number of machines in that cell  
divided by the value M