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PART FAMILY FORMATION FOR RECONFIGURABLE MANUFACTURING SYSTEM CONSIDERING ALTERNATIVE OPERATION SEQUENCES

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ABSTRACT

Reconfigurable Manufacturing System (RMS) has been envisaged to fulfil the dynamic requirements of present manufacturing environment by adjusting its capacity and functionality. The proposed methodology is consisting of three stages. In the first stage, the clustering of Part Operation Incidence Matrix (POIM) is done by using a standard clustering technique. In the second stage, one operation sequence is selected for each part type. Finally, the reduced POIM corresponding to operation sequences selected in the last stage is used for simultaneous formulation of part families and operation groups. The proposed methodology has vast potential for experimentation with other CMS clustering methods.

INTRODUCTION

Manufacturing companies in the 21st century face increasingly frequent and unpredictable market changes driven by global competition, including rapid introduction of new products (Koren Y and Shpitalni M, 2010), reducing lead times, increasing quality and variety. To remain competitive in such a scenario, companies must design manufacturing systems that not only produce high-quality products at low cost, but also allow for rapid response to market changes and consumer needs. For achieving this, the manufacturing system must be able to yield different batch sizes from different product types, with the exact capacity and functionality in each case.

Dedicated Manufacturing Lines (DMLs) are capable of producing the similar products in bulk but are incapable of accommodating the product variety. Cellular Manufacturing Systems (CMS) offer an efficient way to handle large product variety in intermediate batch sizes but they face fast obsolesce and rendered useless with the change of product portfolio (Kumar R 2010; Rajamani D et al., 1996). CMS has also failed to win the favour of practitioners due to lower utilisation of labour and machine and higher investment due to duplication of machines and tools (Singh N and Rajamani D, 2012). Although flexible manufacturing systems (FMS) do respond to product changes; but they are not designed for structural changes (Koren Y et al. 1999 and 2010) and therefore cannot respond to abrupt market fluctuations. Besides the cost of FMSs are very high and therefore have very limited acceptability among the manufacturers (Mehrabi MG et al., 2000).

Koren Y et al. (1999, 2010) named Reconfigurable Manufacturing Systems (RMS) as a new class of system which has the capability to adjust both capacity and functionality in order to cope up with product variety and production volume (ElMaraghy HA, 2005). Like CMS and FMS, RMS also has its foundation in the philosophy of "Group Technology" (GT). The present research work is an attempt to explore cell formation literature for GT based manufacturing systems with an objective to adapt and evolve a methodology for RMS part family formation with consideration of alternative operation sequences.

The present paper is organized in six sections. In second, firstly the manufacturing paradigm of RMS has been introduced and thereafter various cell formation techniques have been reviewed. This section also reviews the limited literature on part family formation for RMS. In third section, on the basis of the observations from the reviewed literature the proposed RMS model is postulated and thereafter terms used in this work are given in fourth section. Fifth Section presents the proposed procedure for RMS part family formation. Section sixth presents results obtained on 4 problems adapted from CMS literature and finally, last section concludes the work with remarks on scope for future work.

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LITERATURE BACKGROUND

The problem of part family formation for Reconfigurable Manufacturing Systems (RMS) first requires understanding what exactly RMS refers to. Then, in order to evolve part family formation methodology for RMS, the extensive research on cell formation techniques for other GT based manufacturing systems need to be reviewed to explore the possible adaptation. In the ensuing subsections these issues have been explored for preparing the necessary background for the work reported in this paper.

Reconfigurable Manufacturing System (RMS)

It has been envisaged that the challenges posed by present-day global market environment could be faced if we have a responsive manufacturing system that can be created by incorporating basic process modules, both hardware and software, that can be rearranged quickly and reliably (Kumar R et al., 2010; Koren Y et al., 1999; Koren Y 2010; Mehrabi MG et al. 2000 and 2002). A manufacturing system to fulfil this objective was proposed by (Koren Y et al., 1999), in the Engineering Research Centre for Reconfigurable Manufacturing Systems (ERC/RMS) at the University of Michigan College of Engineering. It was named as "Reconfigurable Manufacturing System (RMS)" and defined as, "A system designed at the outset for rapid change in its structure, as well as in its hardware and software components, in order to quickly adjust its production capacity and functionality within a part family in response to sudden market changes or intrinsic system change". This has later been acknowledged and supported by other researchers (Kumar R et al., 2010; Koren Y et al., 2010; ElMaraghy HA, 2009).

From the viewpoint of RMS, a manufacturing system should be designed in such a way that it can be rapidly and cost-effectively reconfigured to the exact capacity and functionality needed to match a new market demand. The situation is particularly severe in manufacturing enterprise which offers a large and variable product mix with short product life cycles and variable demand volumes (Koren Y et al., 2010). RMS acquires its advantages because of several inherent design characteristic of its components, incorporated at machine level as well as at system level, such as Modularity, Integrability, Customization, Ease of Mobility, Convertibility, Scalability and Diagnosability (Koren Y et al., 1999; Mehrabi MG et al., 2002; Gumasta K et al., 2011).

Cell Formation in Cellular Manufacturing Systems

The cell formation problem in manufacturing systems is the decomposition of the manufacturing systems into cells. In Cellular Manufacturing System (CMS) as well as in Flexible manufacturing System (FMS), part families are identified such that they are fully processed within a cell, capturing the inherent advantages of GT (Hazarika M and Laha D, 2016). Part family formation is a prerequisite for the efficient manufacture of parts in groups and is probably the main determinant for the overall effectiveness of the cell system of production (Singh N and Rajamani D, 2012). (Chan et al., 1982) described Cellular manufacturing (CM) as a practice that applies GT philosophy to create mutually separable machine cells. (Groover M and Zimmers EW, 1983) described CMS in which parts are grouped together into families on the basis of design and manufacturing attributes to take advantages of their similarities. The central concerns in designing a CMS are to group machines into cells and to allocate parts to these cells in such a way to minimize the required intercellular moves (Nsakanda AL et al. 2006; Vakharia AJ and Chang YL, 1997). As proposed by Wemmerlöv U and Hyer NL (1987), the aim of the part family and machine group formation is to reduce set up and flow times and therefore to reduce inventory and market response times.

Initially, Burbidge JL (1991) proposed a methodology called Production Flow Analysis (PFA) to find a complete division of all the existing machines into associated groups by analysing information in the process routes for parts. Such methods are descriptive methods for the cell formation. In general, these procedures can be grouped into three major categories (Wemmerlöv U and Hyer NL, 1987): Machine groups identification (MGI); Part families' identification (PFI) and Part families/machine grouping (PF/MG). One of the major drawbacks of this method is that it takes the route details the way they are, no check for optimal, consistent or logical routing (Halevi G, 2001).

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Part family formation in RMS

The formation of part families is a core issue in RMS. The key characteristic of RMS part families is to manufacture the components within a family concurrently which may require similar facilities. There are only a few studies on the part family formation of an RMS in the available literature. Majority of them are reviewed below. As an initial attempt, in this work, the implementation of array based clustering methods for CMS cell formation has been explored due to simplicity of their implementation and a method has been suitably evolved for RMS part family formation keeping its peculiarities in consideration.

Abdi MR and Labib AW (2003, 2004) proposed a generic RMS model where 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. Pattanaik et al. (2007) have attempted the cellular layout problem with reconfigurable machines. They have considered the changes in the basic and auxiliary modules to perform variety of operations in a cellular layout through reconfigurable machine tools. Galan R et al. (2007) suggested a mathematical model for selecting families of products that minimizes the costs of reconfiguration and under-utilization of machines by travelling salesman problem which identifies the reconfiguration sequence which reduces the cost and finally uses the hierarchical modelling to generate a dendogram which gives a set of families of different similarity levels. Xiaobo Z et al. (2001) has described RMS as a manufacturing system configured to produce a family of products that share common features. A framework has been proposed for a stochastic model of an RMS, which includes three core issues namely: the optimal configurations in the design, the optimal selection policy in the utilization, and the performance measure in the improvement. Mesa J et al. (2014) noted that the process of part family formation includes the components sharing, functional characteristics and manufacturing processes and further analyzed the characteristics of a part family.

PROBLEM FORMULATION

The problem of exceptional elements has been tackled in CMS by way of allowing intercellular movements. It decreases the machines requirement and increases the machine utilization but it also results into increased material handling making the production planning more complex. RMS enables reconfiguration of machines using common resources therefore the issue of exceptional elements is tackled within the cell. Explicit consideration of alternative operation sequences provides some additional flexibility in the design of RMS and the proposition of selecting only one operation sequence for each part in the family intends to lower net material flow and production planning complexity. Therefore, the problem has been formulated as a part family formation problem considering alternative operation sequences with no consideration to intercellular movements.

The proposed Reconfigurable Manufacturing System has been assumed to have following characteristics:
1. Each part type has a set of alternative operation sequences (maximum five), either of which can be used to manufacture it.
2. RMS can be reconfigured using Reconfigurable Machine Tools (RMTs). An RMT can be configured using basic and auxiliary modules (Mehrabi MG et al. 2000).
3. Only one operation sequence for each part from among its set of various alternative operation sequences will be selected for each part type. It would not be preferable to execute all process plans to avoid enhanced complexity of production planning and associated costs.
4. In the proposed RMS model equal priority is given to all the alternative operation sequences.
5. The processing time for all types of operations on different RMTs is known and constant.
6. The capabilities and capacity of each RMT configuration is known and constant over planning horizon.
7. Intercellular moves are not considered.

NOMENCLATURE

In this section, the notations used in this work are given:

POIM	Part Operation Incidence Matrix
BEM	Bond Energy Measure
PEC	Percent Efficiency Change
PPFD	Part Pair's Family Desirability

PSM	PPFD Score Matrix
P	Number of part types
N	Total number of alternative operation sequences for all P part types
O	Number of operations in the complete set of N operation sequences
Q	Number of operations in the selected set of P operation sequences having only one operation sequence for each part
J_p	Number of alternative operations sequences available for part type p;
a^j_{po}	1, if part p requires operation o in alternative sequence j
	0, otherwise
p	Index of part types; p = 1,2,…, P
j	Index of alternative operation sequences of part type p; j= 1,2,…, J_p
o	Index of operations; o = 1,2,…, O
i	Index of row numbers of POIM; i = 1,2,.... N
η	Clustering performance measure for a POIM
η'	Clustering performance measure for a POIM after removal of its one row

METHODOLOGY

The proposed methodology carrries out part family formation and identification of corresponding operation groups simultaneously through three sequential stages as depicted in Figure 1. The detailed procedural steps have been presented in as a flow chart in Figure 2.
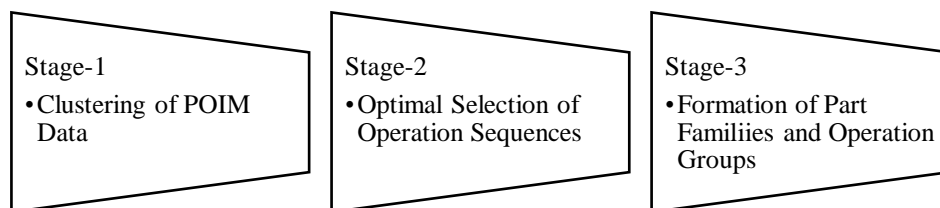
Stage-1
•Clustering of POIM Data

Stage-2
•Optimal Selection of Operation Sequences

Stage-3
•Formation of Part Familiies and Operation Groups

Figure 1: Proposed three stage methodology for formation of RMS part families

Stage-1: In the first stage, N x O sized POIM generated considering all the operation sequences of each part type is subjected to a clustering procedure. It will result into clustering of the scattered data points in POIM so that the resulting POIM has the highest value of the clustering performance measure. A stepwise description of stage-1 procedure is as follows:

1.1 Obtain the information of part types to be manufactured in the RMS cell, their all alternative operation sequences and construct POIM as described in section 4.1.1

1.2 Perform clustering on POIM by any suitable clustering procedure available in CM cell formation literature. In the present work, two array based clustering techniques namely Rank Order Clustering, ROC (King JR 1980a and 1980b) and Bond Energy Algorithm, BEA (Arabie P and Hubert LJ 1990) have been used. These methods accomplish block diagonalization of POIM by re-ordering rows and columns of the incidence matrix.

Stage-2: In this stage, the sub-optimal operation sequences from the POIM clustered in stage-1 are eliminated so that each part is left with only one operation sequence that has the highest contribution in a chosen clustering performance measure. Size of the residual POIM after this stage will be P x Q. Stage-2 procedure is described stepwise as follows:

Take a matrix POIM-1 identical to POIM.
2.1   Find N, the number of rows in POIM-1 and set a row counter.
2.2   Compute η for POIM-1 by either of the methods.
2.3   Starting with first row (i.e. i =1), check whether the part in ith row has alternative operation sequences. If it has no alternative operation sequence, go to step 2.7 to choose option (i) otherwise continue to the next step.
2.4   Remove ith row that has been recognised to represent a part that has alternative operation sequences available in POIM-1. Name the remainder POIM-1 as POIM-2.
2.5   Calculate η of POIM-2 i.e. η` by the same method as chosen in 2.3 and continue to option (ii) of the next step.
2.6   Update ith row of PEC table as follows:
        (i)   assign PEC value of - ∞ (to the ith row detected in step 2.4) or
        (ii)   calculate and assign PEC value.
2.7   Check whether any POIM-1 row has remained unconsidered to update PEC Table. If yes, consider it and go to step 2.4.
2.8   Find the row number having maximum PEC value in the PEC Table and thereon, reconstitute the POIM-1 by removing its row identified in PEC Table.
2.9   Check whether POIM-1 has any part with alternative operation sequences. If yes, perform clustering on it and go to step 2.2.
2.10   POIM-1 with all the parts having only one operation sequence is formed. The size of POIM is reduced from NxO to PxQ.

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 this procedure in contrast to CMS, the issue of part family formation has been treated as primary and operations group recognition as a subsequent consequence. The presence of voids and exceptional elements leads to underutilization of capacity therefore; the methodology in this and the next stage and has been designed to deal with the issue to keep their number at the minimum in the selected part family.

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Stage-3:   With
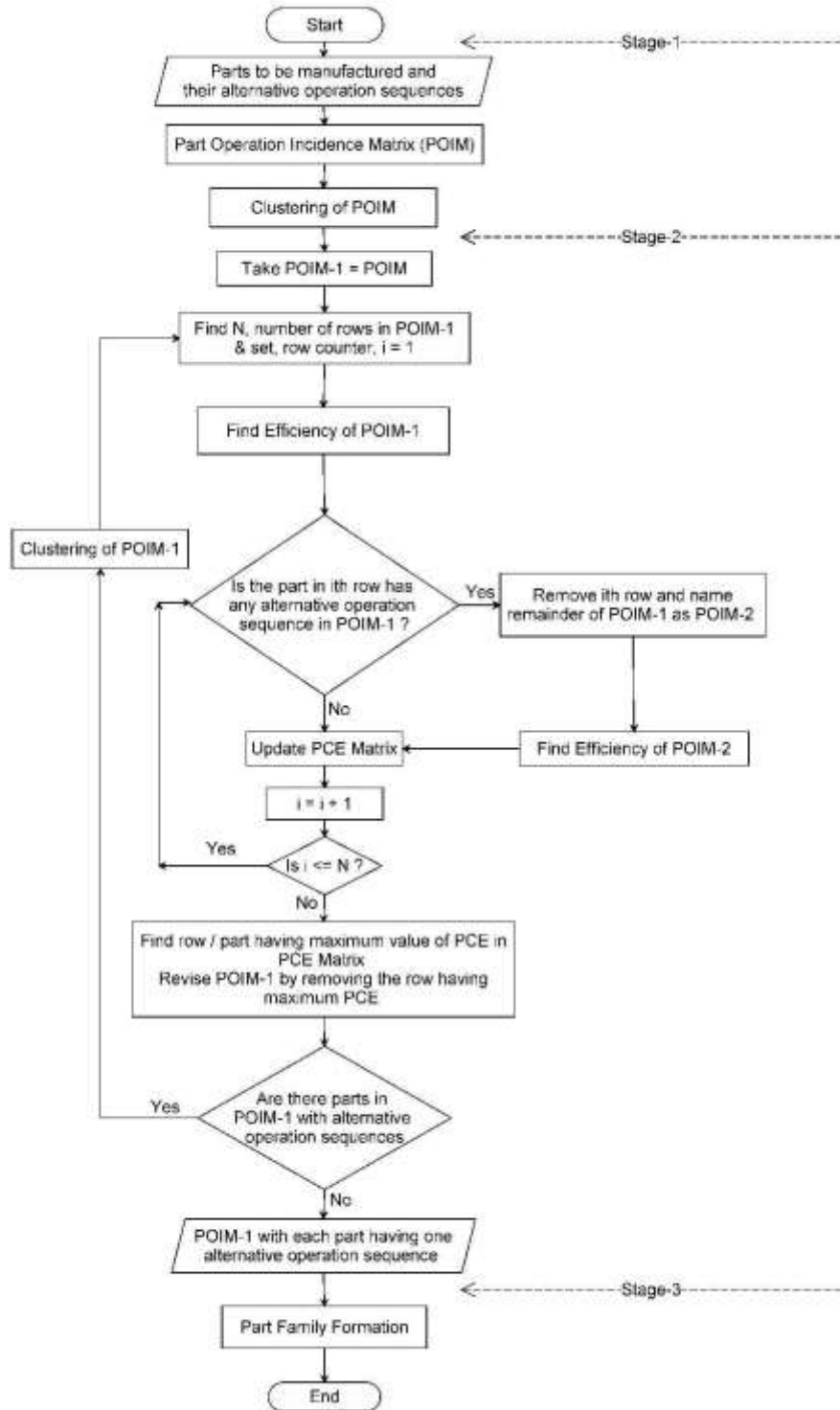

*Figure 2: Flowchart showing procedure for part family formation for RMS
considering alternative operation sequences*

restriction on the maximum size of each operation group as constraint, in this stage simultaneous formation of part families and operation groups is carried out on the POIM obtained in the last stage. The solution procedure

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maximises summed up PPFD score of the RMS cells. The procedure developed by the authors (Arneja GP et al,. 2017) considers peculiarities of reconfigurable manufacturing. An overview of the stage-3 procedure is presented as a flow chart in Figure 3 given below.
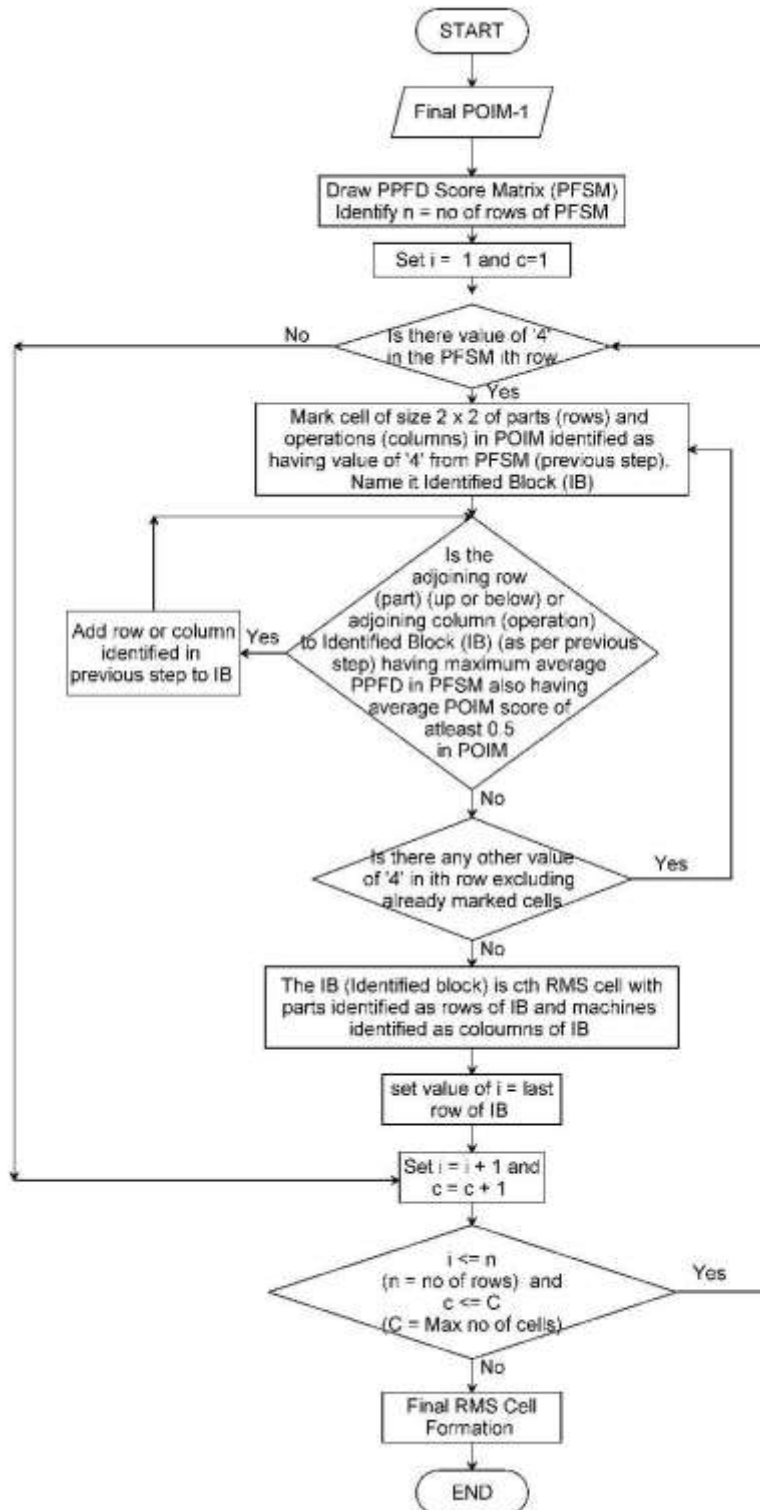
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Figure 3: Flow chart of stage-3 procedure

RESULTS

The methodology proposed in the present work carries out clustering of POIM in stage-1 and stage-2 using two standard clustering techniques namely, ROC and Bond Energy Algorithm. The process of removal of alternative operation sequences in stage-2 has been conducted by using three clustering goodness measures namely Grouping Efficiency (η_{GE}), Clustering Measure (η_c) and Bond Energy Measure (η_{BEM}). This way the methodology has been conducted with six combinations of two clustering methods and three clustering goodness measures. To evaluate the final results (i.e. part families formed) all the three goodness measures have been used. The methodology has been tested on four standard problems taken from existing CMS literature. The results obtained for each problem using each of the six combinations in the procedure are tabulated in Table 1 as given below.

Table 1. Comparison of optional parts removal by different clustering techniques

Sr. No.	References	Performance Measure	Total No of Parts	Total No of Operations	Total No of Alternative Operations	ROC clustering & Parts Removal by η_{BEM}	ROC clustering & Parts Removal by η_c	ROC clustering & Parts Removal by η_{GE1}	BEA clustering & Parts Removal by η_{BEM}	BEA clustering & Parts Removal by η_c	BEA clustering & Parts Removal by η_{GE1}
1	Harhalakis G et al. (1989)	Grouping Efficiency (η_{GE})	20	51	20	0.74	0.73	0.71	0.70	0.69	0.78
		BEM (η_{BEM})				1.24	1.27	1.25	1.29	1.21	1.28
		Clustering Measure (η_c)				1.30	1.77	1.63	1.62	1.54	1.53
2	Sankaran S and Kasilingam RG (1990)	Grouping Efficiency (η_{GE})	10	20	6	0.75	0.65	0.77	0.77	0.76	0.65
		BEM (η_{BEM})				1.22	1.19	1.22	1.86	1	1.11
		Clustering Measure (η_c)				2.09	2.28	1.83	1.68	1.51	1.85
3	Logendran R et al. (1994)	Grouping Efficiency (η_{GE})	14	32	7	0.59	0.53	0.53	0.62	0.52	0.61
		BEM (η_{BEM})				0.92	0.92	0.72	1.20	0.89	1.02
		Clustering Measure (η_c)				1.92	2.70	2.0	1.92	1.85	1.78
4	Kusiak A (1990)	Grouping Efficiency (η_{GE})	12	20	12	0.54	0.65	0.55	0.66	0.72	0.52
		BEM (η_{BEM})				0.75	1.07	0.76	1.22	1.02	0.9
		Clustering Measure (η_c)				3.21	1.58	3.41	1.79	1.44	3.60

η_{BEM} = *Bond Energy Measure* η_{c} = Clustering Measure η_{GE1} = Grouping Efficiency

It is observed that no particular combination has been giving the best results for all the four problems. However, the combination of BEA clustering and removal of alternative operation sequences using Bond Energy Measure (η_{BEM}) has been outperforming the other combinations.

CONCLUDING REMARKS AND FUTURE SCOPE

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In the present work a methodology for formation of part families has been developed by adapting array based clustering methods widely investigated in CMS cell formation literature. Though, the array based methods adapted in this work has the advantage of simplicity of implementation, their performance depends upon the initial structure of the POIM. CMS literature provides many such methods by which this drawback can be tackled to a large extent and therefore, makes the use of these methods quite favourable. Another disadvantage associated to these methods is that the sequence in which the operations are performed is not considered. In fact, even hierarchical clustering and most of the non-hierarchical clustering methods reported in CMS literature has this drawback. Therefore, as a future improvement, there is need to develop methods considering operation sequences. The peculiarities of RMS that has been incorporated in the development of this methodology are the facts that like CMS there are no intercellular movements in RMS and all the operational requirements in an RMS are fulfilled by way of reconfiguration of RMTs. There is, therefore, a good scope for incorporating other RMS characteristics into the procedure making it more realistic. More parameters and more objectives can also be considered in future work. In nutshell, the proposed methodology provides a skeleton on which combinations of various methods tested in CMS literature can be used and further these can be made suitable for implementation for complex and large problems by the use of soft computing methods.

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