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A comprehensive mathematical model for dynamic cellular manufacturing system design and Linear Programming embedded hybrid solution techniques

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ABSTRACT

Considering the ever changing market conditions, it is essential to design responsive and flexible manufacturing systems. This study addresses the multi-period Dynamic Cellular Manufacturing System (DCMS) design problem and introduces a new mathematical model. The objective function of the mathematical model considers inter-cell and intra-cell material handling, machine purchasing, layout reconfiguration, variable and constant machine costs. Machine duplication, machine capacities, operation sequences, alternative processing routes of the products, varying demands of products and lot splitting are among the most important issues addressed by the mathematical model. It makes decisions on many system related issues, including cell formation, inter- and intra-cell layout, product routing and product flow between machines. Due to the complexity of the problem, we suggest two heuristic solution approaches that combine Simulated Annealing (SA) with Linear Programming and Genetic Algorithm (GA) with Linear Programming. The developed approaches were tested using a data set from the literature. In addition, randomly generated test problems were also used to investigate the performance of the hybrid heuristic approaches. A problem specific lower bound mathematical model was also proposed to observe the solution quality of the developed approaches. The suggested approaches outperformed the previous study in terms of both computational time and the solution quality by reducing the overall system cost.

1. Introduction

Nowadays manufacturing systems are expected to deliver large variety of products in smaller lot sizes with competitive prices. Cellular Manufacturing (CM) is among modern manufacturing philosophies that meets these requirements. In a CM System (CMS), products that are similar in their processing requirements are grouped into part families. The machines that process a family of products are grouped together to attain potential benefits of the CMS. Benefits of the CMS include reducing setup times, reduction in material flow and work-in-process inventory, easier and better system management, improved overall system efficiency and product quality (Baykasoğlu, 2004; Urban, Chiang, & Russell, 2000). However, processing all of the processing requirements of a product family in a single machine cell is an ideal. Under real manufacturing conditions it is either uneconomical or practical to design mutually independent cells. Therefore, exceptional elements is common in CMS manufacturing environments (Wang & Sarker, 2002). An exceptional element is a product that is needed to be produced in more than one cell and it causes inter-cell transfer of materials. In some cases, elimination of exceptional elements is possible, but requires additional machine investment.

When designing a Cellular Manufacturing System (CMS) many decisions must be taken into account. Some of these decisions are as follows: (1) cell formation (CF) through grouping of machines into cells, (2) layout of machines within cells (intra-cell layout) and (3) layout of cells (inter-cell layout) (Wemmerlöv & Hyer, 1986). As stated in Alfa, Chen, and Heragu (1992) these decisions are interrelated and addressing them simultaneously is important for a successful CMS design. However, each of these decisions is proven to be complex (Mak, Wong, & Wang, 2000; Sahni & Gonzalez, 1976), thus addressing of these decisions simultaneously is a difficult task. Therefore, most of the studies either consider

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some of these decisions or they handle all, but in a sequential fashion.

Short product life cycles and rapid changes in product demands require reconfiguration of CMS from time to time. Therefore, CMS design must be carried out taking the changes in the demand into account. In CMS and facility layout literature, in order to handle the changes in demand of products, three main approaches are proposed. In the first approach, resources are rearranged by considering only processing requirements of the imminent future. This approach is called agile strategy and requires availability of agile resources (e.g. machine tools that can be easily relocated). The second approach is called robust strategy. It is based on designing a single layout that would be effective over the planning horizon. Although these approaches are easier and simplifies the multi-period design problem, both of these approaches are able to provide good layout solutions in extreme conditions. For example, agile strategy is useful only if the rearrangement costs are negligible. On the other hand, robust strategy is capable of finding layout solutions if the rearrangement costs are prohibitively high. In these strategies, rearrangement costs are either neglected or not even incurred by not changing the layout. Introduced by Rheault, Drolet, and Abdulnour (1995), Dynamic Cellular Manufacturing System (DCMS) design basically considers changes in product mix and demand. In addition to the single period CMS design decisions, DCMS design involves multi-period cell reconfiguration decisions. The reconfiguration of a manufacturing system involves some costly activities such as machine relocation, installation and uninstallation costs, lost production time and relearning costs (Balakrishnan & Cheng, 2007). In a DCMS design, the length of the time periods should be determined carefully and it must be reasonable to make a trade-off between cumulative increased flow costs of inefficient layout and rearrangement costs. If the time period is selected too short or too long, the problem becomes one of the extreme cases that were discussed above because, relative weight of the cumulative increased flow costs of inefficient layout over rearrangement costs changes significantly. Gupta and Seifoddini (1990) found out that one-third of USA companies rearrange their manufacturing facilities every two years. Moreover, Marsh, Meredith, and McCutcheon (1997) concluded that layout changes could occur within six months from the last rearrangement of a cell.

In this study, we focused on a comprehensive CMS design problem with the consideration of rearrangements in multi-period design horizon. We first present a comprehensive mathematical model that incorporates important DCMS design features including inter-cell layout, intra-cell layout, alternative process routes, duplicated machines, machine capacities, processing times, dynamic product demand, lot splitting, machine installation and uninstallation costs, material handling costs, processing costs, machine purchasing costs, and constant machine costs. We also propose two different Linear Programming (LP) embedded meta-heuristic approaches for solving this problem. The first one is the integration of LP and Simulated Annealing (SAeLP) and the second is the integration of LP and Genetic Algorithm (GAeLP). The efficiencies of the SAeLP and GAeLP are shown by comparing our results with those of a previous study (Kia et al., 2012) and a problem specific lower bound mathematical model. The results have shown that both SAeLP and GAeLP are powerful techniques in terms of both solution quality and computational time. The contribution of this study is manifold: (1) the mathematical model of Kia et al. (2012) is improved, (2) two LP embedded meta-heuristics are suggested and their efficiency is demonstrated, (3) a lower bound mathematical model that provides tight lower bound results for the test samples is provided. A brief review of DCMS design will be given in Section 2. Then, in Section 3 the mathematical model of the problem is introduced. The solution methodology is described in detail in Section 4. In order to illustrate the SAeLP and the GAeLP, the solution steps of a small sample problem are given in Section 5. Finally, comparative computational results and the conclusions are included in the Sections 6 and 7, respectively.

2. Literature

Both CMS and DCMS design literatures are very rich. In this section, only some of the remarkable studies are discussed. Harhalakis, Ioannou, Minis, and Nagi (1994) took product demand changes into account, but they tried to obtain a single design that is effective across the periods in the planning horizon. Rheault et al. (1995) introduced the concept of DCMS design with reconfiguration capability. Their study involves production scheduling, routing and loading of parts. The trade-off between material handling costs (MHC) and reconfiguration costs are presented by using an integer programming model. Wilhelm, Chiou, and Chang (1998) proposed a multi-period cell formation model aimed at minimizing reconfiguration, additional machine purchasing and inter-cell material handling costs. In order to handle the variation in product mix, Askin, Selim, and Vakharia (1997) suggested a four-stage technique. Initially, operations were assigned to machine types, and then operations are assigned to specific machines. In the following stages the manufacturing cells were determined and the design was improved. Chen (1998) developed a mixed integer mathematical programming model for DCMS design with reconfiguration issue. The objective function minimizes inter-cell material handling, reconfiguration and machine costs. Wicks and Reasor (1999) proposed another model with reconfiguration, in which they pursued minimization of the reconfiguration and constant machine costs.

Operation sequence of the products and machine replication were the other aspects considered during DCMS design. Chen and Cao (2004) developed a method to concurrently design CMS and to plan manufacturing activities. Their Tabu Search based method minimizes the sum of inter-cell material handling, inventory holding, cell formation costs. Although they took the machine capacities and machine duplication into account, they assumed that there was a single process plan for each product type. Therefore, processing costs were not included in the model. In their another study (Cao & Chen, 2005), they defined product demand in a probabilistic scenarios and they used a two stage Tabu Search based algorithm to minimize machine costs and inter-cell material costs. Similar to their previous study, they did not add processing costs to the objective function. In their study, Tavakkoli-Moghaddam, Aryanezhad, Safaei, and Azaron (2005a, 2005b) proposed a comprehensive mathematical model assuming alternative process routings, operation sequence, machine capacities and machine duplication. In the objective function, inter-cell material handling, variable and constant machine costs and reconfiguration costs were included. They solved this model using Simulated Annealing, Tabu Search and Genetic Algorithms. In another study, Tavakkoli-Moghaddam et al., 2005a, 2005b solved a similar model using Memetic Algorithms. Defersha and Chen (2008a) focused on cell formation under dynamic manufacturing conditions. In addition to the model properties of Tavakkoli-Moghaddam et al. (2005a, 2005b), they considered workload balancing and machine separation constraints as well. Their objective function comprises the sum of machine maintenance and overhead costs, machine procurement cost, inter-cell material handling cost, machining and setup costs, tool consumption cost, and system reconfiguration cost. Then, they solved this model by using a parallelized Genetic Algorithm. Nsakanda, Diaby, and Price (2006) included the option of outsourcing in their model while. Aryanezhad, Deljoo, and Mirzapour Al-e-hashem (2009) integrated worker assignment decisions into the dynamic cell formation decisions.