Chapter 12
Designing Cellular Manufacturing for Next Generation Production Systems

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Abstract Designing cellular manufacturing systems is still under intensive study and has attained significant attention from academicians and practitioners. The major problem in designing cellular manufacturing systems is cell formation. Relevant design objectives, practical issues, and constraints should be taken into consideration. Although there are several cell formation techniques, more work is needed in the areas of the main design objectives, practical issues, and constraints. Over the last three decades, most of the approaches used in cell formation have been based on the machine–part incidence matrix alone and focus only on one or two practical issues sometimes including design objectives and constraints. The practical issues are processing time, alternative routings (process plan), part demand, production volume rate, machine capacity (reliability), and machine capability (flexibility). Hence, solving the cell formation problem is not a simple task, and it must be done concurrently and incrementally. Until now, there has been no practical cell formation approach. This void will lead to the proposal of a new cell formation strategy, which consists of five main phases to improve the quality of solution. In the first phase, a heuristic approach is used to group machines into machine cells based on the similarity coefficient between machines. The second phase uses another heuristic approach to form parts into part families while selecting the best process plans. Initial manufacturing cells are formed in the third phase. In the fourth phase, manufacturing cells are evaluated by measuring the manufacturing cells' performance. Revising the initial manufacturing cells will be included in the fifth phase by considering trade-offs between minimizing the intercellular moves and capital investments, maximizing the efficiency of clustering, and maximizing

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A.K. Kamrani, E.S. Abouel Nasr (eds.) *Collaborative Engineering: Theory and Practice,*
doi: 10.2007/ 978-0-387-47321-5, © Springer Science + Business Media, LLC 2008

machine utilization to evaluate the optimal cell design. The proposed strategy was implemented and demonstrated through a numerical example.

12.1 Introduction

Because of an increasingly competitive global market, the need for shorter product life cycles and time to market, and diverse customers, changes in manufacturing systems have been tried to improve the flexibility and productivity of production and manufacturing systems. There are three different types of manufacturing systems: flow shop (mass production) system, batch production system, and job shop production system. The job shop production system is characterized by high flexibility and low production volume and uses general-purpose machines to accommodate fluctuations in part demand and production volume. The flow shop system has less flexibility but more production volume.

Because of the limitations of job shop and flow shop systems, manufacturing systems are often required to be reconfigured to respond to changes in product design, introduction of a new product, and change in product demand and volume. As a result, cellular manufacturing systems (CMS) using group technology (GT) have emerged as promising alternative manufacturing systems.

CMS design is an important manufacturing concept involving the application of GT, and it can be used to divide a manufacturing facility into several groups of manufacturing cells. This approach means that similar parts are grouped into part families and associated machines into machine cells, and that one or more part families can be processed within a single machine cell. The creation of manufacturing cells allows the decomposition of a large manufacturing system into a set of smaller and more manageable subsystems. There are several reasons for establishing CMS. These reasons include reduced work-in-process (WIP) inventories, reduced lead times, reduced lot sizes, reduced interprocess handling costs, better overall control of operations, improved efficiency and flexibility, reduced space, reduced manufacturing costs, improved product design and quality, and reduced setup times. The main disadvantages in cellular manufacturing include high capital investment (machine installation and re-layout), lower utilization, and lack of flexibility in handling demand changes, product mix changes, and product flexibility.

General descriptions of GT and CMS, cell formation techniques, and an extensive review of the various aspects adopted for CMS are discussed carefully in the literature review [21–24, 38, 40, 41, 47, 48, 50, 62, 68, 75, 78, 84, 88, 99, 103, 106, 117, 122–126].

The remainder of this chapter is organized as follows. Section 12.2 reviews the research-related strategy, elements of cell formation, practical issues, and similarity coefficients between machines and between parts. Section 12.3 presents the proposed strategy. A numerical example will be explained in Sect. 12.4. Section 12.5 presents the results and discussion. The conclusions and recommendations for further work are given in Sect. 12.6.

12.2 Literature Review

This section presents a review of research work related to the cell formation approaches proposed in previous works and identifying the strategies which were used. The elements of the cell formation process, including important design objectives, practical issues, and similarity coefficients, are also discussed.

12.2.1 Strategy

The objective of cell formation is to create mutually separable manufacturing cells so that the cells can operate independently with minimum interaction. Cell formation is multiobjective in nature and seeks to satisfy sometimes conflicting goals.

12.2.1.1 Cell Formation Strategy

There are three main solution strategies in cell formation. The first one is a part family grouping strategy; the second one is a machine cell grouping strategy; and the last one is a simultaneous machine–part grouping strategy (Fig. 12.1). The first and second strategies can be considered as sequential strategies, and the third strategy is a simultaneous strategy. The selection of a strategy depends on the designer's philosophy and size of the problem (i.e., number of machines and parts). This chapter concentrates on grouping machines and parts simultaneously.

12.2.1.2 Cell Formation Techniques

In the design of CMS, most cell formation techniques can be separated into two main techniques: mathematical programming and heuristics approaches (Fig. 12.2).

Most cell formation techniques may be considered heuristic techniques, except mathematical programming. *Mathematical programming techniques* can be classified into four categories based on the type of formation, Linear Programming (LP), Integer Programming (IP), Goal Programming (GP), and Dynamic Programming (DP). They are proposed by Vakharia et al. [118], Askin et al. [7], Dahel and

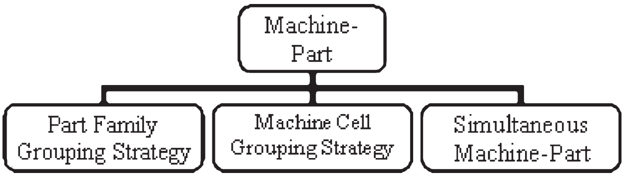


Fig. 12.1 Strategies in cell formation

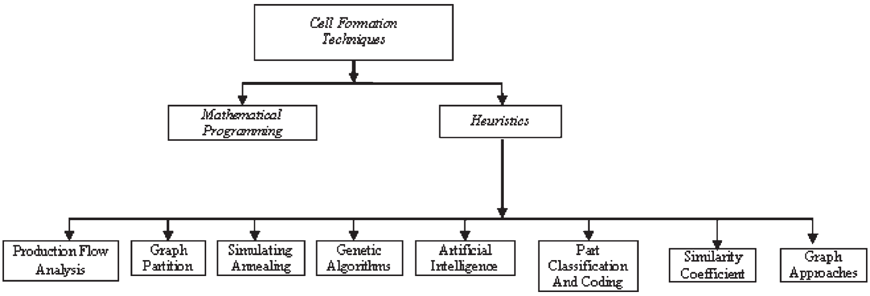


Fig. 12.2 Cell formation techniques

Smith [25], Mungwattana and Shewchuk [71], Abdelmola et al. [2], Sofianopoulou [108], Rajamani et al. [79, 80], Singh et al. [107], Chen [18], Boctor [9], Lozano et al. [56], Akturk and Wilson [3], and Seifoddini [93]. *Heuristic techniques* can be defined as decision procedures or rules that guide the search process toward solving a problem. They are based on the actions selected by the user. The heuristic does not guarantee an optimal solution, but it can generate a good feasible solution in an acceptable time [1]. This means that good heuristic rules lead to good solutions, and bad ones lead to bad solutions [1]. Heuristic techniques can be divided into seven main types: production flow analysis [12], graph partition [67, 70, 132], simulating annealing [8], genetic algorithms [45, 46, 63–65], artificial intelligence [61, 113, 131, 135], part classification and coding [47], and similarity coefficients [72, 97, 98, 121, 129, 130]. Hence, heuristic techniques use some characteristics from other methods to form the part families and machine cells.

In designing CMS, many production and flexibility issues should be included. These issues are operating time, machine capacity (reliability), annual demand per part, production volume, alternative routing (routing flexibility), and machine flexibility. A few cell formation techniques have been developed to incorporate a few of the production and flexibility issues in designing CMS. In this chapter, the proposed heuristic approach based on the two similarity coefficients between machines and between parts will be used in forming part families and grouping machines into machine cells while identifying the best process plan. Improving or revising the manufacturing cells will be considered to achieve a high degree of independence (i.e., minimize the intercellular moves) and to maximize the machine utilization.

12.2.2 Elements of Cell Formation

Cell formation is not a simple task. Vakharia [117] stated that “cell formation should not only be based on one objective; rather it should be a decision based on several objectives which are usually conflicting and thus need to be prioritized.”

The cell formation process should take into consideration design objectives, relevant production and flexibility issues, and design constraints (Fig. 12.3).

12.2.2.1 Design Objectives

There are many design objectives that must be achieved in cell formation. These objectives are minimization of throughput times, minimization of setup times, minimization of inventories, minimization of intracell and intercell movements of parts (minimization of material handling costs), minimization of machine relocation costs, minimization of machine load variation, minimization of operating costs, minimization of capital investment, maximization of resource (machine and labor) utilization, and maximization of output. Some of these objectives can be conflicting. These objectives, with regard to a cell formation, can be considered individually or combinatorially [38, 47, 88, 99,106].

12.2.2.2 Design Constraints

There are also some constraints that should be considered while forming a cell such as the following: minimum and/or maximum cell size, minimum and/or maximum number of cells, and maximum number of each machine type.

12.2.2.3 Practical Issues

Several relevant production issues can be incorporated in the process of cell formation such as the following: machine setup time and cost, materials handling costs, production volume and annual demand, machine capacity and machine availability, number of operations per part, operations sequence, processing time per part, machine requirement, alternative routings, and cell layout [21–23, 38, 47, 48, 75, 88, 99, 103, 106, 122, 124].

Production Issues

Several production issues should be incorporated in the design of CMS, such as operating (processing) times, machine capacity, and demand of the part.

- *Operating (Processing) Time*

  Processing time is the time required by a machine to perform an operation on a part type. Normally, setup time and run times are included in processing time.

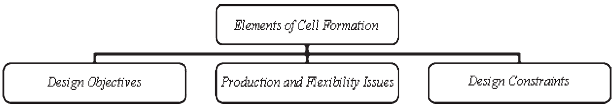


Fig. 12.3 Design cell formation process

The processing time should be provided for every part on corresponding machines in the operation sequence. Processing time is important because it is used to determine resource (machine) capacity requirements. Hence, ignoring the processing times may violate the capacity constraints and thus lead to an infeasible solution [137]. Examples of processing time can be found in several papers [7, 36, 59, 69, 71, 86, 111, 114].

- *Machine Capacity (Reliability)*

  Machine capacity is the amount of time a machine of each type is available for production in each period. When dealing with the maximum possible demand, we need to consider whether the resource capacity is violated or not. In the design of CMS, available capacities of machines need to be sufficient to satisfy the production volume required by parts. Heragu [38] said that machine capacity is more important than the other production factors, and it should be ensured that adequate capacity (in machine hours) is available to process all the parts. Examples of machine capacity are found in papers by Yin and Yasuda [134] and Mungwattana and Shewchuk [71].

- *Demand*

  Demand is the quantity of each part type in the product mix to be produced in each period. The product demand of each part type is expected to vary across the planning horizon. Examples of demand can be found in several papers [4, 7, 71, 86, 119].

Flexibility Issues

In CMS, flexibility can be defined as the ability of the system to adjust its resources to any changes in relevant factors such as product, process, loads, and machine failures [7, 118]. Flexibility could refer to the ability to respond to external disturbances such as volume, mix, and product flexibility, and internal disturbances such as part design and machine flexibility [7, 118]. Although there are at least 50 different terms for various types of manufacturing flexibilities, it is hard to capture the concept [*100*]. There is confusion about the concept of flexibility because of overlapping definitions of different types in different taxonomies in the literature based on the contexts of researchers [33, 54, 116] regarding manufacturing flexibility in general and in CMS to be specific [7, 118]. In discussing flexibility as a management objective, Shewchuk [104], Kumar [32, 35, 51], Gupta et al. [10], Chen and Chung [17], Vakharia et al. [118], and Askin et al. [7] concluded that there was no single measure of flexibility due to its multidimensional definitions and applications. But in practical terms, flexibility has been viewed as a trade-off between efficiency in production and dependability in the marketplace. There exists no rigorous method for identifying the domain of manufacturing flexibility in cellular manufacturing [7, 118].

Flexibility of CMS is currently under intensive study, and the major drawback of most cell formation procedures is the lack of flexibility in designing CMS. Most products (parts) have varying demand and production volume from one period to another, or one or more new products are released to cells every period. The problem gets more complicated when some cells are overutilized, while others are underutilized [111]. This major difficulty occurs when cells stem from unstable machine utilizations due to dynamic and random variations in part demand and/or production volume. The flexibility in a CMS depends on how a machine or group of machines can absorb changes in a given manufacturing environment, changes in demand for products, changes in production volume, changes in costs of operation, changes with the introduction of new parts or products, changes in tooling, and changes in the capacity of machines. Most researchers have dealt with flexibility in general or qualitative terms. Others have attempted to quantify flexibility specifically for manufacturing systems.

Until now, there has been no comprehensive study about flexibility issues in designing CMS. Several types of flexibility issues have been defined by different researchers [87, 100].

- *Machine Flexibility*

  Machine flexibility refers to the capability of machines to perform varying operations without incurring excessive cost from one operation to another. The machine level is fundamental to a manufacturing system, and machine flexibility is a prerequisite for most other flexibilities. Sethi and Sethi [100], Vakharia et al. [118], Askin et al. [7], and Choi and Kim [19] used machine flexibility in cell formation.

- *Routing Flexibility*

  Routing flexibility is the ability of a manufacturing system to produce a product or a part by alternative routes or dynamic assignment of parts to machines with different processing plans. This flexibility will depend on the characteristics of both the product and the equipment. This property is very desirable in situations of equipment breakdown and where uncertainty is prevalent. It has been shown that the flexibility provided by alternative routing creates a very large number of possible routes for each part and is important to consider in forming a configuration of independent cells. Abdelmola [1], Sethi and Sethi [100], Vakharia et al. [118], Askin et al. [7], Albino and Garavelli [6], Dahel and Smith [25, 32, 35], Gupta et al., [71], Seifoddini and Djassemi [95], Sundaram and Doshi [112], Chan [13], Sarker and Xu [89], Wen et al. [127], Ho and Moodie [39], Kannan [49], Albino and Garavelli [5], Drolet et al. [26, 27], Jeon et al. [43–45], Sofianopoulou [108], and Won and Kim [130] proposed routing flexibility in cell formation.

- *Volume Flexibility*

  Volume flexibility of a manufacturing system is its ability to be operated at different overall output levels. This feature will allow the system to deal with volume changes in the current product mix. If the part volume changes, there could be an increase or a decrease in the total number of batches processed in the system. Abdelmola [1], Sethi and Sethi [100], Vakharia et al. [118], Askin et al.

[7], and Shewchuk and Moodie [105] suggested volume flexibility in cell formation. Because of the predominance of routing, machine, and volume flexibilities in the literature review, and because they are the basic components of manufacturing systems, including these characteristics in the design of CMS is very important with the other production issues (operating times, machine capacity, and part demand). In this chapter, the main objectives in the design of CMS is to minimize intercellular movements (minimizing the material handling costs), minimize the number of duplicate machine types, and maximize the machine utilization by incorporating production and flexibility issues, which were explained previously.

12.2.3 Similarity Coefficients

Over the last three decades, many similarity coefficients have been proposed, but a better similarity coefficient between machines and/or parts is still required. Because similarity coefficients can incorporate manufacturing data other than just the binary machine–part incidence matrix, a variety of similarity measures have been defined. The basic idea of CMS design is to take advantage of the similarities in the machines and/or parts. Most clustering algorithms for cell formation rely on the concept of similarity coefficients. This concept is used to quantify the similarity in processing requirements between machines and/or parts, which is then used as the basis for cell formation heuristic methods. The similarity coefficient approaches are a well-known methodology in helping in the design of CMS because they are the most efficient method to group machines and/or parts.

After reviewing 70 articles involving similarity coefficients between machines and between parts [11, 20, 28, 29, 30, 31, 32, 34–37, 39, 42–45, 53, 55, 57, 66, 69, 72, 74, 76, 77, 82, 83, 85, 89, 92–94, 98, 101, 102, 109, 110, 115, 121, 129, 130, 133, 134, 136], one can notice that most similarity coefficients available in the literature on cell formation focus on a single factor and that there are limitations in incorporating various types of production data.

One can also notice that most similarity coefficients, which were used between machines and/or parts, concentrated on data from the machine–part matrix, and few of them took into consideration production data such as production volume, part demand, or processing time. Although a few approaches have been developed to incorporate different factors, there is no comprehensive similarity coefficient between machines and/or parts. The similarity coefficient is flexible in incorporating various types of relevant manufacturing data into the manufacturing cell formation process such as production volume, product demand, process sequence, and machine capacity. It lends itself more easily to computer applications.

Similarity coefficients between parts and/or machines are not absolute, and they still need more attention from researchers. In this chapter, we propose new similarity coefficients between machines and/or parts involving alternative processing routings, processing times, production volumes, annual part demands, machine capacity (reliability), machine flexibility (number of operations done on machine), and maximum number of different operations that can be done on a particular machine.

12.3 The Proposed Cell Formation Strategy

The proposed cell formation strategy will be introduced in five phases. The objective of the first phase is to group machines into machine cells based on the new similarity coefficient between machines. The second phase is used to form parts into part families also based on the new similarity coefficient between parts by identifying the best process plan for each part. The initial formation of manufacturing cells, including machine cells with part families, will be introduced in the third phase. In the fourth phase, the manufacturing cells will be evaluated. In the fifth phase, the initial formation of manufacturing cells will be revised.

Notation

C = number of manufacturing cells.
C_i = capacity of machine i.
C_j = capacity of machine j.
D_k = part demand of part type k per period.
D_p = part demand of part type p per period.
D_q = part demand of part type q per period.
GCI = grouping capability index.
K = subscript of parts ($k = 1, \ldots, n$).
l = subscript of machines ($l = 1, \ldots m$).
m = number of machines in the machine–part incidence matrix.
m_c = total number of machines in the cth cell.
MU = machine utilization.
$m_{\max}$ = maximum number of machines into machine cell.
$\mathrm{m}_{X_{\mathrm{prqul}}}$ = number of machines that both part p and part q visit.
n = number of parts in the machine-part incidence matrix.
$N1$ = total number of 1s in the diagonal blocks of the machine–part incidence matrix.
$N2$ = total number of 1s in the off-diagonal blocks of the machine–part incidence matrix.
$N3$ = total number of 1s in the machine–part incidence matrix.
$N4$ = total number of 0s in the diagonal blocks of the machine–part incidence matrix.
NMC = desired number of machine cells.
NPF = desired number of part families.
n_c = total number of parts in the cth cell.
$n_{\min}$ = minimum number of parts in a part family.
$n_{\mathrm{o_i}}$ = number of operations done on machine i.
$n_{\mathrm{o_j}}$ = number of operations done on machine j.
$N_{\mathrm{o_{imax}}}$ = maximum number of operations available on machine i.
N_{ojmax} = maximum number of operations available on machine j.
$n_{X_{ijkr}}$ = number of parts that can visit both machine i and machine j with R process routings.
q = weighting factor ($0 \leq q \leq 1$) that fixes the relative importance between voids and intercell movements.
r = subscript of alternative routings (r = 1, …, R).
R = number of part routings that can process parts on both machine i and machine j.

$R^{\backslash}$ = number of part routings that can process parts on either machine i or machine j.
S_{ij} = similarity coefficient between machine i and machine j.
$S_{p_{\mathrm{r}}q_{\mathrm{u}}}$ = similarity coefficient between part type p with process plan r and part type q with process plan u.
$t_{ki\mathrm{r}}$ = processing time part k takes on machine i including setup time with process plan r.
$t_{kj\mathrm{r}}$ = processing time part k takes on machine j including setup time with process plan r.
$t_{lp\mathrm{r}}$ = processing time part p takes on machine l with process plan r.
$t_{lq\mathrm{u}}$ = processing time part q takes on machine l with process plan u.
Γ = grouping efficacy.
V_k = production volume rate of part type k per period.
V_p = production volume rate of part type p per period.
V_q = production volume rate of part type q per period.
$X_{ijk\mathrm{r}}$ = 1, if part type k visits both machine i and machine j with process plan r.
$X_{ijk\mathrm{r}}$ = 0, otherwise.
$Y_{ijk\mathrm{r}}$ = 1, if part type k visits either machine i or machine j with process plan r.
$Y_{ijk\mathrm{r}}$ = 0, otherwise.
$X_{p_{\mathrm{r}}q_{\mathrm{u}}l}$ = 1, if part type p with process plan r and part type q with process plan u visit machine l.
$X_{p_{\mathrm{r}}q_{\mathrm{u}}l}$ = 0, otherwise.
$Y_{p_{\mathrm{r}}q_{\mathrm{u}}l}$ = 1, if part type p with process plan r or part type q with process plan r visits machine l.
$Y_{p_{\mathrm{r}}q_{\mathrm{u}}l}$ = 0, otherwise.
η = grouping efficiency.

12.3.1 Phase 1: Grouping Machines into Machine Cells

Machine cells involve the assignment of machines into machine cells based on the new similarity coefficient between two machines, which was described in Section 12.2.3. The procedure to group machines into machine cells will be explained in the following steps:

Step 1: Check the Machine Work Load (MWL) of each machine type capacity ($C_{\_i}$,...,$C_{\_m}$) to produce all parts ($V_{\_1}$,...,$V_{\_n}$) by these machines in the machine–part incidence matrix. The MWL of machine i is based on the production volume rates and processing times of all parts assigned to machine i. The equation for computing the MWL for machine i is shown as follows:

$$\mathrm{MWL}_i = \sum_{k=1}^{n} \left(\sum_{\mathrm{r}_1, \mathrm{r}_2, \mathrm{r}_{\mathrm{r}} \in ki}^{k_{i r_{\mathrm{r}}}} \max \left(t_{ki_{\mathrm{h}}} V_k + t_{ki_{\mathrm{r}2}} V_k + \cdots + t_{ki_{\mathrm{r}_{\mathrm{r}}}} V_k \right) \right) \tag{12.1}$$

Step 2: Compute the similarity coefficient matrix between all machines according to the following equation:

$$s_{ij} = \frac{\sum\limits_{k=1}^{n_{x_{ijkr}}} \sum\limits_{\substack{r \in ki \\ and \\ r \in kj}}^{R} \left[\max\left(\frac{t_{kir}}{c_i} \times \frac{n_{o_i}}{N_{o_{i_{max}}}}, \frac{t_{kir}}{c_j} \times \frac{n_{o_j}}{N_{o_{j\,max}}} \right) X_{ijkr} \right] \frac{V_k}{D_k}}{\sum\limits_{k=1}^{n_{x_{ijkr}}} \sum\limits_{\substack{r \in ki \\ and \\ r \in kj}}^{R} \left[\max\left(\frac{t_{kir}}{c_i} \times \frac{n_{o_i}}{N_{o_{i_{max}}}}, \frac{t_{kir}}{c_j} \times \frac{n_{o_j}}{N_{o_{j\,max}}} \right) X_{ijkr} \right] \frac{V_k}{D_k} + \sum\limits_{k=1+n_{x_{ijkr}}}^{n-n_{x_{ijkr}}} \sum\limits_{\substack{r \in ki \\ or \\ r \in kj}}^{R'} \left[\max\left(\frac{t_{kir}}{c_i} \times \frac{n_{o_i}}{N_{o_{i_{max}}}} \; or \; \frac{t_{kir}}{c_j} \times \frac{n_{o_j}}{N_{o_{j\,max}}} \right) Y_{ijkr} \right] \frac{V_k}{D_k}} \tag{12.2}$$

Step 3: Determine the desired number of machines cells (NMC) by the following equation:

$$\text{NMC} \geq \frac{m}{m_{\max}} \tag{12.3}$$

m = number of machines in machine–part incidence matrix.

$m_{\max}$ = maximum number of machines in the machine cell (at least two machines per cell).

Step 4: Select the largest similarity coefficient between machine i and machine ($j, \ldots m$) from the similarity coefficient matrix in each row directly.

Step 5: Sort the similarity coefficients from the highest to the lowest value and record the values of S_h and the corresponding sets of $m_h\{i,j\}$, where h represents the level of the similarity value.

Step 6: Start forming the first machine cell MC_1 by selecting the highest similarity coefficient valueS_1. Then, this pair of machines $m_1\{i,j\}$will be clustered into the first machine cell.

Step 7: Check the minimum machine cell size constraint (at least two machines per cell).

Step 8: Increase the value of h ($h = 2, \ldots, H$).

Step 9: If $m_h \cap \text{MC}_1 \neq 0$, then, modify MC_1 by the new $\text{MC}_1 = \text{MC}_1 \cup m_h$. Otherwise, form a new machine cell MC_n ($n = 2,\ldots,\text{NMC}$)

Step 10: If any set m_h intersects two cells MC_I and MC_J, then discard the correspondingS_h and go back to Step 8.

Step 11: Check for the maximum number of machines in a machine cell. If the number of machines in this machine cell does not exceed the desired number of machines, then add to this cell. Otherwise, stop adding to this cell and go back to Step 8.

Step 12: If all the machines have not been assigned to machine cells, go back to Step 8. Otherwise, go to Step 13.

Step 13: If the numbe of machine cells formed exceeds the desired number of machine cellsNMC, join two machine cells into one machine cell.

12.3.2 Phase 2: Assigning Parts to Part Families

Parts are assigned to part families based on the similarity coefficient between two parts, which was described in Sect. 12.3.1. The procedure to group parts into part families by selecting the best alternative routings (process plan) will be explained in the following steps:

Step 1: Compute the similarity coefficient matrix between all parts according to the following equation:

$$S_{p_r q_n} = \frac{\sum_{I=1}^{m_{X_{p_r q_n I}}} \max\left[t_{Ip_r}\left(\frac{V_p}{D_p}\right), t_{Iq_u}\left(\frac{V_p}{D_p}\right)\right] X_{p_r q_u I}}{\sum_{I=1}^{m_{X_{p_r q_n I}}}\left[\max\left[t_{Ip_r}\left(\frac{V_p}{D_p}\right), t_{Iq_u}\left(\frac{V_p}{D_p}\right)\right] X_{p_r q_u I}\right] + \sum_{I=m_{X_{p_r q_n I}}+1}^{m-m_{X_{p_r q_n I}}}\left[t_{Ip_r}\left(\frac{V_p}{D_p}\right) or \left(\frac{V_p}{D_p}\right) t_{Iq_u}\right] Y_{p_r q_u I}} \tag{12.4}$$

Step 2: Determine the desired number of part families (NPF) by the following equation:

$$\text{NPF} \le \frac{n}{n_{\min}} \tag{12.5}$$

n = number of parts in machine–part incidence matrix.
$n_{\min}$ = minimum number of parts in the part family (at least one part per family).

Step 3: Select the largest similarity coefficient between part p and part $(q, \ldots, n)$ from the similarity coefficient matrix with each row identifying the associated process plan.

Step 4: Sort similarity coefficients from the highest to the lowest values, record the values of P_h, and record the corresponding sets of $P_h\{p,q\}$, where h represents the level of the similarity coefficient value including the process plan for each part individually.

Step 5: Start grouping the first part family PF1 by selecting the highest similarity coefficient value$P1$. Then, the pair of parts$P1\{p,q\}$will be grouped into the first part family and the associated process plans will also be determined at the same time.

Step 6: Check for the minimum part family size (at least one part per family).

Step 7: Increase the value of h $(h = 2, \ldots, H)$.

Step 8: If $P_h \cap \text{PF1} \neq \phi$ with the same process plan for any part, then modify PF1 byPF1 $= \text{PF1} \cup P_h$. Otherwise, form a new part family PF_n $(n = 2,...,\text{NPF})$.

Step 9: If any set P_h intersects two part families PF_P and PF_Q, then discard the correspondingP_k and go to Step 7.

Step 10: Check to determine if some parts have not been assigned to part families, and if so, go to Step 7. Otherwise, stop.

12.3.3 Phase 3: Initial Formation of Manufacturing Cells

Manufacturing cells are formed by assigning part families to machine cells based on the results obtained from grouping machines into machine cells (Phase 1), and parts into part families (Phase 2), and by rearranging the rows and columns of the incidence matrix.

12.3.4 Phase 4: Performance Evaluation

In this phase, the exceptional parts and exceptional machines will be determined. Machine utilization (MU) and efficiency of clustering [grouping efficiency (η), grouping efficacy (Γ), and grouping capability index (GCI)] will also be determined by the following equations:

Machine Utilization (MU) [*58*]:

$$\mathrm{MU} = \frac{N1}{\sum_{c=1}^{c} m_c n_c} \tag{12.6}$$

Grouping Efficiency (η) [*14–16*, *52, 73, 90, 91*]:

$$\eta = q\left[\frac{N1}{\sum_{c=1}^{c} m_c n_c}\right] + (1-q)\left[1 - \frac{N2}{mn - \sum_{c=1}^{c} m_c n_c}\right] \tag{12.7}$$

Grouping Efficacy (Γ) [*52, 90*]:

$$\Gamma = \frac{1 - N2/N3}{1 + N4/N3} \tag{12.8}$$

Grouping Capability Index (GCI) [*96*]:

$$\mathrm{GCI} = (1 - N2/N3) \tag{12.9}$$

12.3.5 Phase 5: Revise or Improve the Initial Manufacturing Cell Formation

Because the varying nature of production activities and the presence of exceptional elements can cause intercellular movements, the extent of cellularization may be less than 100% [125] and around 60% [60]. The ultimate goal of designing a CMS is to convert the entire manufacturing system into independent manufacturing cells. The most common objectives in cell formation are to minimize intercellular movements and maximize machine utilization. Venkataramanaiah and Krishnaiah [120] said that the entire manufacturing system cannot be converted into manufacturing cells, and typically 40–50% of the total production system may need to be separated as an auxiliary cell in order to accommodate exceptional elements.

On the contrary, forcing exceptional elements to go to manufacturing cells reduces the utilization of machines. Three main objectives must be taken into consideration: minimizing the total intercellular movements (minimizing the material handling costs), maximizing the machine utilization and efficiency of clustering, and minimizing the capital investment costs. Therefore, a trade-off between the conflicting objectives is the major problem of interest in the design of manufacturing cells.

Based on these situations, the revised approach takes into consideration the following steps to obtain the best cell formation:

Step 1: Allocate unassigned machines and parts to manufacturing cells.
Step 2: Evaluate intercellular movements for each part, machine utilization, efficiency of clustering, and machine investment individually.
Step 3: Assign identical machines to the manufacturing cells if necessary.
Step 4: Merge two part families or two machine cells if necessary.

Figure 12.4 shows the entire proposed approach to cell formation.

12.4 A Numerical Example

In order to demonstrate the proposed approach, the following numerical example will illustrate the procedure by including the similarity coefficients and the initial formation of manufacturing cells. Machines will be assigned to machine cells and parts will be grouped into part families. The example is composed of ten types of machines and seven types of parts with different process plans. Table 12.1 presents the incidence matrix between machines and parts. Table 12.2 presents the part information including processing sequences and processing times with each process plan, production volume, and product demand. Information about machines available, including the capacity of the machines, number of operations that can be done on each machine, and maximum number of operations available on each machine, is shown in Table 12.3.

12.4.1 Phase 1: Grouping Machines into Machine Cells

Step 1: Check the capacity of each machine type (availability of time per machine) to produce all parts. For machine one, M1, the capacity = 2400 h. The total consumed time taken from M1 will be calculated as follows:

$$\frac{1}{60}\left[\begin{array}{c}2(2000)+\max\left[3.2(2100)+2.5(2100)\right]+1.1(900)\\+4.83(1800)+2.0(1900)\end{array}\right]=\frac{23{,}784}{60}=396.4\text{h}$$

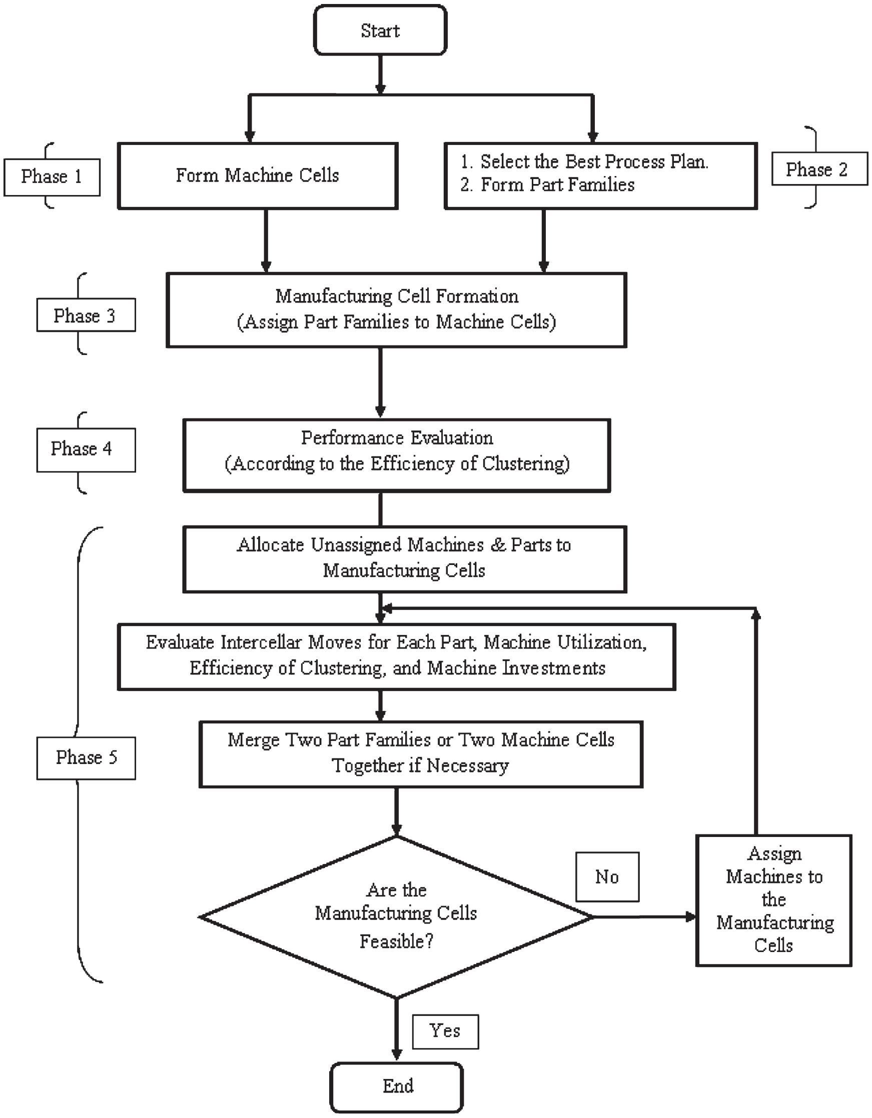


Fig. 12.4 Flow chart of proposed heuristic approach to cell formation

The slack time on machine M1 is 2400 – 396 = 2004 h. So, M1 is okay.
The slack time on machine M2 is 2000 – 412 = 1588 h. So, M2 is okay.
The slack time on machine M3 is 2300 – 439 = 1861 h. So, M3 is okay.
The slack time on machine M4 is 3000 – 509 = 2491 h. So, M4 is okay.
The slack time on machine M5 is 1800 – 144 = 1656 h. So, M5 is okay.
The slack time on machine M6 is 1900 – 453 = 1447 h. So, M6 is okay.
The slack time on machine M7 is 2700 – 229 = 2471 h. So, M7 is okay.

Table 12.1 Incidence matrix between machines and parts

		Parts													
		P1		P2			P3		P4	P5		P6		P7	
		r11	r12	r21	r22	r23	r31	r32	r41	r51	r52	r61	r62	r71	r72
Machines	**M1**	1	0	1	1	0	1	0	0	0	1	0	1	0	0
	M2	0	1	1	0	1	0	0	1	0	1	1	0	0	1
	M3	0	1	0	1	1	0	1	0	1	0	0	0	1	0
	M4	1	0	1	1	0	1	0	1	0	0	1	0	0	1
	M5	1	0	1	0	1	0	1	0	0	0	0	0	0	0
	M6	0	1	1	1	0	0	0	1	1	0	0	0	0	1
	M7	1	0	0	0	1	1	0	0	1	1	1	0	0	0
	M8	0	1	0	0	1	1	1	0	1	0	0	1	1	0
	M9	0	1	0	1	0	1	1	1	0	1	0	1	0	1
	M10	1	0	1	0	1	0	1	0	1	0	1	0	1	0

Table 12.2 Parts information

Part type		Operation sequence	Processing time (minutes)	Production volume	Number of operations per part	Part demand
P1	r11	M1-M4-M5-M7-M10	2.0-3.2-0.9-2.5-0.6	2000	5	1800
	r12	M2-M3-M6-M8-M9	2.7-3.0-4.0-1.35-0.71		5	
P2	r21	M1-M2-M4-M5-M6-M10	3.0-2.5-0.8-1.1-1.7-2.35	2100	6	2000
	r22	M1-M3-M4-M6-M9	2.5-1.8-2.2-3.1-2.11		5	
	r23	M3-M5-M8-M9-M10	2.0-1.2-3.0-1.3-4.4-1.8		6	
P3	r31	M1-M4-M7-M8-M9	1.1-1.8-2.6-1.5-1.35	900	5	650
	r32	M2-M3-M5-M7-M8-M10	3.6-0.6-2.6-0.11-1.93		5	
P4	r41	M2-M4-M6-M9	3.0-3.65-0.5-1.95	2400	4	2000
P5	r51	M3-M6-M7-M8-M10	4.4-2.83-1.1-2.32-2.0	1800	5	1700
	r52	M1-M2-M7-M9	4.83-0.9-0.7-2.28		4	
P6	r61	M2-M4-M7-M10	1.6-2.1-0.9-1.8	1900	4	1700
	r62	M1-M8-M9	2.0-2.3-0.7		3	
P7	r71	M3-M8-M10	2.0-3.1-3.0	2700	3	2100
	r72	M2-M4-M6-M9	0.8-1.9-2.5-4.2		4	

Table 12.3 Machines information

Machine type	Capacity of machine (hours)	Number of operations done on machine (no)	Maximum number of operations available on machine (Nmax)
1	2400	6	6
2	2000	7	7
3	2300	6	6
4	3000	7	10
5	1800	4	4
6	1900	6	9
7	2700	6	8
8	1300	7	10
9	2500	8	9
10	2100	7	10

The slack time on machine M8 is 1300 – 440 = 860 h. So, M8 is okay.
The slack time on machine M9 is 2500 – 475 = 2025 h. So, M9 is okay.
The slack time on machine M10 is 2100 – 383 = 1716 h. So, M10 is okay.
The capacities of all machines are satisfactory at all production volumes for all parts.

Step 2: Compute the similarity coefficient matrix between all machines according to the similarity coefficient equation. The similarity coefficient between machines has been coded in the C programming language and executed on a Pentium IV processor. For example, the similarity coefficient between machine 1 and machine 2 will be explained as the following and the result for similarity coefficients between machines is illustrated in Table 12.4.

$$s_{12}=\frac{\sum_{k=1}^{2}\left[\sum_{\substack{r\in 21\\ r\in 22}}^{1}\max\left(\frac{3.0}{2400}\times\frac{6}{6},\frac{2.5}{2000}\times\frac{7}{7}\right)\frac{2100}{2000}+\sum_{\substack{r\in 51\\ r\in 52}}^{1}\max\left(\frac{4.83}{2400}\times\frac{6}{6},\frac{0.9}{2000}\times\frac{7}{7}\right)\frac{1800}{1700}\right]}{\begin{gathered}\sum_{k=1}^{2}\left[\sum_{\substack{r\in 21\\ r\in 22}}^{1}\max\left(\frac{3.0}{2400}\times\frac{6}{6},\frac{2.5}{2000}\times\frac{7}{7}\right)\frac{2100}{2000}+\sum_{\substack{r\in 51\\ r\in 52}}^{1}\max\left(\frac{4.83}{2400}\times\frac{6}{6},\frac{0.9}{2000}\times\frac{7}{7}\right)\frac{1800}{1700}\right]+\sum_{k=3}^{7-31}\{\sum_{r\in 11}^{1}\left(\frac{2.0}{2400}\times\frac{6}{6}\right)\frac{2100}{1800}+\sum_{r\in 12}^{1}\left(\frac{2.7}{2000}\times\frac{7}{7}\right)\frac{2100}{2000}+\sum_{r\in 21}^{1}\left(\frac{2.5}{2400}\times\frac{6}{6}\right)\frac{2100}{2000}\\ +\sum_{r\in 22}^{1}\left(\frac{2.0}{2000}\times\frac{7}{7}\right)+\sum_{r\in 31}^{1}\left(\frac{1.1}{2400}\times\frac{6}{6}\right)\frac{900}{650}+0+\sum_{r\in 42}^{1}\left(\frac{3.0}{2000}\times\frac{7}{7}\right)\frac{2400}{2000}+0+\sum_{r\in 61}^{1}\left(\frac{2.0}{2400}\times\frac{6}{6}\right)\frac{1900}{1700}+\sum_{r\in 62}^{1}\left(\frac{1.6}{2000}\times\frac{7}{7}\right)\frac{1900}{1700}+0+\sum_{r\in 72}^{1}\left(\frac{0.8}{2000}\times\frac{7}{7}\right)\frac{2700}{2100}\end{gathered}}=0.1856 \qquad (12.10)$$

Step 3: Determine the desired number of machine cells, NMC. The maximum number of machines assigned to cells ranged from 3 to 7 machines [128] and from 5 to 10 machines [81]. Four machines per cell are recommended for easy management and control.

$\mathrm{NMC}\le\frac{10}{4}\ge 2.5$. Therefore, the number of machine cells can start with three cells. Three machine cells will be chosen.

Step 4: Select the largest similarity coefficient between machine *i* and machine (*j*, …, m) from Table 12.4 as follows:

$m_1 - m_7$	0.5072
$m_2 - m_9$	0.5466
$m_3 - m_8$	0.7618
$m_4 - m_7$	0.5097
$m_5 - m_{10}$	0.6015
$m_6 - m_9$	0.6068
$m_7 - m_{10}$	0.4381
$m_8 - m_{10}$	0.6110
$m_9 - m_{10}$	0.0821

Table 12.4 Similarity coefficients between machines

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
M1	0.0000	0.1856	0.0739	0.4613	0.2422	0.2219	0.5072	0.1501	0.4751	0.1996
M2		0.0000	0.1816	0.4218	0.3305	0.5031	0.2510	0.2560	0.5466	0.3057
M3			0.0000	0.0698	0.3928	0.4293	0.2458	0.7618	0.3653	0.6190
M4				0.0000	0.2308	0.3287	0.5097	0.0779	0.3326	0.3339
M5					0.0000	0.0751	0.4640	0.3568	0.0511	0.6015
M6						0.0000	0.1312	0.1909	0.6068	0.1942
M7							0.0000	0.3954	0.2516	0.4381
M8								0.0000	0.3363	0.6110
M9									0.0000	0.0821
M10										0.0000

Step 5: Sort the similarity coefficients from the highest to the lowest value and record the values of S_h and the corresponding sets of $m_h\{ i,j\}$

H	m_h { *i,j\}*	S_h
1	$m_3 - m_8$	0.7618
2	$m_8 - m_{10}$	0.6110
3	$m_6 - m_9$	0.6068
4	$m_5 - m_{-10}$	0.6015
5	$m_2 - m_9$	0.5466
6	$m_4 - m_7$	0.5097
7	$m_1 - m_7$	0.5072
8	$m_7 - m_{10}$	0.4381

Step 6: For S_1 = 0.7618 (between Machine 3 and Machine 8). Then, {MC_1 = **{3, 8}**.

Step 7: Check the minimum machine cell size constraint (at least two machines per cell).

Step 8: S_2 = 0.6110 (between Machine 8 and Machine 10),m_2 = {8, 10}.

Step 9: There is an intersection between Machine 8 and MC_1. The new machine cell is $MC_1 \cup_2 m_2$. Then, the revised machine cell MC_1 = **{3, 8, 10}**. S_3 = 0.6068 (between Machine 6 and Machine 9), m_3 = {6, 9}, and $MC_1 \cap_3 m_3 = 0$. S_3 does not intersect with MC_1. Then, form a new machine cell MC_2 = **{6, 9}**. S_4 = 0.6015 (between Machine 5 and Machine10), m_4 = {5, 10}.

There is an intersection between Machine 10 and MC_1, but there is no intersection with MC_2. The new machine cell is MC_1Um_4. Then, the revised machine cell MC_1 = **{3, 5, 8, 10}**.

Step 10: Check for the maximum number of machines in a machine cell. Machine cell 1 contains four machines. Therefore, no more machines are added to {MC_1. S_5 = 0.5466 (between Machine 2 and Machine 9), m_5 = {2, 9}.There is an intersection between Machine 9 and MC_2, but there is no intersection with MC_1. The new machine cell is {MC_2Um_5. Then, the revised machine cell MC_2 = **{2, 6, 9}**, S_6 = 0.5092 (between Machine 4 and Machine 7), m_6 = {4, 7}, $MC_1 \cap_{m6} = 0$, and $MC_2 \cap_{m6} = 0$. There is no intersection between Machine 4 and Machine 7 with either MC1 orMC_2. Then, form a new machine cell MC_3 = **{4, 7}**, S_7 = 0.5072 (between Machine 1 and Machine 7) m_7 = {1, 7}. There is an intersection between Machine 7 and MC_3, but there is no intersection with {MC_1 or MC_2. The new machine cell is $MC_3 \cup_{m7}$. Then, the revised machine cell MC_3 = **{1, 4, 7}**.

Step 11: All the machines have been assigned to machine cells. Stop.
Machine Cells are as follows:
MC_1 = **{3, 5, 8, and 10}**
MC_2 = **{2, 6, and 9}**
{MC_3 = **{1, 4, and 7}**

12.4.2 Phase 2: Grouping Parts into Part Families

Step 1: Compute the similarity coefficients matrix between all parts with all different process plans. The results of all similarity coefficients between parts are illustrated in Table 12.5.

Step 2: Determine the desired number of part families.

$\text{NPF} \le \frac{7}{1} \le 7$

Then, the number of part families may range from 7 to 1 (7, 6, 5, 4, 3, 2, and 1). Three part families will be chosen.

Step 3: Select the largest similarity coefficients between part *p* and part (*q*, …, *n*) from Table 12.3, including the possible process plans in each level (row) as follows:

P1-P3 (r11-u31)	0.6255
P1-P7 (r12-u72)	0.6383
P2-P4 (r21-u41)	0.5172
P2-P7 (r22-u72)	0.6642
P2-P3 (r23-u32)	0.8100
P3-P5 (r31-u52)	0.6683
P3-P7 (r32-u71)	0.9288
P4-P7 (r41-u72)	1.0000
P5-P6 (r52-u62)	0.6383
P5-P7 (r51-u71)	0.7502
P6-P7 (r61-u72)	0.2667
P6-P7 (r62-u71)	0.3559

Step 4: Sort the similarity coefficients from the highest to the lowest value and record the values of P_h and the corresponding set P_h $\{P_r, q_u\}$

H	P_h *(p,q)*	P_h
1	P4-P7 (r41-u72)	1.0000
2	P3-P7 (r32-u71)	0.9288
3	P2-P3 (r23-u32)	0.8100
4	P5-P7 (r51-u71)	0.7502
5	P3-P5 (r31-u52)	0.6683
6	P2-P7 (r22-u72)	0.6642
7	P1-P7 (r12-u72)	0.6383
8	P5-P6 (r52-u62)	0.6383
9	P1-P3 (r11-u31)	0.6255
10	P2-P4 (r21-u41)	0.5172
11	P6-P7 (r62-u71)	0.3559
12	P6-P7 (r61-u72)	0.2667

Table 12.5 Similarity coeficients between paris

		P1		P2			P3		P4	P5		P6		P7	
		11	12	21	22	23	31	32	41	51	52	61	62	71	72
P1	11	0.0000	0.0000	0.5896	0.3436	0.3623	0.6255	0.1751	0.2477	0.2247	0.4788	0.6248	0.1636	0.1931	0.1789
	12		0.0000	0.3999	0.5143	0.4848	0.1766	0.4612	0.5298	0.6204	0.2634	0.1627	0.2051	0.3770	0.6383
P2	21			0.0000	0.4570	0.3876	0.2658	0.1744	0.5172	0.2539	0.4514	0.5118	0.2048	0.1931	0.4049
	22				0.0000	0.0743	0.4098	0.3201	0.5483	0.0384	0.4341	0.1350	0.3256	0.1235	0.6642
	23					0.0000	0.3652	0.8100	0.1545	0.6074	0.1581	0.3200	0.2654	0.6255	0.0913
P3	31						0.0000	0.2535	0.3689	0.2789	0.6683	0.3908	0.5228	0.2002	0.4066
	32							0.0000	0.1012	0.6685	0.1132	0.1537	0.2901	0.9288	0.2233
P4	41								0.0000	0.1263	0.3500	0.5686	0.1478	0.0000	1.0000
P5	51									0.0000	0.0532	0.1872	0.1476	0.7502	0.1345
	52										0.0000	0.1903	0.6383	0.0000	0.3556
P6	61											0.0000	0.0000	0.2559	0.2667
	62												0.0000	0.3559	0.3196
P7	71													0.0000	0.0000
	72														0.0000

Step 5: P_1 = 1.000 (between part 4 and part 7 with r41 and u72). Then, group the first part family PF1 **= {4, 7}**, with process plan 1 for part 4 and process plan 2 for part 7.

Step 6: Check the number of parts in the first part family after grouping the first part family.

Step 7: P_2 = 0.9288 (between part 3 and part 7 with r32 and u71). Then, P_2 (3,7) = { 3,7}.

Step 8: Part 7 was already assigned to PF1 with process plan 2, and $P_2 \cap PF1 = 0$ So, it is difficult to group part 3 with PF1.

Step 9: There is no intersection with PF1. So, we discard P_2, and go back to Step 7. P_3 = 0.8100 (between part 2 and part 3 with r23 and u32), P_3 (2,3) = {2, 3}. There is no intersection between $PF1 \cap P_3$. Then, form a new part family PF2 = **{2, 3**} with process plan 3 for part 2 and process plan 2 for part 3.

Step 10: Check if all parts have been assigned to part families. If not, go back to Step 7. P_4 = 0.7502 (between part 5 and part 7 with r51 and u71). P_4 (5,7) = { 5,7} Part 7 was assigned to {PF1}} with process plan 2, and there is no intersection with {PF1}} and {PF2}}. So, we discard P_4, and go back to Step 7. P_5 = 0.6683 (between part 3 and part 5 with r31 and u52). P_5 (3,5) = {3,5} Part 3 was assigned to {PF2}} with process plan 2, and there is no intersection with PF2. So, we discard P_5. P_6 = 0.6642 (between part 2 and part 7 with r22 and u72). P_6 (2,7) = {2,7} Part 2 and part 7 were assigned to PF2 and PF1, respectively, with different process plans. There is no intersection with PF1 and PF2. So, we discard P_6. P_7 = 0.6383 (between part 1 and part 7 with r12 and u72). P_7 (1,7) = {1,7} Part 7 was assigned toPF1 with process plan 2, and $P_7 \cap PF1 \neq 0$. Then, the new PF1 = **{1, 4, 7}**, with process plan 2 for part 1. Check if all parts have been assigned to part families. If not, go back to Step 7. P_8 = 0.6383 (between part 5 and part 6 with r52 and u62). P_8 (5,6) = {5, 6} There is no intersection between $PF1 \cap P_8$ and $PF2 \cap P_8$. Then, form a new part family PF3 = **{5, 6**}, with process plan 2 for parts 5 and 6. Check if all parts have been assigned to part families. If so, stop.

The best process plans are as follows:

Part Number	Process Plan
1	2

12.4.3 Phase 3: Initial Formation of Manufacturing Cells

Forming manufacturing cells by assigning part families to machine cells is based on the results obtained from grouping machines into machine cells and parts into part families (PF). This grouping will be done by rearranging the rows and the columns of the incidence matrix. First, arrange the part families, and then, rearrange the machine cells. Figures 12.5 and 12.6 show these formations.

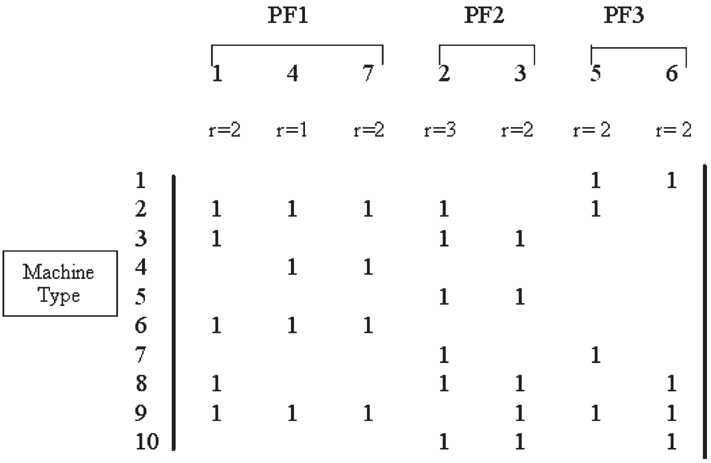
The manufacturing cells are as follows:

Manufacturing Cell 1 consists of PF1 = {1, 4, 7) and MC1 = {2, 6, 9}

Manufacturing Cell 2 consists of PF2 = {2, 3) and MC2 = {3, 5, 8, 10}

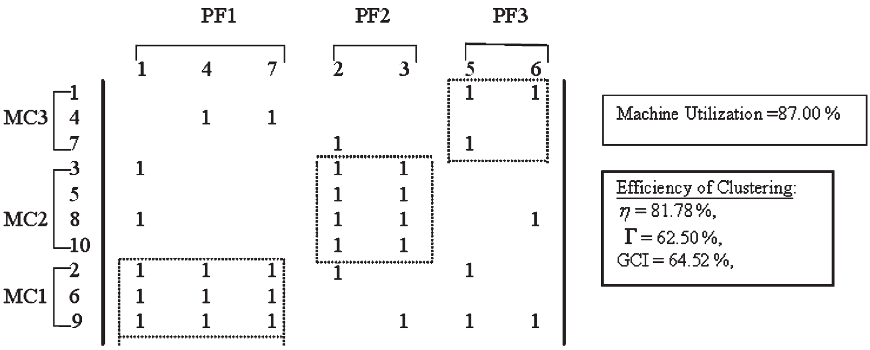
Manufacturing Cell 3 consists of PF3 = {5, 6) and MC3 = {1, 4, 7}

Notice in Fig. 12.6 that there are exceptional elements (parts) and bottleneck machines. Some parts need to be processed in other machine cells in addition to their machine cells. For example, part 1 needs to go to machine cell 2; parts 4 and 7 need to go to machine cell 3; and parts 3 and 5 need to go to machine cell 1. Also, part 2 needs to go to machine cell 1 and machine cell 3, and part 6 needs to go to machine cell 1 and machine cell 2 to complete their operations.



	PF1			PF2		PF3	
	1	4	7	2	3	5	6
	r=2	r=1	r=2	r=3	r=2	r= 2	r= 2
1						1	1
2	1	1	1	1		1	
3	1			1	1		
4		1	1				
5				1	1		
6	1	1	1				
7				1		1	
8	1			1	1		1
9	1	1	1		1	1	1
10				1	1		1

Fig. 12.5 Part families' arrangement



		PF1			PF2		PF3	
		1	4	7	2	3	5	6
MC3	1						1	1
	4		1	1				
	7				1		1	
MC2	3	1			1	1		
	5				1	1		
	8	1			1	1		1
	10				1	1		
MC1	2	1	1	1	1		1	
	6	1	1	1				
	9	1	1	1		1	1	1

Machine Utilization =87.00 %

Efficiency of Clustering:
$\eta = 81.78\,\%$,
$\Gamma = 62.50\,\%$,
GCI = 64.52 %,

Fig. 12.6 Initial formation of manufacturing cells

12.4.4 Phase 4: Performance Evaluation

The values of machine utilization (MU) and efficiency of clustering [grouping efficiency (η), grouping efficacy (Γ), and grouping capability index (GCI)] are as follows:

MU = 87.00%, η = 81.78%, Γ= 62.50%, and GCI = 64.52%.

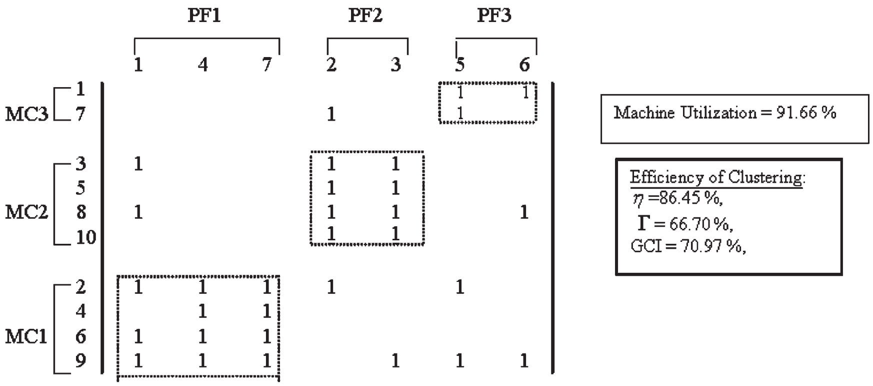
Although there are seven exceptional parts and six bottleneck machines, the machine utilization is equal to 87.00% and grouping efficiency is equal to 81.78%. These results indicate that the system needs some duplicate machine types to minimize or eliminate intercellular movements.

12.4.5 Phase 5: Revise or Improve the Initial Manufacturing Cell Formation

In order to improve the system and solve these problems, there are many procedures that can be taken into consideration:

Step 1: Allocate unassigned machines and/or parts to a manufacturing cell. Machine 4 is assigned to manufacturing cell 3, but there are no parts in part family 3 (PF3) that needs to go to machine 4. Therefore, machine 4 can be assigned to manufacturing cell 1 which has to process parts 4 and 7. Then, the new manufacturing cells without any additional machines will be shown in Fig. 12.7.

Step 2: Evaluate intercellular moves for each part, machine utilization, and machine investment individually. From Fig. 12.7, the machine utilization is equal to 91.66%, and grouping efficiency is equal to 86.45% with five exceptional parts (parts 1, 2, 3, 5, and 6) and five bottleneck machines (machines 7, 3, 8, 2, and 9). The machine investment is still equal to the total sum of machines (machines 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10).



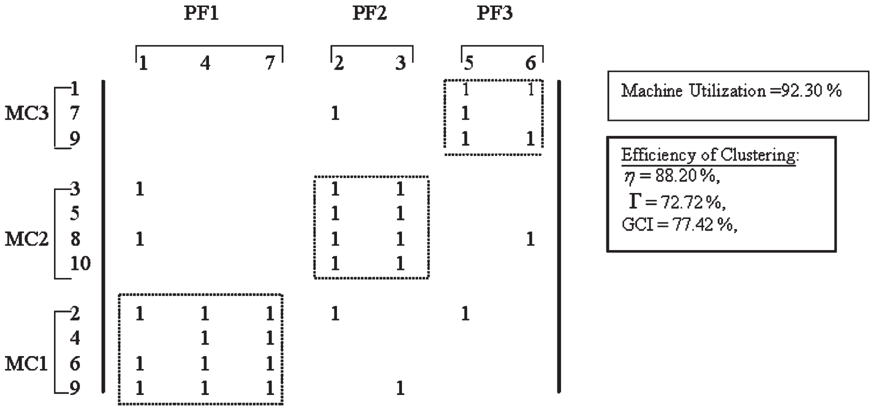
		PF1			PF2		PF3	
		1	4	7	2	3	5	6
MC3	1						1	1
	7				1		1	
MC2	3	1			1	1		
	5				1	1		
	8	1			1	1		1
	10				1	1		
MC1	2	1	1	1	1		1	
	4		1	1				
	6	1	1	1				
	9	1	1	1		1	1	1

Machine Utilization = 91.66 %

Efficiency of Clustering:
η =86.45 %,
Γ = 66.70 %,
GCI = 70.97 %,

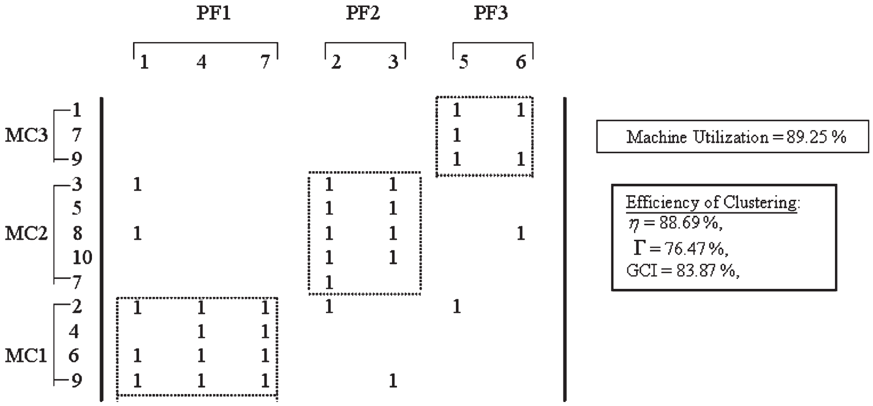
Fig. 12.7 Revised formation of manufacturing cells

Step 3: Add duplicate machines to the manufacturing cells if necessary. Add a duplicate of machine 9 to manufacturing cell 3 to reduce the intercellular moves of parts 5 and 6 to manufacturing cell 1 (Fig. 12.8). The machine utilization is 92.30%, but the number of exceptional parts and bottleneck machines is still the same. The investment in machines is increased by one machine (machine 9). Then, the machine investment is equal to the total sum of machines (machines 1, 2, 3, 4, 5, 6, 7, 8, 9(2), and 10). Steps 2 and 3 are repeated until all the exceptional parts and bottleneck machines are removed from the matrix and are calculated every time with identifying the machine utilization, efficiency of clustering, and machine investments (Fig. 12.9– Fig. 12.11). All these results are shown in Table 12.6.



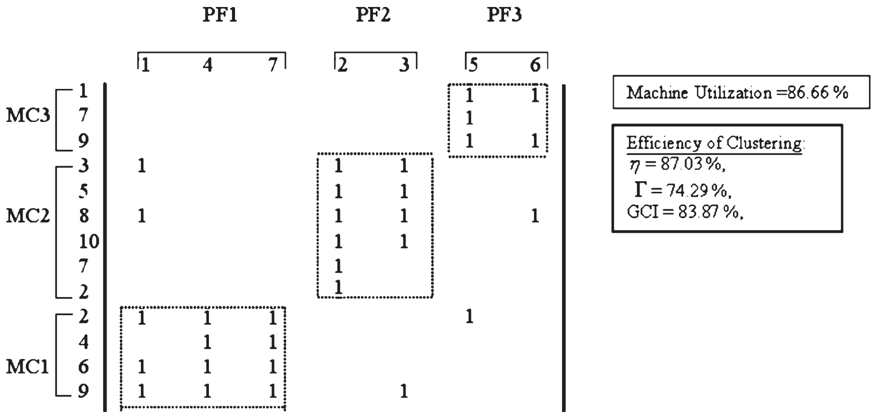
		PF1			PF2		PF3	
		1	4	7	2	3	5	6
MC3	1						1	1
	7				1		1	
	9						1	1
MC2	3	1			1	1		
	5				1	1		
	8	1			1	1		1
	10				1	1		
MC1	2	1	1	1	1		1	
	4		1	1				
	6	1	1	1				
	9	1	1	1		1		

Fig. 12.8 Addition of a duplicate machine 9 to manufacturing cell 3



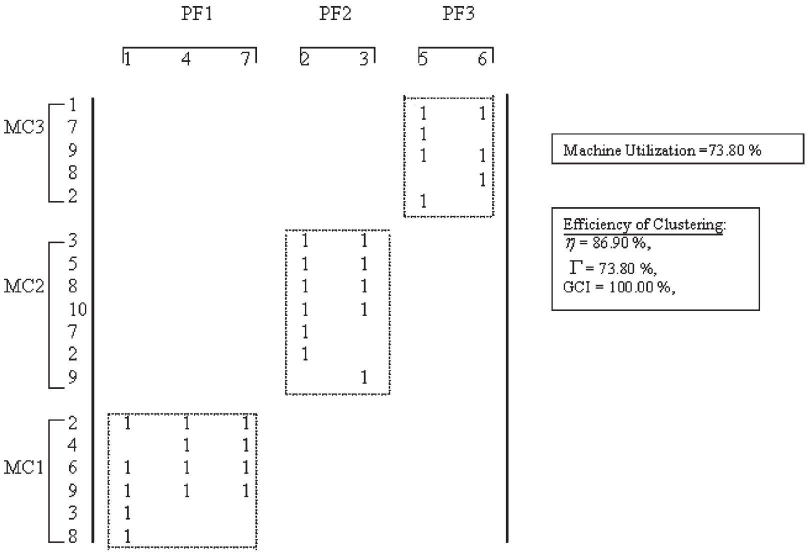
		PF1			PF2		PF3	
		1	4	7	2	3	5	6
MC3	1						1	1
	7						1	
	9						1	1
MC2	3	1			1	1		
	5				1	1		
	8	1			1	1		1
	10				1	1		
	7				1			
MC1	2	1	1	1	1		1	
	4		1	1				
	6	1	1	1				
	9	1	1	1		1		

Fig. 12.9 Addition of a duplicate machine 7 to manufacturing cell 2



		PF1			PF2		PF3	
		1	4	7	2	3	5	6
MC3	1						1	1
	7						1	
	9						1	1
MC2	3	1			1	1		
	5				1	1		
	8	1			1	1		1
	10				1	1		
	7				1			
	2				1			
MC1	2	1	1	1			1	
	4		1	1				
	6	1	1	1				
	9	1	1	1		1		

Fig. 12.10 Addition of a duplicate machine 2 to manufacturing cell 2



		PF1			PF2		PF3	
		1	4	7	2	3	5	6
MC3	1						1	1
	7						1	
	9						1	1
	8							1
	2						1	
MC2	3				1	1		
	5				1	1		
	8				1	1		
	10				1	1		
	7				1			
	2				1			
	9					1		
MC1	2	1	1	1				
	4		1	1				
	6	1	1	1				
	9	1	1	1				
	3	1						
	8	1						

Fig. 12.11 Addition of five more duplicate machines

12.5 Results And Discussion

It should be noted in Table 12.6 for the sixth level that machines 3 and 7 are duplicated twice; machines 2, 8, and 9 are duplicated three times; and no exceptional parts and bottleneck machines exist in the cell formation. It can also be noted for the sixth level that the number of duplicated machines increased to eight machines; machine utilization and grouping efficacy decreased to 73.80%;

Table 12.6 Trade-off between exceptional parts, machine utilization, efficiency of clustering, number of duplicated machines, and capital investments

					Efficiency of clustering			
CF	Number of EP	Number of BM	MU (%)	Number of DM	η (%)	Γ (%)	GCI (%)	Capital investments
1	7	5	87.00	0	81.78	62.50	64.52	1+2+3+4+5+6+7+8+9+10
2	5	5	91.66	0	86.45	66.70	70.97	1+2+3+4+5+6+7+8+9+10
3	5	5	92.30	1	88.20	72.72	77.42	1+2+3+4+5+6+7+8+9(2)+10
4	5	4	89.25	2	88.69	76.47	83.87	1+2+3+4+5+6+7(2)+8+9(2)+10
5	4	4	86.66	3	87.03	74.29	83.87	1+2(2)+3+4+5+6+7(2)+8+9(2)+10
6	0	0	73.80	8	86.90	73.80	100.00	1+2(3)+3(2)+4+5+6+7(2)+8(3)+9(3)+10

CF cell formation level, *EP* exceptional parts, *BM* bottleneck machines, *MU* machine utilization, *DM* Duplicate machines

grouping efficiency and grouping capability index (GCI) are 86.90% and 100.00%, respectively. From the third level to the sixth level, machine utilization decreased as the number of duplicate machine increased because the same total load was divided over a larger number of machines. Although machine utilization may be preferred in selecting the initial formation, it is likely that the cell formation with the lower machine utilization will lead to increases in production volume and demand for parts. Cell formation Levels 3 and 4 give good results in terms of machine utilization, group efficiency, and number of duplicated machines (capital investment), but the number of exceptional parts is five. These results show that there are process and routing flexibilities. Selecting one of the cell formation levels is not an easy task and depends on the management philosophy. Table 12.7 gives more analyses about manufacturing cell performance measures for Level 6 (evaluation).

The design process is terminated after finding a solution which satisfies the objectives (machine utilization, efficiency of clustering, number of exceptional parts and bottleneck machines, and machine investment) and constraints (cell size, number of cells, and number of machine types).

12.6 Conclusions

Research in the design of CMS still needs more extensive study in the areas of production and flexibility issues and cell formation techniques. There are few publications that address manufacturing flexibility and real-life production factors in cell formation when designing CMS. The need for production and flexibility

Table 12.7 Manufacturing cell performance measures for Level 6 (evaluation)

Performance measure	Value
Machine utilization MU	73.80%
Grouping efficiency η	86.90%
Grouping efficacy Γ	
Grouping capability (GCI)	100.00%
Number of part families	3
Number of machine cells	3
Number of exceptional parts	0
Number of bottleneck machines	0
Minimum cost of intercell movements	0
Minimum cost of intracell movements	NA
Cost of fixed cost	[1+2(3)+3(2)+4+5+6+7(2)+8(3)+9(3)+10]
Upper limit of cell size	7 Machines, 3 Parts
Lower limit of cell size	5 Machines, 2 Parts
Maximum number of cells	3
Maximum number of each machine type	3
Minimum number of each machine type	1

factors in designing CMS is forcing traditional manufacturing systems to be agile manufacturing systems and to cope with a changing environment. In this work, production and flexibility factors were incorporated as factors to minimize the intercellular moves and maximize the machine utilization as design objectives were restricted by several constraints to enhance the quality of the solution.

This research suggested a new heuristic cell formation approach which consisted of five main phases. In the first phase, clustering machines into machine cells was suggested through several steps based on the new comprehensive similarity coefficient between machines. The new similarity coefficient between machines was created by considering alternative routings (process plans), processing times, machine capacity (reliability), machine capability (flexibility), production volume rate, and part demand. The second phase was used to group parts into part families following many sequential steps based also on the new similarity coefficient between parts with corresponding part process plans. A new similarity coefficient between parts was also created by considering alternative routings, production volume rate, part demand, and processing times for each part.

The initial formation of the manufacturing cells was presented in the third phase after assigning part families to machine cells. In the fourth phase, performance evaluation of initial cell formation according to machine utilization and efficiency clustering was tested. A revised cell design was introduced in the fifth phase through a new strategy to eliminate exceptional parts and bottleneck machines.

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