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Technical paper

A mathematical programming model for manufacturing cell formation to develop multiple configurations

C.R. Shiyas, V. Madhusudanan Pillai*

Department of Mechanical Engineering, National Institute of Technology Calicut, NIT Campus (P.O), Calicut 673601, Kerala, India

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ABSTRACT

This paper presents and analyses a mathematical model for the design of manufacturing cells which considers two conflicting objectives such as the heterogeneity of cells and the intercell moves. A genetic algorithm (GA) based solution methodology is developed for the model which is also solved using an optimization package. The model is suitable for getting multiple potential solutions in a structured way for the cell formation problem by making a trade-off between the two objectives, instead of reaching at a single negotiating solution. This model provides the decision maker the flexibility of choosing a suitable cell design from different alternatives by considering the practical constraints. A part assignment heuristic is also developed by which part-families can be identified and is integrated with the GA based solution procedure. A comparison of the proposed method is made with other seven methods using 36 problems from the literature. Grouping efficacy is the basis for comparison and it is found to give reasonably good results.

1. Introduction

Cellular manufacturing (CM) has the flexibility of job shops and high production rate of flow lines. It is a group technology (GT) concept and is one of the best methods for achieving flexibility without compromising productivity. GT is a theory of management, based on the principle that a group of things which are having similarities can be done in a similar fashion so as to ensure saving in time, effort and cost. The goal of cellular manufacturing is to have the flexibility to produce a high variety of medium demand products, while maintaining the high productivity of large scale production, by grouping parts and machines according to the similarity between them. Design of a cellular manufacturing system (CMS), generally, involves grouping of parts with similar design features/processing requirements into part-families and the associated machines into machine cells [1]. CMS has reduced cycle time compared to job shops, and increased flexibility and greater job satisfaction compared to flow shops. CMS has been proven to be better than the other traditional layout types given that the demand and the part mix remain constant over the planning horizon.

2. Literature review and problem description

The most widely used methods for CMS design in the literature are based on (i) array management, (ii) hierarchical clustering, (iii) non-hierarchical clustering, (iv) mathematical models, and (v) heuristic techniques. All these methods generally use the part machine incidence matrix as the input. In 1980 King [2] introduced an array based clustering method, namely, rank order clustering (ROC) which can identify part-families and machine groups simultaneously by rearranging the 1's in a part machine incidence matrix to form a block diagonal structure. Later, a modified version called MODROC was developed by Chandrasekharan and Rajagopalan [3]. Other array-based clustering methods include bond energy algorithm (BEA) of McCormick et al. [4], and the direct clustering algorithm of Chan and Milner [5]. The main drawback of array based clustering methods is that the quality of solution depends on the initial configuration of part machine incidence matrix [6]. In hierarchical clustering method, the input data set is described in terms of a similarity or a distance function and produces a hierarchy of clusters [7]. Non-hierarchical methods are used in ZODIAC [8] and GRAPHICS [9]. While CASE [10] describes a CMS design using a similarity coefficient based non-hierarchical clustering for sequence data. Better solution is obtained in the non-hierarchical methods compared to the earlier methods.

The CMS design problems are combinatorial optimization problems and many mathematical programming approaches are available for better solution compared to the other methods. Kusiak and Chow [11] developed a p-median model for CMS design, where

* Corresponding author. Tel.: +91 495 2287804/9895367804; fax: +91 495 2287250.
E-mail addresses: crshiyas@rediffmail.com (C.R. Shiyas), vmp@nitc.ac.in (V. Madhusudanan Pillai).

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the objective is to minimize the sum of distances between each product/machine pair. Another p-median model based on a new similarity coefficient for CMS design is developed by Youkyung and Currie [12]. A two-stage procedure for CMS design was developed by Choobineh [13] which identifies product families initially and then uses an integer programming model for machine cell formation. In their model, the objective is to minimize the production cost and the machine acquisition cost. Srinivasan et al. [14] proposed an assignment model for the part-families and machine grouping problem. They formulated the CMS design problem as an assignment problem and proposed an algorithm for forming manufacturing cells after part-family formation. Adil et al. [15] formulated an assignment allocation algorithm (AAA), a non-linear mathematical model, to identify the part-families and machine groups simultaneously. The objective of the model is to explicitly minimize the weighted sum of the exceptional elements and voids, so that multiple solutions are obtained by varying the weights. Their model may lead to formation of machine cells without any machines, but with part assignment. Mahdavi et al. [16] developed a mathematical model to solve cell formation problem and the objective is to minimize the number of voids and exceptional elements in a three dimensional (cubic) machine-part-worker incidence matrix. This model is able to capture the capability of workers in doing different jobs and such models are rarely seen in the literature.

The early literature in CMS considered single objective functions but there are a certain recent research papers that consider multi-objective mathematical model. Yasuda et al. [17] proposed a multi-objective model for CMS design which can provide a variety of solutions. But, Yin et al. [18] proved that the formulation of Yasuda et al. [17] can be considered as an algorithm for cell formation only. Pitombeira Neto and Goncalves Filho [19] presented a Pareto-optimal multi-objective model based on GA and simulation for solving the manufacturing cell formation problem. The solution fitness analysis is carried out by means of simulation and finally it results in a number of alternative solutions. The bi-objective model proposed by Arkat et al. [20] optimizes voids and exceptional elements in a system. Their solution procedure consists of an ε constrained method based on GA which is a step by step procedure and it uses new constraints in every step. This solution procedure leads to a single solution. Rabbani et al. [21] suggested a bi-objective model for cell formation under stochastic production situations and developed a two-phase fuzzy linear programming approach as solution methodology. They compared their approach with other two methods to prove the effectiveness. Raflei and Ghodsi [22] modelled a dynamic cell formation problem as a bi-objective problem and a hybrid ant colony optimization-genetic algorithm solution methodology is developed.

Other cell formation methods are mainly based on heuristic approaches such as genetic algorithms (GA), simulated annealing (SA), tabu search, bacteria foraging algorithm (BFA). They are used either directly or as a solution method for mathematical models. These approaches are generally applied when pure mathematical modelling is not possible or the models require long computational time for a solution under available methods, especially for large size problems. Chan et al. [23], Rogers and Kulkarni [24], Leepost [25], Mak et al. [26], Wu et al. [27], Onwubolu and Mutingi [28], Tariq et al. [29], Joines et al. [30], and Deljoo et al. [31] used GA based solution methodology in part-family identification and cell formation problems. Wide use of GA, in solving cell formation models, is due to the combinatorial nature of the problem and the possibility of easy representation of solutions in the form of chromosomes. Arkat et al. [32], Zolfaghari and Liang [33], Adil et al. [15] and Chen et al. [34], Ariafar and Ismail [35] used simulated annealing for solving their cell design models while, Zolfaghari and Liang [36] used hybrid of tabu search and simulated annealing for developing optimization algorithms for CMS design. They conducted a comparative study using GA, simulated annealing and tabu search in solving cell formation problems and their study indicate that simulated annealing outperforms both GA and tabu search mostly for large size problems. These studies also reveal that GA seems slightly better than that of the tabu search method for the comprehensive grouping problems which involve machine/part types, processing times, lot sizes, and machine capacities, etc. Islier [37] used an ant system algorithm for a general cell formation problem which is found to be better than GA, tabu and SA when an equal number of solution alternatives are concerned. Fuzzy programming approach [38] and algorithms based on neural networks [39–41] are also used in recent researches to obtain good configuration for traditional cell formation problems. The bacteria foraging algorithm (BFA) is a new computation technique developed from the foraging behaviour of *Escherichia coli* (*E. coli*) bacteria. BFA is found to be an efficient optimization tool used to solve a large class of problems by exploring all regions of the state space and exponentially make use of potential areas through chemotaxis, swarming, reproduction, and elimination–dispersal operations of *E. coli* bacteria [42]. This technique is used in many scientific applications which require optimization. Nouri et al. [42] presented the first application of BFA in the design of CMS. In their work, an algorithm has been developed based on BFA to solve the CMS design problem, while taking into consideration the minimization of number of voids in the cells and the number of inter-cell travels based on operational sequences of the parts visiting the machines. CMS design models considering operation time [43], and cell load variation [44] are also available based on BFA. Other newly developed approaches of CMS design include a new branch and bound algorithm for the design of CMS [45], firefly inspired algorithm [46], etc.

Generally, solution procedure for all the cell formation methods converges to a single configuration so that the decision maker has no choice other than selecting it. But in real situations, implementation of such a configuration is compromising as the solution may be difficult to implement due to some practical conditions which are not quantified in the model. Rarely, all the practical conditions are modelled into the mathematical model. So developing alternative configurations has specific advantages in such conditions and the proposed model is able to provide multiple configurations. AAA [15] gives the possibility of different solutions, but it may lead to formation of cells with part assignment for which there are no machines assigned. The algorithm for multi-objective optimization by Dimopoulos [47] also gives an opportunity of multiple solutions, but it lacks the presence of a complete mathematical formulation for forming machine cells. In their model part assignment is not discussed and as a result the quality of solutions cannot be analyzed in a traditional way using grouping efficiency or grouping efficacy, etc. The model of Pitombeira Neto and Goncalves Filho [19] provides alternative configuration; however it is different from the proposed model when we consider the nature of input parameters and objectives.

Usually, models in the literature receive number of cells as input [11,14,19,24,26,28–32,37,38]. In the proposed model, number of cells is automatically evolved and can be interpreted from the value of the decision variables. So, the main advantages of the proposed model are (i) the number of cells is not an input, (ii) multiple configurations are obtained by solving the model, and (iii) a comparison with other models based on the quality of solutions is possible unlike other multi-objective models. The present paper focuses on the fundamental cell formation problem and a mathematical (non-linear programming) model has been developed for that situation. Moreover, a software package (LINGO 11.0) is used for solving the proposed model of small size problems. A GA based solution methodology is also developed since the computational