



Proceedings of GLOGIFT 07
November 15-17, 2007
UP Technical University
Noida, pp. 107-127

AN EFFICIENT ALGORITHM FOR THE MACHINE/PART GROUPING PROBLEM CONSIDERING MACHINES OVERLOADING AND IMPORTANT PRODUCTION PARAMETERS

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ABSTRACT

Machine/part grouping problem consists of identifying machine groups and part families in cellular manufacturing system. A large number of papers on cell formation have been published so far, but very few of them have considered machine overloading constraint at the design stage. Little work have reported which incorporated real-life production parameters like operation sequence, production volume, batch size, material handling capacity, processing time, setup time, machine capacity and allocating units of identical machines into different cell with balanced workload. Considerations of these important parameters make the cell formation problem more complex but realistic. The paper describes a solution methodology (algorithm) for the problem of cell formation to minimize the total intercell movements and allocate the duplicate machines to appropriate cells such that the workload is uniform on the machines. The financial benefit of reallocation of duplicate machines to different cell is also presented. The computational procedure of the algorithm has been illustrated by an example. Numerical results indicate that the proposed methodology is flexible, efficient and effective even for industrial problems.

Keywords: Cellular Manufacturing Systems, Duplicate Machines, Inter-cell movement, operation sequence, void, exceptional element.

Introduction

Cellular manufacturing has been proved as an attractive compromise between flow line production and job shop production as it incorporates the attributes of both of them. Cellular manufacturing is basically based on the philosophy of Group Technology. Group Technology (GT) is an approach to manufacturing and engineering management that helps to manage diversity by capitalizing on underlying similarities in products and activities. In the manufacturing context, GT has been defined as a manufacturing philosophy identifying similar parts and grouping them together into families to take advantage of their similarities in manufacturing and design. Grouping the production equipment into machine cells, where each cell specializes in the production of part families, is called as cellular manufacturing. So cellular manufacturing is the application of the GT philosophy in manufacturing. Cellular Manufacturing is concerned with the creation and operation of manufacturing cells which are dedicated to the production of a set of part families. In order to introduce cellular manufacturing, it is necessary to identify parts and machine types to be used in the cellular configuration.

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The first problem faced in implementing Cellular Manufacturing is cell formation. Cell formation deals with the identification of the family of parts and the group of machines to process these parts. The problem of cell formation is defined as: "If the number, types, and capacities of production machines, the number and types of parts to be manufactured, and the routing plans and machine standards for each part are known, which machines and their associated parts should be grouped together to form cells?" (Wu and Salvendy 1993). In some cells the definition of cell formation is expanded to allow choice of processing operations to achieve specific features. Since last three decades, a considerable amount of researches have been directed to ease this type of problem. Burbidge (1971) developed an intuitive method, namely Production Flow Analysis (PFA) which is relatively easy to implement. PFA may be suitable for the small size problem, but it would definitely have difficulties coping with real life cell formation problems when the machine-part incidence matrix becomes more complex because of problem size.

Many approaches have been developed to deal with the difficulties of intuitive method. These approaches are usually classified into Part-oriented approaches (based on part characteristics) and Process-oriented approaches (based on production methods). The part-oriented techniques usually employ some classification and coding system, and analyze parts for their similarities in design features and functionalities. However, these do not influence directly the configuration of manufacturing cells (Choobineh 1988). The process-oriented approaches to the cell formation are based on manufacturing data such as production methods, part routing information and process plans. The process-oriented approach is classified into four groups namely:- Descriptive methods, Array-based methods, Similarity coefficient methods and other analytical methods (Yasuda and Yin 1990).

Most of the suggested algorithms/models consider binary machine-part incidence matrix $A = [a_{ij}]$, with =

$$a_{ij} = 1 \text{ if part type } i \text{ requires machine type } j, \\ 0 \text{ otherwise}$$

The binary part-machine matrix only represents the occurrence of an operation on a machine but not the actual intercell movements of parts. Most of the cell formation methods based on binary part-machine matrix do not consider the following:

1. Operation sequence of parts. The sequence of operation is an important manufacturing attribute in the design of cellular manufacturing systems. The operation sequence may be defined as an ordering of the machines on which the part is sequentially processed. The sequence of operation has an impact on the flow of material in the system. An intermediate operation of a component to be performed outside its cell requires two inter-cell transfers while the first or last operation requires only one such transfer (Choobineh 1988). Vakjaria and Wammerlov (1990), Logendran (1991), Wu and Salvendy (1993), Yin and Yasuda (2002), Defersha and Chen (2006) considered operation sequence matrix in the design of manufacturing cell. Sarker and Xu (1998) presented a brief review of cell formation based on the operation sequences.
2. Production Volume. The production volume is total number of different parts to be manufactured in the given period. The merits of incorporating production volume were depicted by Gupta and Seifoddini (1990).
3. Number of intercell movements. Parts are generally processed in batches with unequal volumes. A 1 outside the diagonal block indicate only one intercell movement. In fact the volume of intercell movement depends upon the batch size and capacity of material handling

device. If the batch size is large and the capacity of material handling system is limited than the volume of intercell movement will be large.

4. **Machine Capacity.** The basic requirement, in the design of a cellular manufacturing system, is to have the adequate capacity to process all the parts. The machine capacity has an impact on the workload induced by the part. In binary part-machine matrix, the 0s inside the diagonal block are referred as VOIDS. A void indicates that a machine assigned to a cell is not required for the processing of a part in the cell. The corresponding machine is said to be underutilized. But the actual utilization of machine depends upon the machine capacity and the workload imposed by the parts on it.
5. **Processing and setup times.** The processing and setup time required by the part on a machine is another important parameter. It influences workload and machine utilization.
6. **Material Handling Capacity.** The material handling capacity is considered as the number of parts transported to the machines/cells. So it depends upon the load carrying capacity and the pallet size.

In the recent years, some of the researchers considered different production parameters in cell formation problem (Dixit and Mishra 2004, Kumar and Vanneli 1987, Kusiak and Chow 1987, Choobineh 1988, Askin and Subramaniam 1987, Harhalakis et al. 1990, Wu 1998, Adil et al 1996).

Multi-objective Cell Formation- A Review

The multi-objective cell-formation problem can be defined as; A grouping of machines into cells and parts into associated families needs to be identified that will simultaneously optimizes all the considered objectives. Practical cell formation design consists of a number of conflicting objectives. For these conflicting objectives, each objective corresponds to a different optimal solution. Hence, a single solution that simultaneously optimizes all the objectives does not generally exist. Instead, there exists a set of solutions, in which no solution is better the other (non-dominated) with respect to all objectives considered. So there is a need to search for a satisfactory solution. For last two decades, different solution methodologies have been developed to deal with such problems.

Ho and Moodie (1996) developed a two-stage solution approach. Part families were formed in stage I based on the similarities in their operation sequences by means of a heuristic procedure. In second stage, the machines were allocated to the part families through a mixed integer programming model. They assumed flexible routing for parts. The objective function of the first stage was composed of three cost functions i.e. operation cost, machine duplication cost, and a penalty cost for those operations that need to be performed in cells other than the ones that they have been assigned. The latter term could be considered as another definition for the inter-cell movement cost. The authors employed, in stage 2, the weighting approach to unify the three cost criteria.

Rajamani et al. (1996) developed a mixed integer programming model for the multi-criterion problem. The objective function of the model is to minimise the sum of investment, process and material handling costs as a weighted sum of the three different cost functions. They considered alternate process plans for parts. To solve the relaxed linear model the authors make use of a column generation scheme and the branch and bound technique.

Lee and Chen (1997) applied a weighting approach to combine two criteria, i.e. minimising inter-cell movement of parts, and maximising workload balance among duplicated machines. Their solution methodology is a three-phase heuristic based approach, which determines

machine cells and part families and allows for machine duplication where necessary. At the beginning, an estimation procedure is developed to determine workload balances for duplicated machines. In the second phase, machine cells and part families are constructed by means of a heuristic algorithm. Finally, a heuristic procedure is employed to improve the solution quality of the formation result.

Su and Hsu (1998) considered three objectives (minimising the total cost of inter-cell transportation, intra-cell transportation and machine investment, intra-cell machine (in cell) load unbalance, and inter-cell machine (in plant) load unbalance.) in their model of cell formation. The authors applied weighted approach to formulate the problem in single function. They solved the model by means of parallel simulated annealing.

Zhao and Wu (2000) employed a genetic algorithm approach to the machine-component grouping problem with multiple objectives. These objectives include minimising cost due to intercell and Intracell part movements, the total within cell load variation, and exceptional elements. Production data like part routing sequence, routing flexibility, production volume and work load was taken into consideration.

Zolfagari and Liang (2003) applied Genetic algorithm to get the near optimal solution. A generalized grouping efficacy index was used to check the performance of the algorithm. The algorithm was tested for large size problems. The different manufacturing attributes such as processing time, lot size and machine capacities were also considered. The algorithm was tested on the large size problems.

Dixit and Mishra (2004) present a heuristic based approach dealing with exceptional elements. They develop an initial solution using Genetic algorithm. Exceptional elements are then primarily eliminated using part subcontracting or machine duplication through an optimisation model. The authors include three cost factors in the form of a single minimisation objective function, i.e. cost associated with intercellular transfer, machine duplication, and part subcontracting. In fact they use a weighting approach to unify three different objectives with equal weights.

Jayaswal and Adil (2004) considered sum of machine investment cost, machine operating cost and cost of intercell moves in the objective function. The production parameters like operation sequence, alternative routings, cell size, production volume and identical machines was also considered as a constraint in the problem formulation. Author proposed an algorithm comprise of simulated annealing and a local search heuristics to solve the problem.

Solimanpur et al (2004) developed a multi-objective programming model and solved the model with genetic algorithm. The objective function considered four factors, maximising the total similarity of parts, minimising the total processing cost and minimising the total investment cost. Author proposed a systematic uniform design-based approach to set the weights of the objectives. Solution space in GA was proposed to be multi-directional instead of uni-directional.

Yasuda and Hu (2005) considered the minimization of both the cell load variation and intercell flow in the objective function. Constraint manufacturing attributes like machine capacity, part volume, and part processing time has been considered in the mathematical model. A Grouping genetic algorithm (Falkenauer's) was proposed to solve the problem Author used weighted approach to deal with the multi-criteria objectives.

Defersha and Chen (2006) employed mixed integer programming model. The objective function consists of machine maintenance and overhead cost, machine procurement cost, intercell material handling cost, machine operating cost, setup cost, machine relocation cost

and sub-contracting parts. Mathematical model also considered tool requirement of parts, tool available on machines, dynamic cell configuration, alternating routing, lot splitting, operation sequence, duplicating machines, machine capacity, workload balancing. LINGO software was used to solve the integer problem. In spite of comprehensive model, it involves large number of variable.

In this paper, lexicographic method has been applied to solve the multi-objective problem. The primary objective is to minimize the intercell movements, maintaining the acceptable utilization level of the machines. If the requirement of a machine is beyond its capacity then multiple identical machines of same type are added to the system. These machines have to be assigned into different cells such that the machine utilization variation is minimized. A comprehensive cost based analysis is performed to justify the importance of assigning the machines to the different cells with minimum workload variations.

The paper is organized as follows: Notations and definitions are explained in section 3. The problem formulation is presented in section 4. The proposed solution methodology is presented in section 5. Computational analysis and results are presented in section 6. Conclusion is presented in section 7.

Notations and Definitions

i	part type index
j	machine type index
k	cell type index
n	operation type index
m	number of machines $M= (m_1, \dots, m_j, \dots, m_m)$.
p	number of parts $P= (p_1, p_2, \dots, p_i, \dots, p_p)$.
c	number of cells $C= (c_1, c_2, \dots, c_k, \dots, c_c)$.
k_j	number of identical machines of machine type j
r_i	maximum number of operations for components i
pv_i	total production volume of part type i
bs_i	batch size of part type i .
MHC_i	capacity of material handling device for part i .
t_{ij}	processing time of part type i on machine type j
st_{ij}	st setup time of part type i on machine type j
t_j	time capacity of a machine type j over a period
O_j	Operation cost per hour of machine type j
P_j	Procurement cost of machine type j
IT_i	Intercell movement cost per batch of part type i
MO_j	maintenance and overhead costs of machine type j
w_j^i	proportionate workload induced by part type i on machine type j

$$W_j^i = \frac{\left[t_{ij} \times pv_i + st_{ij} \times \left[\frac{pv_i}{bs_i} \right] \right]}{T_i} \quad (1)$$

w_j^i wc workload on machine type j in cell type k

$$WC_j^k = \sum_{j=1} X_{jk} Y_{ik} W_j^i \quad (2)$$

$\forall k, j$

wc_j^k avgwc average load on machine type j. (3)

$$avgwc_j = \frac{\sum_{k=1}^c wc_j^k}{k_j}$$

$X_{jk} = 1$ if machine j is in cell k and 0 otherwise

$Y_{ik} = 1$ if part i is assigned in cell k and 0 otherwise

EE_j^s number of exceptional elements belong to cell type s and processed on machine type j

EE total number of exceptional elements in the solution

UB upper bound on cell size (maximum number of machines in a cell)

$m(k)$ Number of machines in cell type k.

ab y total movement between two distinct cells ca and cb

$$y_{ab} = \sum_{i=1}^p \left(\frac{pv_i}{MGC_i} \right) \times \varepsilon_{ab}^i \quad (4)$$

Where,

ε_{be}^i number of times any machine belong to cell ca is the immediate successor of any machine assigned to cell cb

Problem Formulation

The most fundamental objective of cell formation is to achieve cell independency which in turn significantly simplifies shop floor control. Further, the potential to increase the accountability, responsibility, and autonomy of the workers is enhanced. It also reduces material handling that results in less damage to work-in-process (Shafer and Rogers 1991). To achieve cell independency, intercell movements must be minimized. In this paper, we have considered the multi-objective machine-component grouping problem. Though there are several important objectives associated with the cell formation problem, explicit consideration of too many objectives is difficult (Venugopal and Narendran 1992). Hence, the decision maker must select a manageable number of objectives that are distinct and measurable. In this study, efforts have been made to minimise intercell flow, variation of workload among the alternative machines and optimize the utilization level of machines. There is no unique solution for a multi-objective

An Efficient Algorithm for the Machine/Part Grouping Problem Considering Machines Overloading and Important Production Parameters

problem. Instead, a set of satisfactory solutions will have to be found. A solution is satisfactory if there exists no other solution which can improve one or more objectives without detriment to other objectives (Venugopal and Narendran 1992,b).

Following three objectives have been considered:

(F1): Minimize the volume of intercell movements.

$$\text{Minimize } F_1 = \sum_{a=1}^{m-1} \sum_{b=a+1}^m \left(\frac{\Psi_{ab}}{m(a) + m(b)} \right) \quad (5)$$

(F2): Minimize the workload variation within identical machines.

$$\text{Minimize } F_2 = \sum_{j=1}^m \sum_{k=1}^m x_{jk} (wc_j^k - avgwcj)^2 \quad (6)$$

(F3): Maintain acceptable utilization level of machines.

Subject to constraint:

$$m(a) + m(b) \leq UB \quad (7)$$

$$\sum_{k=1}^c x_{jk} = 1 \quad \text{for } j = 1, 2, \dots, m. \quad (8)$$

$$\sum_{j=1}^m x_{jk} \geq 1 \quad \text{for } k = 1, 2, \dots, c. \quad (9)$$

$$\sum_{i=1}^p y_{jk} \geq 1 \quad \text{for } k = 1, 2, \dots, c. \quad (10)$$

$$wc_j^k \leq 1 \quad \forall j, k \quad (11)$$

where, objective function (5) represents the 6 Normalized intercell flow and objective function (6) represents the extent of variation of the load on the machines in the cell with the average load. Constraint (7) ensures that the merging cells/groups satisfy cell size. Constraint (8) ensures that each part can only be assigned to one cell. Constraint (9) and (10) ensures that each cell must contain at least one machine and one part. Constraint (11) ensures that the machine is within acceptable utilization level.

The evaluation criterion for the performance of the proposed algorithm is given as:

$$\text{Maximize } z_{GM} = (\eta_{GT}) \times (1 - \lambda_{MLV}) \quad (12)$$

η_{GT} Group Technology Efficiency (Harhalakis et al. 1990), is defined as the ratio of the difference between the maximum number of inter-cell movements possible and the number of inter-cell movements actually required by the system to the maximum number of inter-cell movements possible. Mathematically GT h can be defined as:

$$\eta_{GT} = (I - U)/I \quad (13)$$

$$I = \sum_{i=1}^p pv_i (r_i - 1) \quad (14)$$

$$U = \sum_{i=1}^p pv_i \sum_{r=1}^{r_i-1} ir \quad (15)$$

Where

$$ir = \begin{cases} 0 & \text{if operations } r, r + 1 \text{ are performed in the same call} \\ 1 & \text{otherwise} \end{cases}$$

$$\lambda_{MLV} = \sum_{\substack{k=1 \\ \forall j^* \in C_k}}^c \left[\frac{wc_{j^*}^k}{k_{j^*}} - avgwc_j \right]^2 \quad (16)$$

λ *MLV* is defined as the index of load variation on the machines. Lower the value of *MLV* , lower will be the workload variation on the machines.

The Cost function, for the evaluation of the impact of identical machines assignment to different cells, comprise of operating cost of machines, procurement cost of machines and cost of intercell movement of parts (in batches). It can be expressed mathematically as below:

$$Z_1 = \sum_{i=1}^p \sum_{j=1}^p \left[pv_i \cdot t_{ij} + \frac{st_{ij} \cdot pv_i}{bs_i} \right] \times o_j \quad (17)$$

$$Z_2 = \sum_{j=1}^m k_j \times p_j \quad (18)$$

$$Z_3 = \sum_{i=1}^p \left[\frac{pv_i}{bs_i} \right] \times IT_i \left| \sum_{r=1}^{(r_i-1)} ir \right| \quad (19)$$

Total Cost is given as:

$$Z = Z_1 + Z_2 + Z_3 \quad (20)$$

Solution Methodology

The design of cellular manufacturing is combinatorial complex. The number of ways in which m machines may be assigned to exactly k cells is given by the Stirling number of the second kind (Venugopal and Narendran 1992, a).

An Efficient Algorithm for the Machine/Part Grouping Problem Considering Machines Overloading and Important Production Parameters

$$S^{(k)} = \frac{\sum_{j=1}^k (-1)^{k-j} \binom{k}{j} j^m}{k!}$$

So there will be 34105 distinct partitions of 10 machines into 4 cells, but this number increases to 1125966000 approximately; if 19 machines are to be partitioned into 4 cells. However, the number of cells is usually not known in advance. But the maximum and minimum limit of the number of cell can be 1 and m respectively. The total number of ways in which machine-cell assignments may be made explodes to

$$\sum_{k=1}^k s^{(k)} = \sum_{j=1}^k \left[\frac{\sum_{j=1}^k (-1)^{k-j} \binom{k}{j} j^m}{k!} \right]$$

Therefore, this class of problem is NP-complete. Many approaches have been proposed by different researchers to solve the problem. Heuristic approaches are also used to obtain good solutions within acceptable amount of time. Numerous papers can be found in the literature for cell formation using heuristics Carpenter and Grossberg (1987); Harhalakis et al (1990); Burke and Kamal (1992); Venugopal and Narendran (1992 a,b); Chen et al (1995); Gupta et al (1995); Sofianopoulou (1997); Su and Hsu (1998); Baykasoglu et al (2001); Lozano et al 7 (2001); Onwubolu and Mutinigi (2001); Dobando et al (2002); Xambre and Vilarinho (2003); Zolfagari and Liang (2003); Cao and Chan (2004); Dixit and Mishra (2004); Peker and Kara (2004); Solimanpur et al (2004); Adenso-Diaz et al (2005); Muruganandam et al (2005); Yasuda et al, (2005).

We have also applied the heuristic based approach for manufacturing cell design.

Phase-I

In phase-I, initial basic feasible solution is obtained. The machine cells and part families are identified at this stage. Initially, a symmetric matrix with [m*m] entries is constructed using equation (4). An entry ψ_{ab} in the matrix indicates the number of immediate movements between distinct machines m_a and m_b . Then, the machine-pair having maximum normalized intercell flow are grouped into a machine cell and the matrix is again revised. The procedure of iteration is continued until the upper bound condition on cell size is not violated.

Once the machine cell is constructed, the parts are assigned optimally to the cells. Later a local refinement procedure is applied to find the better solution.

The general procedure of the proposed heuristic algorithm is presented as follows:

Machine cell formation Algorithm:

- Step 1 Assign each machine to a cell i.e. (Number of cells = Number of machines).
- Step 2 Determine S_{ab} between the cells from the operation sequence matrix and construct a symmetric matrix.
- Step 3 Determine the Normalized Intercell flow between the cells.
- Step 4 Select the maximum normalized Intercell flow value for the given cell-pair satisfying

the limit of cell size.

Step 5 If tie occurs (more than one cell-pair has same value), then cell-pair having less number of machines is selected.

Step 6 Merge the cell-pair to form new cell. Revise the matrix.

Step 7 Repeat step (2-4) till upper bound condition on cell size is not violated.

Step 8 Stop.

Part Allocation Algorithm:

Step 1 Part will be assigned to the cell having MAXIMUM number of machines required by the particular part.

If the tie occurs:

If operations are in same sequence in TIE cells then the part will be assigned to the cell having minimum number of machines. If number of machines is also equal in TIE cells then part will be assigned to the cell having MINIMUM operation sequence.

If operations are not in a sequence in one of the TIE cells then the part will be assigned to the cell having operations in sequence. If operations are not in sequence in all the TIE cells the Part will be assigned to the cell having minimum number of machines. If number of machines are same then part will be assigned to the cell having MINIMUM operation number.

Refinement of Phase-I

Step 1 Identify the exceptional elements, bottleneck machines, bottleneck parts and their respective cells.

Step 2 Identify the bottleneck machine which is more involved for exceptional elements as compared to their regular operations for the part families within the cell.

Step 3 If these exceptional elements are from the same cell (having bottleneck parts) then "shift the machine to the new cell"

Step 4 If TIES occurred: (Number of exceptional elements are equal to the number of operations within the parent cell of the machine.) and if number of parts in Parent cell > number of parts in cell having bottleneck parts, then "Shift the machine to the new cell".

Step 5 Repeat the step (2-4) for all the bottleneck machines.

Step 6 Apply the part allocation algorithm.

Step 7 Stop.

Phase-II

The basic purpose of phase-II is to identify the 8 overloaded machines, so that the requirement of the number of identical machines can be found. These identical machines are then optimally assigned to different cells. The procedure is as follows: (Identical Machines Allocation Algorithm)

Step 1 Evaluate the load induced by parts on machines $i j w$. Also calculate the cumulative

Step 2 Identify the overloaded machines and calculate the number of identical machines required to balance the load.

$$\text{load on machines. } \sum_{j=1}^k w_j^i$$

Step 3 if $1 < \sum_{\substack{j=1 \\ \forall j}}^p w_j^i < \Rightarrow$ two identical machines of machine type j are required ($k_j = 2$).

Similarly if the above limit is 2-3, then three identical machines of machine type j are required ($k_j = 3$).

Step 4 Evaluate the load induced by individual cells on machines ($w_c^{k^*}$) and the average load on machines due to parts in respective cells.

Step 5 Optimally assign the identical machines to the cells which are inducing the maximum workload. Distribute the load of exceptional elements of other cells to these identical machines in such a way that the workload variation is minimized on these machines.

Step 6 If any machine (m_j) is overloaded within its parent cell (ck^*) i.e. ($w_c^{k^*} > 1$), then identify the cell (C_s) which is imposing the next maximum workload in order on the m_j . Calculate the net change in the number of exceptional elements due to assignment of machine in this cell $EE_{net} = EE - EE_j^s$ and the amount of workload variation with the average load $\Delta w = |w_c^{k^*} - avgw_c|$.

Step 7 Identify the part pi^* corresponding to machine m_j in cell ck^* having $\min(\Delta w - w_j^i) \forall i \in k^*$ in case of tie preference will be given to first and last operation.

Step 8 Shift the workload w_j^i induced by pi^* to the recently shifted identical machine m_j^* . Due to this shifting, number of exceptional element is increased by one. $EE = EE + 1$ new net. If $(EE - EE) > 0$ new, proceed to next step otherwise repeat step 5-7 for other cells. If $(EE - EE) < 0$ new k , identical machine will be assigned to the cell as obtained in phase-I.

Step 9 Calculate the modified values of workload.

Step 10 Repeat step 5-8, until $w_c^{k_j} < 1$.

$$w_c^{k^*} = \sum_{\substack{i=1 \\ \forall i \in k^*}}^p w_j^i - w_j^{i^*}$$

$$w_c^s = \sum_{\substack{i=1 \\ \forall i \in s}}^p w_j^{i^*} + w_j^{i^*}$$

Step 11 Stop

Computational Analysis and Results

The purpose of this section is to provide some computational analysis and results that can be widely used to benchmark the effectiveness of heuristic approaches which may be proposed in future research in this field, rather than addressing the algorithmic aspect. In order to validate the proposed heuristic, initial part-machine sequence matrix is taken from the published research papers. Due to non-availability of few production data, some of the input parameters were

randomly generated. The values in the surveyed publications are used as a guideline for determining the range of the values of parameters. Table1 summarizes the value for parameters.

The algorithm has been implemented in script programming in MATLAB 7.0 and the experiments have been run on a Pentium IV, with 1.8 GHz and 256 MB RAM.

The first data set contains 9 machines and 15 parts (Lee and Chen, 1997). The predicted demand of the parts, batch size, machine capacity and material handling device capacity has been generated as per the guideline of table1. The operation sequence has been same as suggested by (Lee and Chen, 1997). Table2 shows the attributes of part type such as operation sequence, demand, and batch size pallet size and Intercell movement cost per batch. Table3 shows the attributes of machine type which includes procurement cost of the machine type, operating cost of machine per hour and machine capacity. Machine 9 capacity is considered to be fixed to 2000 hours. It is assumed that machine operates 8 hour/day, 5 days/week for 50 weeks (nearly one year). The processing time per part and setup time per batch is shown in Table4.

Table 1: Value of Parameters

Parameters	Values	Remark
Machine part sequence matrix	Taken from published papers	In case of 0-1 matrix, the entry 1 is replaced by Non-repetitive Discrete uniform distributed number
Part Demand	U(100 – 1000)	uniformly distributed Random No.
Processing time	U(0.5-2) min	Discrete uniform distribution
Setup Time	U(0.05-.5) min	Discrete uniform distribution
Machine capacity	2000 hr/period	Fixed (8 hr/day, 5 days/week for 50 weeks ie 1year)
Material handling device capacity	U(100-500)	Discrete uniform distribution
Batch size	U(50-100)	Discrete uniform distribution
Investment cost	U(10,000-50,000)	Discrete uniform distribution
Operating cost	N(mean-50, SD-20)	Normal Distribution
Intercell Cost	U(20, 50)/batch	Discrete uniform distribution

Table 2: Part Type Attributes (Input)

Part type number	Operation Sequence	Demand	Batch Size	Pallet Size	Inter cell cost
1	M8-M5-M4-M3	519	100	116	44.80
2	M3-M1-M8-M9-M4-M5	274	77	283	36.89
3	M6-M5-M8-M4-M2	722	70	129	36.52
4	M6-M7-M9-M2	483	71	172	48.30
5	M7-M9-M2-M4-M6	619	79	292	36.81
6	M1-M3-M9-M8-M4-M2	801	75	389	26.85
7	M6-M5-M8-M4-M2	143	59	405	26.22
8	M8-M3-M1-M4	842	59	186	35.38
9	M5-M4-M8-M6-M2	981	56	241	27.62
10	M6-M5-M4-M8-M2	309	68	420	44.59
11	M9-M3-M1-M4-M8	658	62	402	28.42
12	M6-M7-M9-M2	649	98	125	21.71
13	M6-M7-M9-M2	626	99	259	35.74
14	M8-M9-M3	332	82	202	46.78
15	M9-M1-M8-M3	692	56	342	47.29

An Efficient Algorithm for the Machine/Part Grouping Problem Considering Machines Overloading and Important Production Parameters

Table 3: Machine Type Attribute (Input)

Machine Type	Machine Capacity	Investments Cost	Operating Cost
1	2000	36695.82	50.06
2	2000	47999.82	53.07
3	2000	26602.16	46.16
4	2000	26319.35	49.49
5	2000	13336.47	48.80
6	2000	17816.86	50.44
7	2000	15462.42	52.51
8	2000	46862.38	45.53
9	2000	29356.09	45.18

Table 4: Processing and Setup Times (Underlined Nuderlined numbers in dicate the Processing Time

		Machine Type									
		1	2	3	4	5	6	7	8	9	
Components	1			<u>1.09</u> 0.08	<u>0.91</u> 0.23	<u>1.49</u> 0.37			<u>0.81</u> 0.22		
	2	<u>1.20</u> 0.20		<u>0.94</u> 0.28	<u>1.85</u> 0.49	<u>1.71</u> 0.10			<u>1.90</u> 0.10	<u>0.65</u> 0.49	
	3		<u>0.99</u> 0.25		<u>1.75</u> 0.08	<u>0.80</u> 0.19	<u>1.64</u> 0.44		<u>1.72</u> 0.28		
	4		<u>1.94</u> 0.48					<u>1.31</u> 0.08	<u>0.79</u> 0.46		<u>1.32</u> 0.39
	5		<u>1.26</u> 0.45		<u>1.66</u> 0.12		<u>1.20</u> 0.08	<u>1.69</u> 0.07			<u>1.72</u> 0.13
	6	<u>1.85</u> 0.20	<u>1.77</u> 0.32	<u>0.95</u> 0.44	<u>1.86</u> 0.20					<u>1.63</u> 0.24	<u>1.68</u> 0.24
	7		<u>0.90</u> 0.18		<u>1.58</u> 0.36	<u>1.05</u> 0.34	<u>1.34</u> 0.42		<u>1.68</u> 0.06		
	8	<u>1.42</u> 0.28		<u>1.01</u> 0.46	<u>1.54</u> 0.26				<u>1.28</u> 0.11		
	9		<u>1.62</u> 0.13		<u>0.70</u> 0.26	<u>1.05</u> 0.39	<u>1.57</u> 0.38		<u>1.05</u> 0.34		
	10		<u>1.26</u> 0.27		<u>0.55</u> 0.36	<u>1.13</u> 0.47	<u>1.67</u> 0.38		<u>1.26</u> 0.36		
	11	<u>1.96</u> 0.29		<u>0.57</u> 0.22	<u>1.27</u> 0.50				<u>0.68</u> 0.35	<u>1.31</u> 0.29	
	12		<u>1.12</u> 0.48					<u>0.84</u> 0.50	<u>1.15</u> 0.07		<u>1.53</u> 0.16
	13		<u>1.64</u> 0.34					<u>1.64</u> 0.23	<u>1.34</u> 0.31		<u>1.18</u> 0.38
	14			<u>1.00</u> 0.12						<u>0.87</u> 0.23	<u>1.18</u> 0.07
	15	<u>1.41</u> 0.23		<u>1.55</u> 0.35						<u>1.94</u> 0.15	<u>1.82</u> 0.08

Table 5: Machine/Part grouping Considering only operation sequence (after phase-I)

		Machine Type								
		1	3	2	6	7	9	4	5	8
Components	6	1	2	6			3	5		4
	8	3	2					4		1
	11	3	2				1	4		5
	14		3				2			1
	15	2	4				1			3
	4			4	1	2	3			
	5			3	5	1	2	4		
	12			4	1	2	3			
	13			4	1	2	3			
	1		4					3	2	1
2	2	1				4	5	6	3	
3			5	1			4	2	3	
7			5	1			4	2	3	
9			5	4			2	1	3	
10			5	1			3	2	4	

In the phase-I of the algorithm, all machine types were treated as a unique machine. As a result three cells are obtained (Table 5): cell 1 contains machine type set (1, 3) for processing part types (6, 8, 11, 14, and 15); cell 2 contains machine type set (2, 6, 7, 9) for processing part types (4, 5, 12, 13); cell 3 contains machine type set (4, 5, 8) for processing part types (1, 2, 3, 7, 9, 10). The total number of exceptional elements and voids are 26 and 1, respectively.

The workload on machine type (1, 2, 3, 4, 5, 6, 7, 8, 9) are approximately 2.64, 3.87, 2.11, 4.01, 1.68, 3.20, 1.51, 4.16, 3.74 respectively. Hence, all the machine types are overloaded. In order to maintain the utilization level of the machines within the acceptable limit, additional identical machines are required for each machine type. The numbers of machines required are (3, 4, 3, 5, 2, 4, 2, 5, 4). The average load on these machines has now reduced to (0.88%, 0.70%, 0.97%, 0.80%, 0.75%, 0.94%, 0.80%, 0.84%, and 0.83%). The workload values are summarized in table 6. Table 7 shows the workload induced by part families, belonging to different cells, on the machine.

In the phase-I of the algorithm, all machine types were treated as a unique machine. As a result three cells are obtained (Table 5): cell 1 contains machine type set (1, 3) for processing part types (6, 8, 11, 14, and 15); cell 2 contains machine type set (2, 6, 7, 9) for processing part types (4, 5, 12, 13); cell 3 contains machine type set (4, 5, 8) for processing part types (1, 2, 3, 7, 9, 10). The total number of exceptional elements and voids are 26 and 1, respectively.

Table 6: Workload on machines due to given product mix (Without assigning the identical machines to different cells)

		Machine Type								
		1	3	2	6	7	9	4	5	8
Components	6	0.74	0.38	0.71			0.67	0.75		0.65
	8	0.60	0.43					0.65		0.54
	11	0.65	0.19				0.43	0.42		0.23
	14		0.17				0.20			0.14
	15	0.49	0.54				0.63			0.67
	4			0.47	0.32	0.19	0.32			
	5			0.39	0.37	0.52	0.53	0.51		
	12			0.36	0.28	0.37	0.50			
	13			0.52	0.51	0.42	0.37			
	1		0.28					0.24	0.39	0.21
	2	0.16	0.13				0.09	0.25	0.23	0.26
	3			0.36	0.59			0.63	0.29	0.62
	7			0.06	0.10			0.11	0.08	0.12
	9			0.80	0.77			0.35	0.52	0.52
	10			0.19	0.26			0.09	0.18	0.20
Load	2.64	2.11	3.87	3.20	1.51	3.74	4.01	1.68	4.16	
Number of machines	3	3	4	4	2	4	5	2	5	
Average Load	0.88	0.70	0.97	0.80	0.75	0.94	0.80	0.84	0.83	

Table 7: Workload induced by the cells on each Machine Types (Without allocation of duplicate machines in different cells)

	Machine Type								
	1	2	3	4	5	6	7	8	9
Cell1	2.48	0.71	1.70	1.82				2.24	1.93
Cell2		1.74		0.51		1.48	1.51		1.72
Cell3	0.16	1.41	0.41	1.67	1.68	1.72		1.93	0.09
Total Load	2.64	3.87	2.11	4.01	1.68	3.20	1.51	4.16	3.74

An Efficient Algorithm for the Machine/Part Grouping Problem Considering Machines Overloading and Important Production Parameters

Table 7 Workload induced by the cells on each Machine Types (Without allocation of duplicate machines in different cells) In the phase-I of the algorithm, all machine types were treated as a unique machine. As a result three cells are obtained (Table 5): cell 1 contains machine type set (1, 3) for processing part types (6, 8, 11, 14, and 15); cell 2 contains machine type set (2, 6, 7, 9) for processing part types (4, 5, 12, 13); cell 3 contains machine type set (4, 5, 8) for processing part types (1, 2, 3, 7, 9, 10). The total number of exceptional elements and voids are 26 and 1, respectively. The workload on machine type (1, 2, 3, 4, 5, 6, 7, 8, 9) are approximately 2.64, 3.87, 2.11, 4.01, 1.68, 3.20, 1.51, 4.16, 3.74 respectively. Hence, all the machine types are overloaded. In order to maintain the utilization level of the machines within the acceptable limit, additional identical machines are required for each machine type. The numbers of machines required are (3, 4, 3, 5, 2, 4, 2, 5, 4). The average load on these machines has now reduced to (0.88%, 0.70%, 0.97%, 0.80%, 0.75%, 0.94%, 0.80%, 0.84%, and 0.83%). The workload values are summarized in table 6. Table 7 shows the workload induced by part families, belonging to different cells, on the machines.

In the identical machine allocation algorithm (Phase-II), the duplicate machines are optimally assigned to the cells. In the initial solution (after phase-I), the machine m1 was assigned to cell1. The value of wc_1^1 and wc_1^3 is 2.48 and 0.16, respectively. Hence, 3 units of m1 are assigned to cell 1. Similarly 3 units of m3, 2 units of m5 and 2 units of m7 are assigned to their original cell type 1, 3, and 2, respectively.

The machine m2 was originally assigned to cell type 2. As the workload on m2 due to different cells is $0.71 \cdot 12$ (wc_2^1), $1.74(wc_2^2)$ and $1.41(wc_2^3)$, therefore two identical units of the machine type 2 (m2*) is assigned to cell 2 and cell 3. Also the load induced by cell 1 on machine type 2 is assigned to identical machine m2, located in cell3. The average workload on m2 and m2* is 0.87 and 1.06, respectively. The machine type m2* is still overloaded. The average workload on m2 is 0.97.

$$\Delta w = |wc_{2^*}^3 - avgwc_{2^*} \times k_{2^*}| = 0.2$$

$$\min(\Delta w - w_2^i)_{\forall i \in c_3} = 0.01 \text{ for } i=10.$$

Hence, the workload of part type 10 is assigned to m2 in cell 2. As a result, the average workload on m2 and m2* is .97 and .97, respectively. The number of exceptional elements has now reduced from 26 to 23.

The workload induced by cell 1, 2 and 3 on the machine m4 is 1.82, 0.51 and 1.67. Therefore, Two identical machines (m4*) has been assigned to cell 1 and processing part type (6, 8 11) table 6. Three units of m4 have been assigned to cell 3 and processing part type (1, 2, 3, 7, 9, 10 and bottleneck part 5). The average workload 4 $avgwc = 0.73$ and 4* $avgwc = 0.91$. it indicates that the machine is under acceptable utilization level.

Table 8: Final Cell configuration ((After Optimal Allocation of identical machines in different cells))

		Machine Type														
		1	3	4*	8*	9*	2	6	7	9	2*	4	5	6*	8	
components	6	0.74	0.38	0.75	0.65	0.67					0.71					
	8	0.60	0.43	0.65	0.54											
	11	0.65	0.19	0.42	0.23	0.43										
	14		0.17		0.14	0.20										
	15	0.49	0.54		0.67	0.63										
	4						0.47	0.32	0.19	0.32						
	5						0.39	0.37	0.52	0.53		0.51				
	12						0.36	0.28	0.37	0.50						
	13						0.52	0.51	0.42	0.37						
	1			0.28								0.24	0.39		0.21	
	2	0.16	0.13							0.09		0.25	0.23		0.26	
	3											0.36	0.63	0.29	0.59	0.62
	7											0.06	0.11	0.08	0.10	0.12
	9											0.80	0.35	0.52	0.77	0.52
	10						0.19					0.09	0.18	0.26	0.20	
Load		2.64	2.11	1.82	2.24	1.93	1.94	1.48	1.51	1.81	1.93	2.18	1.68	1.72	1.93	
Number of machines		3	3	2	3	2	2	2	2	2	2	3	2	2	2	

Table 9: Workload induced by the cells on each Machine Types

	Machine Type													
	1	3	4*	8*	9*	2	6	7	9	2*	4	5	6*	8
Cell1	2.48	1.70	1.82	2.24	1.93					0.71				
Cell2						1.74	1.48	1.51	1.72		0.51			
Cell3	0.16	0.41				0.19				1.22	1.67	1.68	1.72	1.93

NOTE: (* indicates the duplicate machine)

Similarly other identical machines have been assigned to appropriate cells. Table 8 shows the final solution and total/average workload on the machines. The number of exceptional elements are seven. The total intercell movement of parts is 8 (considering unit demand). The average workloads on the identical machine type (2, 4, 6, 8, 9) in their respective cells are (97%, 97%), (91%, 73%), (74%, 86%), (75%, 97%) and (97%, 91%) respectively. All the machines are in acceptable utilization level. The value of group technology efficiency and load variation index is 0.8519 and 0.0477 respectively. The 13 value of performance measure is 0.8113. Table 8 shows the resulted formation of cells. The total cost of final cell configuration is \$36,24,680.85. 6.1 Result Comparison The significance of considering important production factors in the design of cell formation has been analyzed on the basis of cost factor and group technology efficiency. Table 5 shows the cell configuration with considering the operation sequence only. The number of exceptional elements is 26 and the group technology efficiency is 0.5370. Such solution seems to be incomplete, as it does not provide any information regarding the number of machines of each type required to meet production demand within the schedule date. Table 6 is the replacement of operation sequence data by the workload

induced by the parts on the machines. The cumulative load on the machines, due to different parts, evaluates the required number of machines. The cost of the given cell configuration is found to be \$ 36,30,566.25 . The average workload on the identical machines is uniform. Table 8 shows the final machine/part grouping with proper allocation of identical machines to different cells. The cost of given cell configuration is \$ 36,24,680.85. Hence, the cost is reduced by \$ 5,885.40. The number of exceptional elements has been reduced by 19. The group technology efficiency is 0.8519. The algorithm has been implemented for the large number of problems. The result of few of them is given in the appendix. Complete data sets can be obtained from the authors upon request.

Conclusion

In this paper, an efficient algorithm for multi-objective machine-part grouping problem has been proposed. While most of the existing methods of grouping are solely based on binary machine-part incidence matrix and a few have used either the operations sequence or combination of processing time, setup time, part demand, machine capacity, material handling capacity and lot size. Simultaneous consideration of all these factors makes the cell formation problem complex but more realistic. This paper addresses the machine-part grouping problem considering all of these production parameters simultaneously. In real manufacturing system, there are multiple identical machines of some machine type and the number of machines is determined by capacity requirement, which should be constraint in the design of cellular manufacturing system. Therefore, the proper assignment of identical machines into different cells is important in designing of cellular manufacturing system. This fact is taken into consideration in the phase-II of the proposed algorithm. A cost based comparison is made to justify the importance of phase-II.

The algorithm was applied to the numerical problems reported in different research papers and computational experience has been reported. The results obtained suggested that the algorithm is efficient and provides better solutions. The algorithm was also tested for large problems and the quality solution was obtained within acceptable time. The proposed heuristic approach is also capable of solving the industrial problems. This approach incorporates many of the real-life production parameters. Hence, it is bound to provide a solution that is closer to implementation in real life.

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An Efficient Algorithm for the Machine/Part Grouping Problem Considering Machines Overloading and Important Production Parameters

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Appendix

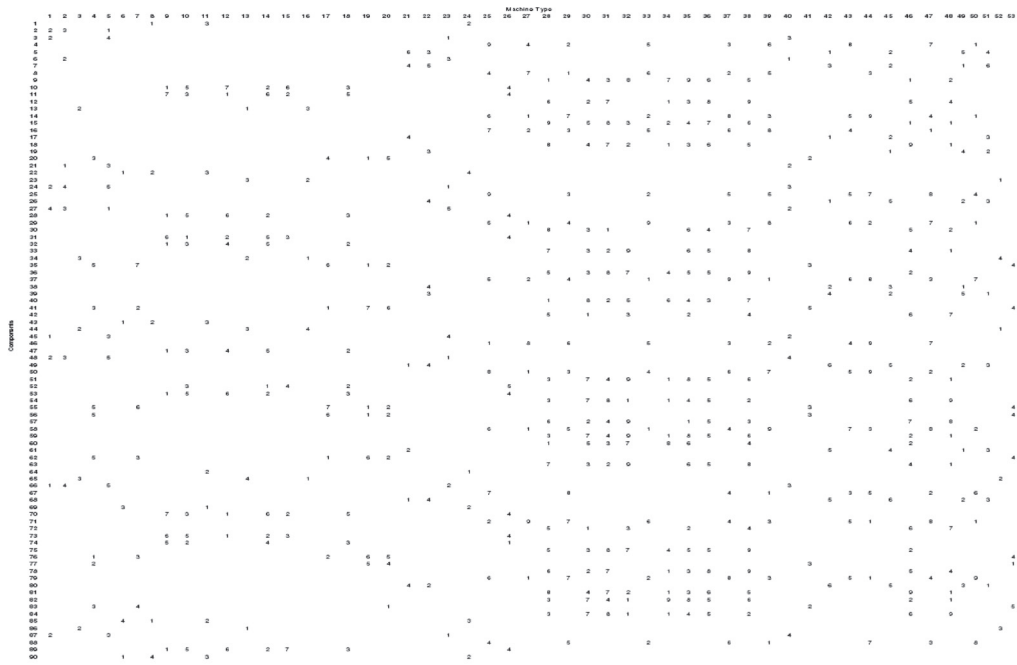


Figure 1: Data set 1 (Machine-part sequence matrix)

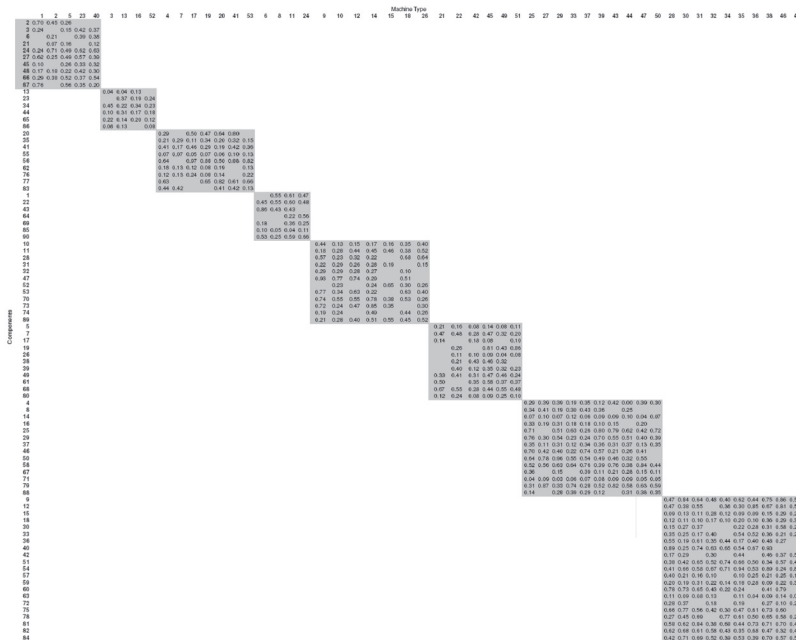


Figure 2: Solution (Data set 3) (Number in matrix indicates workload on machine induced by respective parts)

An Efficient Algorithm for the Machine/Part Grouping Problem Considering Machines Overloading and Important Production Parameters

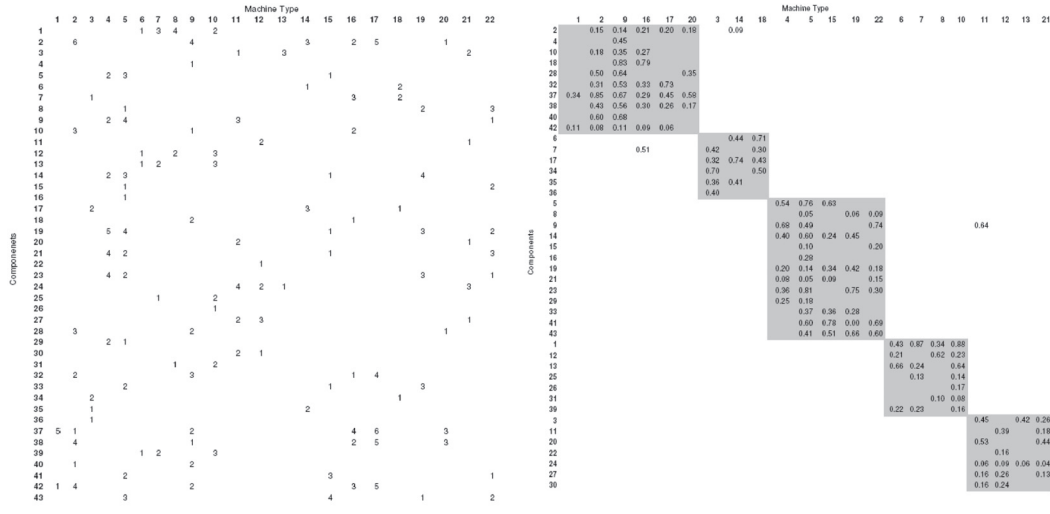


Figure 3: Data set 2 (left) and its solution (right) (King 1980)

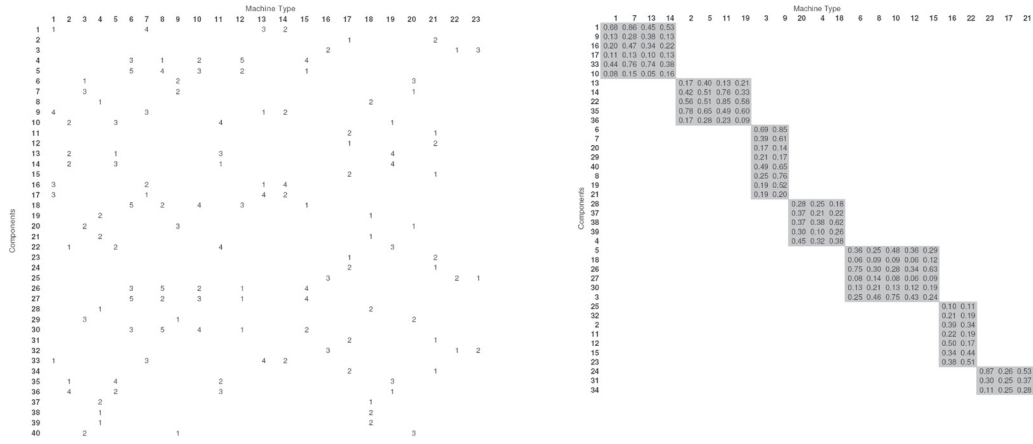


Figure 4: Data set 3 (left) and its solution (right) (Chandrashekhara & Rajagopalan 1989)