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A capacity constrained mathematical programming model for cellular manufacturing with exceptional elements

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ABSTRACT

Most of the research on cellular manufacturing focuses on cell formation, the initial step of setting up a cellular manufacturing system. Numerous methods exist for organizing efficient manufacturing cells for existing equipment and parts. However, when cell redesign is not possible or desired, opportunities still exist for further optimization and cost savings with the existing cell formation. Exceptional elements (EEs) in cellular manufacturing are bottleneck machines and exceptional parts that span two or more manufacturing cells. This paper develops a mathematical programming model that retains the original cell formation, which is assumed to be optimal in the long term, and minimizes total costs of a cellular manufacturing system with exceptional elements through (1) intercellular transfer, (2) machine duplication, and (3) subcontracting while taking machine capacities into account to avoid capacity violations.

1. Introduction

Cellular manufacturing has long been known as a way to increase manufacturing productivity and efficiency. By locating equipment in a cellular arrangement, manufacturers have been able to achieve cost savings through minimizing part movements and improving process flow. Often times, however, even the best cellular manufacturing layout will have parts that have processes outside of its cell. Bottleneck machines and exceptional parts that span two or more manufacturing cells are called exceptional elements (EEs).

Shafer et al. [1] introduced a model to deal with EEs in three ways after other efforts were exhausted: (1) intercellular transfer, (2) purchase additional machinery, or (3) subcontract the part. The model that was presented created the optimal application of intercellular transfer, machine duplication, and subcontracting based on one year of planned production. The model assumes that the cells are previously set up, but makes no mention of the number of machines contained in each cell. If the model chooses to perform an intercellular transfer, there are no capacity constraints on the receiving cell. Capacity within the cell is infinite despite the capacity constraints that the model has dictated for each machine. The capacities that are specified are used for new equipment purchases related to exceptional elements only. This paper will build upon the model presented by Shafer et al. [1] by eliminating the assumption of infinite capacities for existing machinery. Therefore, when the model looks into an intercellular transfer, constraints assure that the transferred parts cannot exceed the preset capacity of the applicable machinery in the receiving cell. Predefining the number of existing machines and adding capacity presents a more realistic option for implementation in industry, which for these types of models most often involves simulation [2].

2. Literature review

Most of the literature in cellular manufacturing focuses on cell formation instead of dealing with minimizing cost in a system that has already been established. All kinds of mathematical programming techniques and heuristic methods including genetic algorithms, neural networks, simulated annealing, ant colony optimization, Tabu search, data mining, and the bacteria foraging algorithm have been applied to the problem of cell formation in various scenarios for both deterministic and probabilistic demand [3–16]. In addition, several literature review papers exist on the numerous optimization methods for the design and formation of manufacturing cells [17–20]. Offodile et al. [18] present a review that illustrates how few cellular manufacturing articles take machine capacity into consideration. Ahkioon et al. [21] look at cellular manufacturing design slightly differently by focusing on

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routing flexibility with the goal of incorporating machine breakdowns into cellular manufacturing system design.

Pillai and Subbarao [22] look at the cell formation problem for a multi-period problem and introduce a robust cell design methodology using a genetic algorithm that does not allow the composition of the machine cells to change over time. This comes closer to the scenario that this paper addresses involving a fixed manufacturing layout. Often times the cost and downtime associated with moving and reorganizing machinery and redesigning the shop floor layout is unreasonable and companies need to focus on minimizing cost with the existing cellular manufacturing layout. In addition, the existing layout may still be considered optimal in the long term, but short-term manufacturing of some parts requires intercellular transfers, subcontracting the entire manufacturing process of select parts, or purchasing new equipment. This is where papers on dealing with EEs in cellular manufacturing take over. The remaining literature review is on this subset that focuses on EEs and not cell formation.

Burbidge [23] observed the problem associated with EEs, which are defined as bottleneck machines and exceptional parts that span two or more manufacturing cells and suggested five approaches for eliminating EEs: (1) reroute the part, (2) modify the manufacturing process, (3) modify the part's design, (4) subcontract the part, or (5) modify the cells to accommodate the EEs.

The problems associated with EEs are common. Wemmerlöv and Hyer [24] conducted a survey of 29 manufacturers and found that only three of these respondents did not have any instances of EEs. Dealing with EEs is an ongoing problem that is not going to go away. Part design and initial cellular formation can only do so much and EEs are an issue that companies must address as efficiently as possible particularly when encountering short-term product-mix changes or when a redesign of the cellular manufacturing layout is inappropriate or impractical.

Many methods have been proposed for dealing with EEs. As mentioned in the introduction, Shafer et al. [1] developed a mathematical programming approach for dealing with exceptional elements involving intercellular transfer, duplicating machinery, and subcontracting. Kern and Wei [25] developed a method of creating a prioritized list of EEs for decision makers to see which actions would be the most cost-effective. Mansouri et al. [26] employed a genetic algorithm for dealing with EEs in the form of a Multi-Objective Genetic Algorithm in order to minimize: (1) intercellular movements of parts, (2) total cost of machine duplication and subcontracting, (3) system underutilization, and (4) deviations among the cells' utilization. These objectives are different than the objectives in this paper, which are purely based on minimizing total costs where costs have been assigned to each activity. When cost-based accounting, which is an accepted practice in manufacturing for activities like quote estimating and schedule optimizations [27], is not available for every activity, the solution procedure presented by Mansouri et al. [26] would be an excellent option. Berardi et al. [28] compared costs associated with alternative cluster formations using the same numerical example illustrated by Shafer et al. [1] and this paper. However, as in Shafer et al. [1], existing machinery capacities are not considered in the comparisons.

The model developed in this paper uses the notation presented by Shafer et al. [1] and the same example, which appears several times in the literature. The next section of the paper presents the model designed to minimize the costs of the cellular manufacturing system related to EEs using intercellular transfers, machine duplication, and subcontracting while taking the predefined existing machine capacities into consideration.

3. The model formulation

This model operates under several assumptions. Subcontracting of parts is total production subcontracting, which means the subcontractor produces the part from start to finish. Floor space exists for machine duplication. Intercellular transfer cost is set to be appropriate for the sequence of operations. A full redesign of the production layout is not feasible or appropriate at this time and, therefore, the cost minimization must retain the current cellular formation.

The capacity constrained mathematical programming model for cellular manufacturing with exceptional elements contains the following notation.

Indexing sets

f	index for machine cells.
i	index for parts.
k	index for machines.
nf	number of cells indexed by $f = 1, 2, \ldots, nf$.
ni	number of parts indexed by $i = 1, 2, \ldots, ni$.
nk	number of machines indexed by $k = 1, 2, \ldots, nk$.

Sets

EE	set of all exceptional elements consisting of a part and machine combination ik where the part i needing machine k reside in different cells.
L_{kf}	set of all parts using machine k in cell f.
N_f	set of machines in cell f needed by parts outside cell f.
T_f	set of machines not in cell f needed by parts in cell f.
EEM_{kf}	set of all parts in cell f that require a machine, k, outside of cell f.
EEP_{kf}	set of all parts outside of cell f that require a machine, k, in cell f.

Decision variables

X_i	units of part i to be subcontracted
Y_{kf}	number of machines of type k to be purchased for cell f
Z_{ik}	number of intercellular transfers required by part i as a result of machine type k not being available within the part's manufacturing cell

Parameters/other variables

S_i	incremental cost of subcontracting a unit of part i
I_i	incremental cost for moving part i outside of a cell as opposed to moving it within the cell (this cost can also reflect the disruptive effects of having intercellular transfers)
D_i	annual forecasted demand for part i
A_k	annual cost of acquiring a machine of type k
C_k	annual capacity of machine type k
P_{ik}	processing time needed to produce part i on a machine of type k
M_{kf}	number of machines of type k needed in cell f
B_{kf}	beginning capacity for available machines of type k in cell f
V_{kf}	machine minutes available for machines of type k in cell f (includes new equipment capacity)
R_{kf}	machine minutes required for machines of type k in cell f

The capacity constrained mathematical programming model for cellular manufacturing with exceptional elements is:

$$\min \sum_{i} (X_i S_i) + \sum_{T_f} (Y_{kf} A_k) + \sum_{EE} (Z_{ik} I_i) \tag{1}$$