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RMS Cell Formation using Block Diagonalized Matrix

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Abstract

Objectives: To develop a methodology for cell formation (i.e. recognition of part families and corresponding operation groups) for a Reconfigurable Manufacturing System (RMS) using a block diagonalized matrix. **Method:** Like Cellular Manufacturing System (CMS), the foundation of RMS lies on the premise of group technology. The present work highlights the peculiarities of RMS Vis a Vis CMS. CMS cell formation problem has a vast literature available. The present work intends to evolve a methodology for RMS cell formation relies on adapting suitably a CMS cell formation methodology with RMS peculiarities in focus. The method consists of two steps, first the matrix representing part-operation data is diagonalized and then the adapted cell formation methodology is applied on this diagonalized matrix to form the RMS cells. **Findings:** The effectiveness of the proposed methodology has been compared with some standard problems from the CMS literature and reported to work satisfactorily. **Novelty/Improvement:** The present work provides an initial framework for the RMS design which is a promising Manufacturing System paradigm for future. General Terms: Cell Formation, Reconfigurable Manufacturing Systems.

Keywords: Cell Formation, Group Technology, Operation Group, Part Family, RMS

1. Introduction

In the present market scenario, companies are forced to compete in product varieties and speed to market as well as in price[1]. A manufacturing enterprise cannot stay competitive and survive without agile and swift adapting to this increasingly turbulent manufacturing environment[2]. To face these challenges, a new manufacturing paradigm is proposed[3], namely Reconfigurable Manufacturing System (RMS) that has the capability to provide the capacity and functionality as and when required. In this manufacturing paradigm, the customer's varying demands are fulfilled as the machines can be reconfigured to provide different functionality and capacity simply by incorporating their basic (slide ways, base, columns etc.) and auxiliary (tool changer, spindle head, spacer etc.) modules[2-4]. The built-in modular structure of basic and auxiliary modules along with the open architecture software plays an important role in the execution of Reconfigurable Machine Tools (RMTs)[3,4] and hence provides the particular operational capability to the machine[5].

Group Technology (GT), the management philosophy of handling similar problems together, has found essential place in most of new manufacturing paradigms. GT was core to the concept of Cellular Manufacturing System (CMS) in which manufacturing is done in machine cells which can manufacture a family of parts grouped together due to similarity in their manufacturing requirements. The Group Technology has also been used to form part families in Flexible Manufacturing System (FMS) and Virtual Cellular Manufacturing System. In RMS too, the issue of finding appropriate part families and corresponding operation groups is innermost to the problem of RMS design. It is also founded on the philosophy of GT taking advantage of the RMT design characteristics and similarities of manufacturing requirements[6].

In RMS, part family formation is considered as the first step to implement it. In following paragraphs, RMS literature has been overviewed where the part family formation base on GT philosophy has been dealt with.

In[7] has suggested that at the design stage itself, it must be ensured that the parts have similar routes so that they can be considered to be falling in same part family and hence the reconfiguration effort and cost is minimised. A. In[8] have also emphasised the importance of considering operational issues of assembly systems at the early product design stage for minimisation of reconfiguration effort. In

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this work an analytical model has been proposed in two sub-problems: operation assignment and scheduling of products.

In[9-11] stochastic model of an RMS has been proposed where each part family of products uses one system configuration. The model has four stages: a framework, optimal configurations, and optimal selection policy and performance measure. The authors initially developed the algorithm to select optimal configuration of each part family from several feasible configurations so as to maximize the profit. In[12] generic RMS model has been proposed in which each configuration can not only produce a variety of products grouped into a family, but also give a positive response to new products introduced within each family by dividing the stages into strategic and tactical levels. In[5], the cellular layout problem is handled with reconfigurable machines. The authors have considered the changes in the basic and auxiliary modules to perform variety of operations in a cellular layout through Reconfigurable Machine Tools (RMTs). In[13] two phased approach for optimal selection of RMS configurations in which they proposed near optimal alternative configurations for different demand scenarios and Genetic Algorithm (GA) has been applied to determine alternative solutions but they have handled physical machine arrangement.

In[1] have clearly recognised that the effectiveness of a RMS depends on the formation of the best set of product families. They used similarity between pairs of products to carry out hierarchical clustering procedure on parts to be divided into families. In[6], have proposed an RMS model which is characterised by highly variable demand, compulsion to adopt new processes, frequent changes of the product mix and frequent introduction of new products. The authors have suggested considering the part families' primary reconfiguration sequence and secondary reconfiguration sequence according to the various combinations of the basic modules and auxiliary modules in RMT configurations. Their research has presented a logical and systematic procedure to group the parts into families and simultaneously an operation sequence has been selected from a set of operation sequences for each part. Therefore, an operation group corresponding to each part family has also been recognized. The base of this work is founded on recognition of part families using heretical clustering method adapted to work with alternative operation sequences.

It can be observed that earlier papers on reconfiguration of manufacturing systems have focussed on designing the products at the outset to have similar manufacturing requirements [e.g. 7,8]. But for an industry that has hundreds of parts in its portfolio, it is practically impossible to achieve this goal. Later research, especially after the RMS paradigm is envisaged, has recognised the unavoidable variability of manufacturing requirements. Though most of the authors have taken part family as the basis of manufacturing planning in RMS, there are only a few papers [e.g. 1,5,6 etc.] on developing methodology for the same.

2. RMS VIS A VIS CMS

In CMS, various part families recognised are to be manufactured on their corresponding machine cells in different locations of the plant area. Therefore, the primary focus is on formation of machine groups and consequently the part families are recognised. This is due to the fact that the CMS was envisaged to overcome the shortcomings of existing process layout of the manufacturing system that uses conventional machine tools. Intercellular movements of parts are allowed to fulfil operational demand of certain parts in the part families. The most common or uncommon machines are provided at central locations. Therefore, in general, while using clustering methods for CMS, machines are taken as entities to be grouped and the parts are considered as attributes of machines on the basis of which machine cells are formed.

In case of RMS, it is envisaged that the manufacturing system is configured at the outset exactly as per the manufacturing requirements providing exact functionality and capacity at a particular location in the plant area. Next part family is considered for manufacturing after completion of manufacturing one part family by reconfiguring the manufacturing system at the same location in the plant area[2]. Also, in RMS manufacturing operations are considered instead of machines as the machines are configured to provide these operations as required. RMS has no question of intercellular movements as all the operations/functionalities have to be provided in the RMS cell. Therefore, in RMS the primary focus is on formation of part families and consequently the operation groups are recognised.

Therefore in the present work, it is proposed, while using clustering methods for RMS, parts are taken as entities to be grouped and the operations are considered as attributes of parts on the basis of which part families will be formed.

3. Important Terms and Concepts

In this section, first the notations used in this work are given in sub-section 3.1. Thereafter, in sub-section 3.2 the common terms and concepts from the cell formation literature which are used in this work also are briefly revisited. In the present work few new concepts are evolved and accordingly terms are also coined which are described in subsections 3.3 to 3.5.

3.1 Terminology and Notations

POIM Part Operation Incidence Matrix
PPFD Part Pair's Family Desirability
PFSM PPFD Score Matrix
P Total number of parts to be manufactured
O Total number of operations required by P parts
C Maximum number of RMS cells
p,o,c Index for parts, operations, cells
N,n Number of rows of POIM, PFSM

$$a_{po} \begin{cases} 1, & \text{if part p requires processing on operation o} \\ 0, & \text{Otherwise} \end{cases}$$

3.2 Terms and Concepts

3.2.1 Part Operation Incidence Matrix (POIM)

In Part Operation Incidence Matrix (POIM), the set of machines which are required to process each part is summarised in 0-1 form. The matrix element a_{po} is equal to 1 if the part p is required by the operation o; it is equal to 0 other-wise. The POIM size is P x O. It is to note that the array of incidence does not explicitly consider the sequence of operations for individual parts. An example 7 x 5, POIM is given in Table 1.

Table 1. Example of POIM

Operation → **Part ↓**	**1**	**2**	**3**	**4**	**5**
1	1	0	1	1	0
2	1	0	0	1	0
3	0	1	1	0	1
4	0	1	1	0	1
5	1	0	1	1	0
6	0	1	0	0	1
7	0	1	0	0	1

3.2.2 Diagonalized POIM

The diagonalized POIM is generated from POIM using an algorithm to sort the matrix into best possible blocks. Examples of the most popular block diagonalization methods from CMS literature are Rank-order clustering (ROC), Direct Clustering Analysis (DCA), Single Linkage Clustering (SLC), Complete Linkage Clustering (CLC), Average Linkage Clustering (ALC), Linear Cell Clustering (LCC) and Bond Energy Algorithm (BEA)[14].

These clustering methods are also called matrix manipulation methods which attempt simultaneous grouping of parts and machines through block diagonalization by reordering rows and columns of the binary incidence matrix. Table 2 gives an example of Diagonalized POIM based on POIM given in Table 1.

Table 2. Example of Diagonalized POIM

Operation → **Part ↓**	**1**	**4**	**3**	**2**	**5**
2	1	1	0	0	0
1	1	1	1	0	0
5	1	1	1	0	0
3	0	0	1	1	1
4	0	0	1	1	1
6	0	0	0	1	1
7	0	0	0	1	1

3.3 Part Pair's Family Desirability (PPFD)

Let us suppose we have a pair of parts p1 and p2, represented as (p1 p2) and a pair of operations o1 and o2 represented as (o1 o1). The desirability of part pair (p1 p2) to be grouped together as a part family has been abbreviated as PPFD. It may have 4 different levels from 0 (the least) to 4 (the maximum) depending upon their operational requirements for o1 and o2 as described below.

- The least PPFD corresponds to following situations:
    - None of the two parts use any of the two operation
    - One part uses only one operation and the other uses none
    - Each part require one operation that is not required by the other

The examples of above cases are as given in Table 3 to Table 5.

Table 3.

	o1	o2
p1	0	0
p2	0	0

$$a_{po} = a_{p(o+1)} = 0$$
$$a_{(p+1)o} = a_{(p+1)(o+1)} = 0$$

Table 4. Desirability Level-1

	o1	o2
p1	1	0
p2	0	0

$$a_{po} \neq a_{p(o+1)}$$
$$a_{(p+1)o} = a_{(p+1)(o+1)} = 0$$

Table 5.

	o1	o2
p1	1	0
p2	0	1

$$a_{po} \neq a_{p(o+1)}$$
$$a_{(p+1)o} \neq a_{(p+1)(o+1)}$$

- For second level PPFD the situation is that both the parts require same one operation but none require the other or vice versa referred Table 6.

Table 6. Desirability Level-2

	o1	o2
p1	0	0
p2	1	1

$$a_{po} = a_{p(o+1)} = 0$$
$$a_{(p+1)o} = a_{(p+1)(o+1)} = 1$$

- Third level of PPFD corresponds to the situation when both the parts require same one operation and only one part require the other referred Table 7.

Table 7. Desirability Level-3

	o1	o2
p1	1	1
p2	0	1

$$a_{po} = a_{p(o+1)} = 1$$
$$a_{(p+1)o} \neq a_{(p+1)(o+1)}$$

- The maximum PPFD is when both the parts require both the operations as shown in Table 8.

Table 8. Desirability Level-4

	o1	o2
p1	1	1
p2	1	1

$$a_{po} = a_{p(o+1)} = 1$$
$$a_{(p+1)o} = a_{(p+1)(o+1)} = 1$$

3.4 PPFD Score

PPFD scores as given in Table 9 are proposed depending upon the desirability level of the part pair to be grouped as a family. These scores are decided after all possible trials on different situations.

Table 9. PPFD Levels and Scores

Desirability Level	Desirability Score
Level-1	0
Level-2	1
Level-3	2
Level-4	4

For PPFD Score = 0, there are four different cases as mentioned below:--

For PPFD Score = 1, there are four different cases as mentioned below:--

For PPFD Score = 2, there are two different cases as mentioned below:--

$a_{po} = a_{p(o+1)} = 0$ $a_{(p+1)o} = a_{(p+1)(o+1)} = 0$	$a_{po} \neq a_{p(o+1)}$ $a_{(p+1)o} = a_{(p+1)(o+1)} = 0$	$a_{po} = a_{p(o+1)} = 0$ $a_{(p+1)o} \neq a_{(p+1)(o+1)}$	$a_{po} \neq a_{p(o+1)}$ $a_{(p+1)o} \neq a_{(p+1)(o+1)}$ $a_{po} \neq a_{(p+1)o}$

$a_{po} = a_{p(o+1)} = 1$ $a_{(p+1)o} = a_{(p+1)(o+1)} = 0$	$a_{po} = a_{p(o+1)} = 0$ $a_{(p+1)o} = a_{(p+1)(o+1)} = 1$	$a_{po} = a_{(p+1)(o)} = 1$ $a_{p(o+1)} = a_{(p+1)(o+1)} = 0$	$a_{po} = a_{(p+1)(o)} = 0$ $a_{p(o+1)} = a_{(p+1)(o+1)} = 1$

$a_{po} = a_{p(o+1)} = 1$ $a_{(p+1)o} \neq a_{(p+1)(o+1)}$	$a_{po} \neq a_{p(o+1)}$ $a_{(p+1)o} = a_{(p+1)(o+1)} = 1$

For PPFD Score = 4, there is one case as mentioned below:-

$$a_{po} = a_{p(o+1)} = 1$$
$$a_{(p+1)o} = a_{(p+1)(o+1)} = 1$$

3.5 PPFD Score Matrix (PFSM)

PFSM is a (P-1) x (O-1) matrix, where rows represent part pairs, columns represent operation pairs and an element represents the PPFD score value for the corresponding part pair and operation pair. Table 10 gives an example 6x4 PFSM based on a 7x5 POIM given in Table 2.

4. Problem Formulation

In the light of the reviewed literature, the present work attempts to propose a methodology to form RMS cells. It has been assumed the POIM formed using the operation sequence information is already diagonalized using any of the methods available in literature as enlisted in sub-section 3.2.2.

Since the issue of exceptional elements is not handled by way of allowing intercellular movements as in CMS, but by configuring RMTs for providing all the operations needed by the family. Therefore, in the proposed method for cell formation the issue of part family formation has been treated as a first and operation group recognition as a subsequence.

The presence of voids and exceptional elements leads to underutilization of capacity therefore; the methodology has been designed to deal with the issue to keep their number at the minimum in the selected part family.

5. Description of Methodology

The proposed methodology for RMS cell formation (part family formation and identification of corresponding operation groups), depicted as a flow chart in Figure 1 has been divided into following procedural steps:

Step 1: Diagonalizable POIM using any standard POIM diagonalization method.

Step 2: Draw PPFD Score Matrix (PFSM) for the diagonalized POIM.

Step 3: Set a counter variable 'i' equal to 1.

Step 4: Select i^{th} row and find value of PPFD score of '4' in the PFSM. If i^{th} row is not having value of PPFD score of '4', go to next row by incrementing i^{th} value by one.

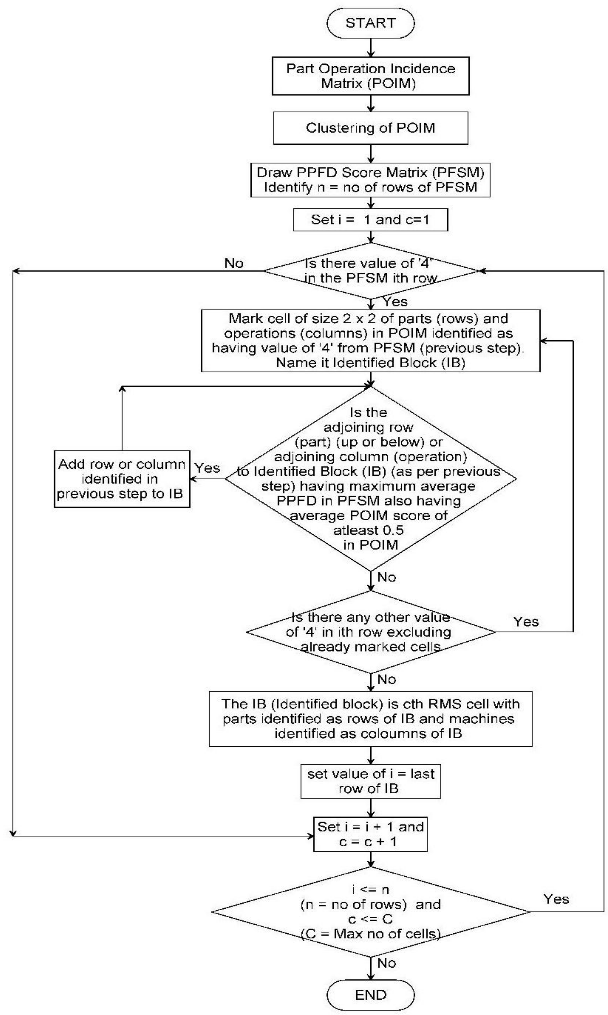

Figure 1. Flow Chart of the Proposed Methodology.

Step 5: Mark the cells of size 2x2 (parts x operations) in POIM identified as having value of '4' from PFSM. Give this cell name of 'Identified Block' (IB).

Step 6: Find the adjoining row (part) (up or below) or adjoining column (operation) to the IB (as per previous step) having maximum average PPFD from PFSM. If the corresponding adjoining row / column having maximum PPFD in POIM also having value of minimum average POIM score of 0.5, add the corresponding row (part) or column (operation) to the already IB. The size of IB now is increased by either one row or one column. The process of adding either row or column to IB continues until we get the value of average POIM score less than 0.5 in POIM of adjoining row or column to IB identified as having maximum average PPFD from PFSM gets.

Step 7: Find the rows of IB having any other value of '4' excluding cells of IB in PFSM. Although there will be very less probability of finding such value because we are already having block diagonalized POIM. In such exceptional cases we again go to step 5 again and process is repeated again from step 6 to step 7.

Step 8: The Identified Block (IB) of POIM is now our c^{th} RMS cell having rows identified as part family and columns identified as operation group.

Step 9: The value of 'i' is now set as last row of IB.

Step 10: The value of 'i' and 'c' are incremented by '1'.

Step 11: Check whether value of 'i' is less than equal to 'n' (number of rows of PFSM) and value of 'c' is less than 'C' (maximum number of cells). If this is true we go to step 4 again and repeat steps from step 4 to step 11, otherwise the process is stopped and the IB's becomes RMS cells.

After the above procedure, if some parts are not allotted among RMS cells, such cases will be dealt manually, by lowering the value of PFSM score.

5.1 Demonstration through Example

For demonstrating the procedure POIM taken as example shown in Table 1 has been considered.

Step 1: The POIM is Block Diagonalized using Bond Energy Algorithm. The diagonalized POIM has been shown in Table 2.

Step 2: In this step PPFD Score Matrix (PFSM) is formed as shown in Table 10.

Table 10. Example of PFSM

	(o1 o4)	(o4 o3)	(o3 o2)	(o2 o5)
(p2 p1)	4	2	0	0
(p1 p5)	4	4	1	0
(p5 p3)	1	2	2	1
(p3 p4)	0	1	4	4
(p4 p6)	0	0	2	4
(p6 p7)	0	0	1	4

Step 3: The value of 'i' is set equal to '1'.

Step 4: Select the i^{th} row and find value of PPFD score of '4' in the PFSM. In this example, we find PPFD score of '4' in first cell of PFSM. The parts and operation corresponding to this cell are p1; p2 and o1, o2.

Step 5: Mark the cells (containing p1, p2 and o1, o2) of size 2x2 (parts x operations) in POIM identified as having value of '4' from PFSM. Give this cell name of 'Identified Block' (IB).

Step 6: Find the adjoining row (part) (up or below) or adjoining column (operation) to the IB (as per previous step) having maximum average PPFD from PFSM. So, the row immediately below IB is cell containing (p1, p2 and o1, o2), i.e. cell of (p1, p5 and o1, o4) is having maximum PPFD of '4' compared to value of '2' on right side of IB (cell of p2, p1 and o4, o3). The average POIM score of this identified row is checked from POIM which is '1'. As the score is greater than '0.5', so we add row containing part 5 to IB in POIM. Size of IB now become 3 rows and 2 columns (parts p2, p1, p5 and operations o1, o4). The process of adding either row or column to IB continues until we get the value of average POIM score less than 0.5 in POIM of adjoining row or column to IB identified as having maximum average PPFD from PFSM gets. The IB after first set of iterations becomes of size 3 x 3 which includes parts 2,1,5 and operations 1,4,3.

Step 7: As there is no rows of IB having any other value of '4' excluding cells of IB in PFSM, so we move to step 8.

Step 8: The IB of POIM is now our 1^{st} RMS cell having parts 2,1,5 identified as part family and operations 1,4,3 identified as operation group.

Step 9: The value of 'i' is now set as 3 which is last row of IB.

Step 10: The value of i=i+1, becomes 4 and value of c=c+1 becomes 2.

Step 11: As value of i=4 is less than n=6 (number of rows of PFSM), so we go to step 4 again and repeat steps from step 4 to step 11. And, the process is continued till either value of i becomes greater than n or c becomes greater than C.

Final formulation of part families and operation cells by PFSM is given in Table 11.

Table 11. Part Families and Operation Groups

Operation → **Part ↓**	**1**	**4**	**3**	**2**	**5**
2	1	1	0	0	0
1	1	1	1	0	0
5	1	1	1	0	0
3	0	0	1	1	1
4	0	0	1	1	1
6	0	0	0	1	1
7	0	0	0	1	1

Table 12. Comparison of PFSM results with Problems from Literature

S. No	References	Size Parts x machines	Grouping Efficiency η		Grouping Efficacy τ		BEM η_{BE}	
			η	By PFSM	τ	By PFSM	η_{BE}	By PFSM
1	15	15 x 9	0.80	0.88	0.61	0.71	0.90	1.18
2	16	15 x 12	0.61	0.81	0.71	0.60	0.8	1.2
3	17	25 x 15	0.89	0.89	0.79	0.80	1.37	1.50

6. Results

The proposed algorithm is found to run satisfactorily with minimum average PPFD score of 0.5 for identified block. The performance of the algorithm is compared using three different performance measures with three problems from the literature as given in Table 12. The better results of various performance measures, namely Grouping Efficiency (η), Grouping Efficacy (τ) and BEM (η_{BE}) obtained by PFSM are highlighted in bold. All the results obtained from the proposed methodology are better except Grouping Efficacy value (τ) in case of second problem.

7. Conclusions and Future Scope

There is a vast literature available on CMS cell formation. But, due to its limitations in the background of current market scenario, it has practically become obsolete. RMS has emerged as a new manufacturing paradigm that has potential to face all modern day manufacturing challenges. Like CMS, RMS too is founded on GT based cell formation. This work is an effort to evolve a methodology for RMS part family formation. The present work considers only the operations required by parts as available in operation sequences as GT attributes. In future work, flow direction of operation sequences and more production related parameters can be considered to solve the problem more realistically.

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