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An efficient approach to determine cell formation, cell layout and intracellular machine sequence in cellular manufacturing systems

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ABSTRACT

Cellular manufacturing systems (CMS) are used to improve production flexibility and efficiency. They involve the identification of part families and machine cells so that intercellular movement is minimized and the utilization of the machines within a cell is maximized. Previous research has focused mainly on cell formation problems and their variants; however, only few articles have focused on more practical and complicated problems that simultaneously consider the three critical issues in the CMS-design process, i.e., cell formation, cell layout, and intracellular machine sequence. In this study, a two-stage mathematical programming model is formulated to integrate the three critical issues with the consideration of alternative process routings, operation sequences, and production volume. Next, because of the combinatorial nature of the above model, an efficient tabu search algorithm based on a generalized similarity coefficient is proposed. Computational results from test problems show that our proposed model and solution approach are both effective and efficient. When compared to the mathematical programming approach, which takes more than 112 h (LINGO) and 1139 s (CPLEX) to solve a set of ten test instances, the proposed algorithm can produce optimal solutions for the same set of test instances in less than 12 s.

1. Introduction

Cellular manufacturing systems (CMS) involve the identification of part families and machine cells so that intercellular movement is minimized and the utilization of the machines within a cell is maximized. This cell formation process is one of the most important steps in CMS. Extensive research has been performed on cell formation problems (CFP), many of which have been developed on the basis of heuristic clustering techniques to obtain approximate solutions. Sun, Lin, and Batta (1995) presented a short-term tabu search-(TS) based algorithm for solving CFP in order to minimize the intercellular part flows, whereas Wu, Low, and Wu (2004) maximized the part flows within cells using a long-term TS-based algorithm. Chung, Wu, and Chang (2011) proposed a TS algorithm based on a similarity coefficient to solve the CFP with alternative process routings and machine reliability considerations.

Moon and Kim (1999) considered the process plans for parts and manufacturing factors such as production volume and cell size. Lee, Luong, and Abhary (1997) developed a genetic algorithm (GA) to deal with CFP by considering production volumes, alternate routings, and the process sequence, whereas Sofianopoulou (1999) developed a simulated annealing (SA) method to deal with CFP considering alternate routings and process sequences.

Furthermore, some studies considered multiple objectives in the design of CMS. Su and Hsu (1998) introduced a parallel SA algorithm to minimize the following decision objectives: (1) the total cost of machine investment and the inter and intracellular transportation costs, (2) intracellular machine-loading unbalance, and (3) intercellular machine-loading unbalance. Lei and Wu (2005) presented a Pareto-optimality-based multi-objective TS algorithm for solving the same problem.

The cell formation, cell layout, and intracellular machine sequencing are three critical steps that are required in the design of CMS. A good cell layout reduces the number of intercellular part movements; similarly, a good arrangement in machine sequencing within each cell can reduce the number of intracellular part movements. Therefore, it is observed that the decisions regarding cell and intracellular machine layouts are very critical in the design of CMS. This is even more significant when production volume is large. A few studies, Chiang and Lee (2004) and Chan, Lau, Chan, and Choy (2006), addressed problems considering both CFP and cell layout, whereas Akturk and Turkcan (2000), solved problems considering both CFP and the intracellular machine layout. Wu, Chu, Wang, and Yan (2007), Wu, Chu, Wang, and Yue (2007)

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developed a hierarchical GA to concurrently integrate cell formation and intracellular machine sequencing decisions in CMS design. The above studies considered either cell layout or intracellular machine sequencing in their problem formulation, but not both.

In contrast, research on integrating all the three critical issues in CMS design is still very limited, as can be seen in Table 1. Ahi, Aryanezhad, Ashtiani, and Makui (2009) applied the multiple attribute decision making concepts and proposed a heuristic approach to solve this integrated and complicated problem. However, practical production factors such as alternate process routing and production volume were not considered in that study. To the best of our knowledge, the study by Chan, Lau, Chan, and Lo (2008) is possibly to be the only one to integrate CFP, cell layout and intracellular machine sequencing issues and to consider practical factors including operation sequences, alternate process routing, and production volume in the problem formulation. However, only linear layout was considered in their study. Our study follows their problem scope. In addition, both linear single- and double-row layout are allowed and investigated in our study.

Although these three critical issues should be addressed simultaneously in order to reflect the reality and obtain the best results, it is difficult to formulate one single mathematical model that can provide optimal decisions for all issues in the design of CMS. Moreover, intracellular machine layout is a detailed layout planning process that starts only after the cell formation and cell layout are determined. Thus, we propose a two-stage mathematical programming model in this study. The aim of stage I is to solve CFP and cell layout problems simultaneously, whereas the primary function of stage II is to determine the machine layout (sequencing) in each cell on the basis of the cell formation determined in stage I.

It is known that both CFP and cell layout problems are NP-hard combinatorial problems (Kusiak, 1990), not to mention the problem complexity of the integrated problem being studied. Hence, it is difficult to obtain optimal solutions through mathematical programming approach for these problems within an acceptable time duration, especially for large-sized problems. Since the TS has been widely adopted in solving CFP related problems, the TS approach is employed in both stages to solve problems more effectively and efficiently.

The remainder of this study is organized as follows: Section 2 describes the problem definition including the CFP, cell layout, and intracellular machine sequencing; Section 3 presents the mathematical models; Section 4 deals with the proposed two-stage TS approach in detail; Section 5 presents the use of a numerical example to illustrate the proposed algorithm and demonstrate the effectiveness of the proposed model and methodology; Section 6 reports the computational results of the test problems; and Section 7 concludes the study.

2. Problem definition

2.1. Cell formation

A simple CFP involves the rearrangement of its rows and columns to create part families and machine cells. After the rearrangement, blocks can be observed along the diagonal of the matrix. In the matrix, any 1s outside the diagonal blocks are called "exceptional elements," and any 0s inside the diagonal blocks are called "voids."

When parts have more than one process route, as in the case shown in Table 2, the grouping of parts can be more effective due to the flexibility of the routes. In this case, not only the formation of part families and machine cells must be determined but also the selection of routings for each part has to be determined to achieve decision objectives. As an example, Table A1 provides the final solution to the sample problem mentioned in Table 2.

2.2. Cellular layout

Heragu and Kusiak (1988) indicated that the layout of machines (cells) is determined by the type of material-handling devices used. Among various layout types, the linear single- and double-row layouts (shown in Fig. 1) are very popular; these layouts are frequently used because of their flexibility to incorporate different material-handling facilities. The movement distance between a pair of cells, (l, l'), can be obtained by calculating the corresponding Euclidean distance, as shown in

$$D_{l,l'} = \left[(X_{l'} - X_l)^2 + (Y_{l'} - Y_l)^2\right]^{1/2}, \quad (1)$$

Table 1
Summary of related literature.

Authors	Production data		Layout		Number of cells		Solution method
	Operation sequences	Alternative process routings	Inter-cell layout	Intra-cell layout	Pre-scribed	Auto determining	
Gupta, Gupta, Kumar, and Sundaram (1996)			✓	✓	✓		GA
Lee et al. (1997)	✓	✓			✓		GA
Su and Hsu (1998)	✓		✓	✓	✓		SA
Sofianopoulou (1999)	✓	✓			✓		SA
Bazargan-Lari, Kaebernick, and Harraf (2000)	✓		✓	✓	✓		SA
Akturk and Turkcan (2000)	✓	✓		✓	✓		Heuristic
Chiang and Lee (2004)	✓		✓			✓	GA
Lei and Wu (2005)	✓		✓	✓	✓		TS
Wu, Chu, Wang, and Yan (2006)	✓		✓	✓	✓		GA
Boulif and Atif (2006)	✓				✓		GA
Chan et al. (2006)	✓		✓		✓		GA
Arkat, Saidi, and Abbasi (2007)	✓	✓			✓		SA
Wu, Chu, Wang, and Yan (2007)	✓			✓	✓		GA
Wu, Chu, Wang, and Yue (2007)	✓			✓	✓		GA
Mahdavi and Mahadevan (2008)	✓	✓			✓		Heuristic
Chan et al. (2008)	✓	✓	✓	✓	✓		GA
Ahi et al. (2009)	✓		✓	✓		✓	Heuristic
Wu, Chung, and Chang (2009)		✓				✓	SA
Chung et al. (2011)	✓	✓	✓			✓	TS
The current study (2013)	✓	✓	✓	✓		✓	TS