A NEW MULTI-OBJECTIVE MODEL FOR A CELL FORMATION PROBLEM CONSIDERING MACHINE UTILIZATION AND ALTERNATIVE PROCESS ROUTES

R. Tavakkoli-Moghaddam*

Department of Industrial Engineering and Department of Engineering Science
College of Engineering, University of Tehran
P.O. Box 11155-4563, Tehran, Iran
tavakoli@ut.ac.ir

M. Ranjbar-Bourani

Department of Industrial Engineering, Graduate School
Islamic Azad University-South Tehran Branch, Tehran, Iran
ranjbar.mehdi@yahoo.com

H. Mirzahosseinian and M.B. Aryanezhad

Department of Industrial Engineering, Iran University of Science and Technology
P.O. Box 16844, Tehran, Iran
mirzahosseinian@iust.ac.ir - mirarya@iust.ac.ir

*Corresponding Author

Abstract   This paper presents a novel, multi-objective mixed-integer nonlinear programming (MINLP) model for a cell formation problem (CFP) with alternative means. Due to existing contradiction among objectives, three are considered: 1) Minimizing the total cost consisting of; intercellular movements, purchasing, operation, and maintenance; 2) maximizing the utilization of machines in the system; 3) minimizing the deviation levels between the cell utilization (i.e., balancing the workload between cells). Furthermore, alternative process for each part, which is a key characteristic for flexible manufacturing systems, is considered in this paper. The main goals of our proposed model are to; 1) Select a process plan for each part with minimum cost, simultaneous machine grouping and complete series of all parts; 2) Identify the appropriate level of overall utilization of machines; 3) Balancing the workload among the cells in the production system.

Keywords   Multi-Objective Cell Formation Problem, Alternative Process Plan, Alternative Routes

چكيده   در این مقاله، یک مدل جدید چندهدفه برنامه‌ریزی عدد صحیح مختلط بصورت غیرخطی برای مساله تشکیل سلول تولیدی با در نظر گرفتن مسیرهای عملیاتی چندگانه ارائه می‌شود. به دلیل وجود تعارض میان اهداف مورد مطالعه، بهینه سازی هر یک از اهداف به صورت: ۱) حداقل نمودن هزینه کل شامل هزینه حمل و نقل بین‌سلولی، هزینه خرید، عملیاتی و نیز نگهداری ماشین‌ها؛ ۲) حداکثر نمودن سطح بهره‌گیری از ماشین‌ها در سیستم تولیدی و ۳) حداقل کردن انحراف میان سطوح بهره‌گیری از سلول‌ها (یعنی بالانس نمودن بارکاری بین سلول‌ها) ارائه می‌شود. همچنین قابلیت تولید قطعات از طریق مسیرهای عملیاتی چندگانه که از ویژگی‌های مهم سیستم‌های تولیدی انعطاف‌پذیر است، در این مقاله لحاظ شده است. هدف نهایی مدل پیشنهادی عبارت است از ۱) انتخاب برنامه فرایندی برای هر قطعه با حداقل هزینه کل همراه با تشکیل همزمان گروه ماشین‌ها و خانواده قطعات ۲) تعیین مناسب‌ترین سطح بهره‌گیری کل از ماشین‌ها و ۳) بالانس کردن بارکاری میان سلول‌های مختلف سیستم تولیدی.

1. INTRODUCTION

Cellular manufacturing (CM) is the application of group technology (GT) in manufacturing systems. GT is a manufacturing philosophy, which determines and divides the components into

families and the machines into cells, by considering the similarity of parts in processing and design functions. Since GT allows for the combined benefits of mass production while dealing with multi-product small lot-sized production. The reported benefits of CM are simplified and reduced to material handling, reduced set-up time, shorter lead times, reduced work-in-process, improved productivity, simplified scheduling and better overall control of operations [1]. Identification of similar parts (part families) and machine cells in the design of a cellular manufacturing system (CMS) is commonly referred to as cell formation. A number of current cell formation problems have been developed based on single process plan for each part. While, we assume that there are many machine type with high capability, so that each part can be processed on machines with having the capability of doing related operation for specific part. Alongside the alternative process routes (APR) issue, the competitive nature which is imposed on the manufacturer, entails a number of conflicting criteria in a cell design. With these criteria taken into consideration, a multi-objective problem is formed. In order to enlighten the readers as to the necessity of this creative approach, a review of the most previous research done in this area is introduced in the following section.

2. LITERATURE REVIEW

In the first step, a brief description of the work addressed alternative route issue in CMSs is provided, and then multi-objective approaches in CMS are briefly discussed.

2.1. Alternative Process Routes   Most cell formation methods in the literature assume that parts have only a unique process routing. However, it is well known that alternatives may exist in any level of a process plan. When each part can have more than one process routing, the CF problem becomes generalized [2] or CF problem with APR. Explicit consideration of alternative process routings provides some additional flexibility in the design of cellular manufacturing systems, so that a lower material flow cost can be achieved. The

following researches have considered APR while dealing with the CF problem:

Kusiak, et al [3] proposed a generalized *p*-median model in the presence of alternative routings. Adil, et al [4] considered the APR in their model, considering a nonlinear integer programming to identify part families and machine cells. They used a binary machine-component matrix to model this situation. The model uses a weighting approach to deal with minimizing voids and exceptional elements simultaneously. Furthermore, they used a linearization of the model procedure. Tavakkoli-Moghaddam, et al [5] developed a model, which was first proposed by Chen [6], with additional assumptions, such as alternative process plan, sequence operation, machine capacity, and machine replication with the aim of minimizing the sum of machine total costs and inter-cell movements cost simultaneously. Caux, et al [7] considered machine capacity constraints in the traditional CF problem with the APR. They used an approach combining the simulated annealing (SA) method for the CF problem and a branch-and-bound method for a routing selection problem. Hwang, et al [8] proposed a two-stage procedure for the CF problem with the APR. The first stage tries to solve the routing selection problem with the objective of maximizing the sum of compatibility coefficients among selected process plans. Through a *p*-median model, the second stage forms the part families by means which had resulted from the first stage.

Sofianopoulou, et al [9] proposed a comprehensive model for the design of medium-sized cellular manufacturing systems with duplicate machines and/or alternative process plans for some or all the parts produced. Arkat, et al [10] used a SA procedure to deal with the APR. They showed that in comparison with genetic algorithms (GA), the SA algorithm produces a better solution in much shorter time and with less programming skill requirements. Askin, et al [11] developed a CM design method that considers the routing flexibility and volume flexibility during the design process. Their definition of routing flexibility is the ability of the cell system to process parts completely in multiple cells, whereas volume flexibility is the ability of cell system to deal with volume changes in the current part mix.

2.2. Multi-Objective CFP Although, numerous heuristic or meta-heuristic methods have been proposed for the single-objective version of CF problems, there has been relatively little research on the multi-objective version of the given problem, despite the fact that practical considerations during the design of a manufacturing system are most likely to consider multiple conflicting objectives.

Kim, et al [12] presented a two-phase heuristic algorithm to deal with multi-objective CF problems. This problem is characterized as determining part route families and machine cells so that the total sum of intercellular part movements and maximum machine workload imbalance are minimized simultaneously. Tavakkoli-Moghaddam, et al [13] proposed a new multi-objective mixed-integer nonlinear programming (MINLP) model for a cell formation (CF) problem under fuzzy and dynamic conditions with three objectives. Their objectives are to minimize the total cost consisting of the costs of intercellular movements, subcontracting, purchasing, operation parts, maintenance, and reconfiguration of machines, to maximize the preference level of the decision making, and to balance the intracellular workload. Shafer, et al [14] presented a goal programming model to deal with three objectives as follows: minimizing intercellular movements, minimizing the investment in new equipment, and maintaining an acceptable utilization level. Their proposed model composes the *p*-median to specify part families and the traveling salesman problem to identify the optimal sequence of parts. They also applied heuristic to solve real world problems. Venugopal, et al [15] proposed a bi-criteria mathematical model for the machine-component grouping problem in such a way that the volume of inter-cell moves and the total cell load variation were minimized.

Mansouri, et al [16] employed a multi-objective genetic algorithm, called XGA, to provide the decision-makers with Pareto-optimal solutions. Their model aims at deciding on which parts to subcontract and which machines to duplicate in a CMS which exists in some exceptional elements. The main objectives of their model are to minimize intercellular movements, minimize the total cost of machine duplication and part subcontracting,

minimize under-utilization of machines in the system, and to minimize the imbalance of the workloads among the cells. Yasuda, et al [17] presented a grouping genetic algorithm to solve the multi-objective cell formation problem. Processing time, production requirements, and available time on machine in a given period have been considered for the two objectives, inter-cell flows and cell load variation. Liang, et al [18] developed a bi-criteria nonlinear integer programming model to improve the efficiency and flexibility on the production floor. The weighted approach is employed to unify the two objectives, (i.e. maximizing the system flexibility and efficiency). No inter-cell movement is allowed and all exceptional parts must be sub-contracted. They used a degree of similarities of parts and a number of part types, accommodated into the focused cell, to measure the efficiency and flexibility, respectively.

Mansouri, et al [19] provided comprehensive reviews of multi-criteria decision-making (MCDM) in the design of manufacturing cells considering the inputs comparison, criteria, solution approaches, and outputs across selected models.

The rest of this paper is organized as follows: detailed description of the proposed model is described in Section 3. Section 4 discusses some approaches to multi-objective CF problems. Numerical examples and the related computational results are reported in Section 5. Finally, conclusion and direction for future research are presented in Section 6.

3. PROBLEM FORMULATION

In this section, we present a new multi-objective cell formation model with alternative process routes. The considered manufacturing system consists of several parts which require a number of operations on different machines with limited capacities according to a given sequence. Each machine can process different operations based on the tooling available and it can be considered as alternative route for part processing. Table 1 shows the alternative routes for each part and the appropriate data required by the proposed model.

For instance, either M1 or M2 can be used to process part type 2 in operation 1. By considering three operations for this type part, there are $2 \times 1 \times 2$ ways to proceed with these machines. This part (type 2) may be processed using any of four process routes as depicted in Figure 1. Feasibility of these routes primarily depends on time capacity of corresponding machines.

In our proposed model, parts families and machine groups are formed simultaneously. However, it can be more complicated to model, which requires a substantial amount of time to solve. We also assume that no part splits into different cells for the processing of an operation. Moreover machines can be duplicated to meet capacity requirements and to reduce (or eliminate) inter-cell movements.

The following assumptions are considered in the given problem:

- The processing time for all types of part operations on different machine types are known and constant.
- Each part must be processed according to a known sequence of operations.
- The demand for each part is known.

TABLE 1. Capability of Five Machines for Four Parts in a Cell.

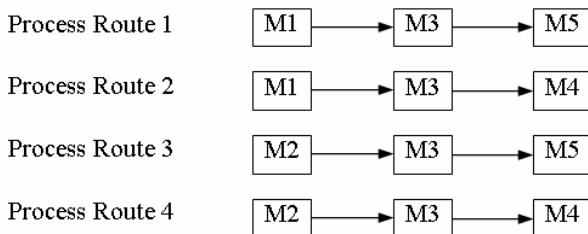| Part Type	Operation		
	1	2	3
1	M2, M3	M4, M5	
2	M1, M2	M3	M5, M4
3	M2		M3
4	M1, M3	M2	M5

Figure 1. Alternative process routes for part type 2.

- The capabilities and capacity of each machine type is known and constant over planning horizon.
- The number of cells used must be specified prior to the operation.
- Bounds and quantity of machines in each cell need to be specified in advance and they remain constant over time.
- Parts are moved between cells in batches. The inter-cell material handling cost for each batch between cells is known and constant (i.e., independent of quantity of cells).
- Each machine type can perform one or more operations (i.e., machine flexibility).
- Each operation can be done on one machine type with different times (i.e., routing flexibility).
- Delayed order is forbidden.
- No inventory is considered.
- Setup times are not considered.
- No queue in production is allowed.
- Machine breakdowns are not considered.
- Batch size is constant for all productions.

3.1. Definition of Objectives The following set of criteria is considered for developing the multi-objective CFP model:

1. Minimizing the total sum of machine maintenance costs, machine operating costs, inter-cell material handling costs, and machine purchase costs.
2. Maximizing the overall utilization of machinery in manufacturing system.
3. Minimizing deviation caused by imbalanced levels of utilization among cells.

Although, there are several important objectives associated with CF problems; however, it is very difficult to consider all objectives in a particular formulation. Ideally, it is preferred that a whole family of parts be processed in one machine cell. However in typical industrial applications, it is difficult to accomplish as such, and hence, most studies have focused on minimizing inter-cell moves [20]. In fact, minimizing inter-cell part movements is specially important, since it is the key factor to make cells independent.

It is worthy noting that the considered objectives in the form of a total cost (i.e., first objective function) have different and conflicting natures. For instance, minimization of inter-cell traffic, as a major CMS design goal, increases the system efficiency through decreasing the required movement, reducing mean flow time, and simplifying shop floor control. However, considering minimization of machines duplication conflicts with the former objective (i.e., decreasing machine number will result in an increase in intercellular movements). Therefore, all these objectives are proposed as a total cost in an integrated objective function in order to overcome the inherent conflict [13].

As the second independent objective, maximizing the overall utilization of machinery in manufacturing system or minimizing the overall under-utilization of all machines present in the system has been considered. The aim of this term is to reduce the under-utilization of machinery, which is increased by the first objective function. As a final point, we propose the third objective function as minimizing the load variation among cells, which is computed as the difference between the utilization of each cell and the overall utilization of machines, which aids to smooth out the workload between the cells to increase the balancing amount of work for the operators working in each cell.

3.2. Notations The notations of the proposed model are described as follows:

P Number of parts
M Number of machines
J_p Number of operations for part type p
C Number of manufacturing cell to be formed
p Part types; $p = 1,2,\dots,P$
m Machine types; $m = 1,2,\dots,M$
j Operations required by part P; $p = 1,2,\dots,P$
c Manufacturing cell; $c = 1,2,\dots,C$
T_m Capacity of machine type m
D_p Demand of part type p during planning horizon
B_p Batch size of part type p
α_m Purchase cost of machine type m
β_m Operating cost per hour of machine type m
M_m Maintenance cost of machine type m
γ_p Inter-cell material handling cost for each

batch of part type p
t_{jpm} Time required performing operation j of part type p on machine type m

$$\alpha_{jpm} = \begin{cases} 1, & \text{if operation } j \text{ of part type } p \text{ can be done} \\ & \text{on machine type } m \\ 0, & \text{otherwise} \end{cases}$$

UB Upper bound for the cell size
LB Lower bound for the cell size
ou Overall utilization of machines in the system (total average of workload on all machines in the system)
cu_c Utilization of machines in cell c (total average of workload on all machines in each cell)

3.3. Decision Variables

N_{mc} Number of machines type m required in cell c

$$X_{jpmc} = \begin{cases} 1, & \text{if operation } j \text{ of part type } p \text{ is done} \\ & \text{on machine type } m \text{ in cell } c \\ 0, & \text{otherwise} \end{cases}$$

$$z_{jpch} = \begin{cases} 1, & \text{if operation } j \text{ of part type } p \text{ is done} \\ & \text{in cell } c \\ 0, & \text{otherwise} \end{cases}$$

3.4. Mathematical Formulation According to the above-mentioned definitions, the objective function and constraints of our proposed model are given in the following equations.

$$\text{Min } F_1 = \frac{1}{2}\sum_{p=1}^{P}\left\lceil \frac{D_p}{B_p} \right\rceil \times \gamma.\sum_{j=1}^{J_p-1}\sum_{c=1}^{C}\left|Z_{(j+1)pc}-Z_{jpc}\right| +$$

$$\sum_{m=1}^{M}\sum_{c=1}^{C}N_{mc}.M_m + \sum_{m=1}^{M}\sum_{c=1}^{C}N_{mc}.\alpha_m + \qquad (1)$$

$$\sum_{c=1}^{C}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{j=1}^{J_p}D_p.X_{jpmc}.t_{jpm}.O_m$$

$$\text{Min } F_2 = \left|ou-1\right|$$

$$\text{Min } F_3 = \sum_{c=1}^{C}\left|cu_c - ou\right|$$

s.t.

$$\sum_{c=1}^{C=1}\sum_{m=1}^{M} a_{jpm}.X_{jpmc}=1 \qquad \forall j,p \qquad (2)$$

$$\sum_{p=1}^{P}\sum_{j=1}^{J_p} D_p.t_{jpm}.X_{jpmc}\leq T_m\times N_{mc} \qquad \forall m,c \qquad (3)$$

$$Z_{jpc}=a_{jpm}\times\sum_{m=1}^{M}X_{jpmc} \qquad \forall j,p,c \qquad (4)$$

$$N_{mc}\leq\sum_{p=1}^{P}\sum_{j=1}^{J_p} a_{jpm}.x_{jpmc} \qquad \forall m,c \qquad (5)$$

$$\sum_{m=1}^{M}N_{mc}\leq UB \qquad \forall c \qquad (6)$$

$$\sum_{m=1}^{M}N_{mc}\geq LB \qquad \forall c \qquad (7)$$

$$ou=\left(\sum_{c=1}^{C}cu_c\times\left(\sum_{m=1}^{M}T_m.N_{mc}\right)\right)\Bigg/\left(\sum_{c=1}^{C}\sum_{m=1}^{M}T_m.N_{mc}\right) \qquad (8)$$

$$cu_c=\left(\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{j=1}^{O_p}D_p.t_{jpm}.X_{jpmc}\right)\Bigg/\left(\sum_{m=1}^{M}T_m.N_{mc}\right);\forall c \qquad (9)$$

$$X_{jpmc},Z_{jpc}\in(0,1)\text{ and }N_{mc}\geq 0 \qquad \forall j,p,m,c \qquad (10)$$

The multi-objective function given in Equation 1 is a mixed-integer nonlinear equation consisting of three sub-functions. The first function (F_1) minimizes the total sum of inter-cell material handling costs, machine maintenance costs, machine purchase costs and machine operating costs. The first term is obtained by summing the products of the number of inter-cell transfers in batches and the unit batch inter-cell movement cost. The operation sequence directly affects the intercellular movements; i.e. if two consecutive operations must processed by two machines in two different cells, only one unit inter-cell movement cost will incur. The second term of this equation is obtained by the product of the number of machine type m in cell c and their associated constant costs. The third term is the machine procurement cost. The forth term is the sum of the product of the

operational time that each machine needs to process the allocated quantity of parts and their associated variable costs.

The second and third functions (i.e., F_2 and F_3), are to overcome the deviation of the desired overall machinery utilization and average workload among cells, respectively. F_2 tries to minimize the deviation of the overall utilization from the ideal overall machinery utilization (i.e., 1) or all parts and in the whole planning horizon. The last objective function also minimizes the deviation of each cell utilization as well as the overall, in order to balance the workload among cells because of parts processing.

Equation 2 guarantees that each part's operation is assigned to a machine, which has the required tools for processing the job. Equation 3 ensures that machine capacities are not exceeded and can satisfy the demand. Moreover, this constraint determines the desired number of each machine type in each cell. In Equation 4, if at least one operation of type p part proceeds in cell c, then the value of z_{jpch} is equal to one; otherwise, it is equal to zero. This constraint is used to compute the inter-cell material movements in the first term of the first objective function. Equation 5 guarantees that each machine type can be added in any cell providing the capability to do at least one operation required for that cell. Equations 6 and 7 specify the upper and lower boundary of the cell size, respectively. Equation 8 computes overall utilization of all machines in manufacturing system. Equation 9 identifies the utilization of all machines in each cell.

3.5. Linearizing the Absolute Function The first term in the objective function can be linearized by introducing two non-negative variables τ_{jpc}^{+} and τ_{jpc}^{-}. The first objective function is rewritten as follows [6]:

$$\text{Min } F_1=\frac{1}{2}\sum_{p=1}^{P}\left\lceil\frac{D_p}{B_p}\right\rceil\times\gamma.\sum_{j=1}^{J_p-1}\sum_{c=1}^{C}\left(\tau_{jpc}^{+}+\tau_{jpc}^{-}\right)+$$

$$\sum_{m=1}^{M}\sum_{c=1}^{C}N_{mc}.M_m+\sum_{m=1}^{M}\sum_{c=1}^{C}N_{mc}.\alpha_m+ \qquad (11)$$

$$\sum_{c=1}^{C}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{j=1}^{J_p}D_p.X_{jpmc}.t_{jpm}.O_m$$

By adding the following set of constraints:

$$Z_{j+1,pc} - Z_{jpc} = \tau_{jpc}^{+} - \tau_{jpc}^{-} \qquad \forall j, p, c \qquad (12)$$

4. MULTI-OBJECTIVE SOLUTIONS

A mono-objective optimization algorithm is terminated upon obtaining an optimal solution, yet it is unlikely to find a single solution for a multi-objective problem and due to the contradictory objectives, we generally find a set of solutions. There are many available methods to tackle multi-objective optimization problems. Collette, et al [21] classified these methods into five sets: scalar methods, interactive methods, fuzzy methods, methods using meta-heuristics and decision aid methods.

In the first approach, which is applied in this paper, a set of objectives which are considered is converted into a single objective by the weight sum of individual objectives. Although this approach offers only a compromised solution whose non-dominance is not guaranteed, it provides the flexibility of assigning different weights to different objectives based on decision maker (DM) requirements, which is a great advantage in MODM and fuzzy environments [15]. It looks very complicated for the proposed model, where solving the model by exact method requires a substantial amount of time. For this reason, the use of meta-heuristics is more suitable than other methods for solving multi-objective optimization problems. Some work has been done in multi-objective optimization area from which the following can be mentioned: multi-objective simulated annealing (MOSA), multi-objective genetic algorithm (MOGA), vector evaluated genetic algorithm (VEGA), Niched Pareto genetic algorithm (NPGA), Pareto archive evaluation strategy (PAES), non-dominated sorting genetic algorithm (NSGA and NSGAII), strength Pareto evolutionary genetic local search (MOGLS), multi-objective scatter search (MOSS) [22].

These methods are not addressed in this paper; however, they are recommended for future studies to prevail over computational complexity of our novel proposed model. Since the proposed triple-objective model consists of a total cost function,

overall utilization, and deviation minimization objectives, we use a type of the weighting method and consider two monetary penalty parameters, named λ_1 and λ_2, to overcome the decline of the desired overall machines utilization and average workload among cells, respectively.

λ_1 Unit penalty of the overall utilization deviation from ideal utilization (i.e., one)

λ_2 Unit penalty of each cell utilization deviation from the overall utilization

Consequently, the multi-objective function proposed by Equation 1 is converted to an integrated cost-based single-objective one.

$$Min = W_1.(\lambda_1.F_1) + W_2.(\lambda_2.F_2) + W_3.F_3 \qquad (13)$$

In addition, the DM defines the penalties in order to provide required flexibility and consider the real-world conditions. However, by the prescribed range to both, the parameters can be obtained by analyzing multiple examples with different values.

5. COMPUTATIONAL RESULTS

To illustrate the behavior of the proposed model and verify the performance of the developed approach, three numerical examples generated at random, in which the first one is solved by a branch-and-bound (B and B) method and the rest are solved by a global solver using the LINGO 8 software package and run on the Pentium 4, processor at 2.4 GHz and Windows XP using 512 MB of RAM. Then, the associated computational results are reported.

As a general setting, all relative weights have the same importance and are equal to 1, in the last two examples. In addition, the maximum cell size (number of machines in each cell) is set to 10 and some of the operations can be done on two or three alternative machines with different processing times. In addition, the deviation penalties, λ_1 and λ_2, are *assumed to be* 100,000 monetary units. The NP-hardness of standard CFP models has been explicitly discussed in some previous studies [6, 10, 23 and 24]. Therefore, the proposed model cannot be solved optimally within a reasonable

amount of time for real-world instances. Because of its nonlinear and NP-hard nature for this reason, the software run time is limited to half hour (i.e. 1800 seconds).

The first example considers M = 4, P = 3, and C = 3 to produce parts that must be processed under 2 through 3 operations. This instance considers that only one function is optimized in each time (related weighting value is 1), that are illustrated in Tables 3 to 5, respectively (i.e., Table 2 shows the solution of instance 1 while $w_1 = 1$, $w_2 = 0$ and $w_3 = 0$ and the like). Data required for this example is based on Table 2. As shown in Tables 3 to 5, data include the machine type, quantity of required machine type, machine grouping, utilization of each cell, overall utilization, objective function, objective function bound obtained according to LINGO

documentation and operations of each part must be done in per cell.

Table 3 illustrates part 2 is processed in cell 1 and cell 2, in which first two operations are done in cell 1 and the last one is done in cell 3.

In this case, one inter-cell movement has occurred due to transferring part 2 form cell 1 to cell 3 after the first two required operations. Figures 2 and 3 demonstrate the utilization of each cell and overall utilization of machines while only one objective function is optimized. Figure 2 shows unbalanced workload among cells has been minimized however; the efficiency of these cells will decrease. These figures show the confliction between two objectives (i.e., maximizing overall utilization and minimizing deviation of utilization of cells).

TABLE 2. Input Data for the First Test Problem.

Cell Info.		UB	10	Part Info.	D_p	300		250			275	
		LB	2		γ_p	30		35			25	
		C	3		B_P	15		18			12	
Machine Info.				t_{jpm}		p_1		p_2			p_3	
β_m	α_m	M_m	T_m			j_1	j_2	j_1	j_2	J_3	j_1	j_2
5	20000	200	2900	m_1		7				7	6	7
4	18000	380	3800	m_2			8	10		10	8	
6	22000	350	3200	m_3				6	5			9
7	19000	300	3100	m_4		6	5		8			

TABLE 3. Solution of the First test Problem Considering Only the First Objective Function.

Cells	cu_c	Machine		Parts			Output Information	
		Type	Quantity	Part 1	Part 2	Part 3		
Cell 1	0.7357143	2	1	2			Best objective	350409
		3	1		1,2		Obj. bound	327072
Cell 2	0.6163793	1	2			1,2		
Cell 3	0.6163793	1	2	1	3		*ou*	0.6760753

TABLE 4. Solution of the First Test Problem Considering Only the Second Objective Function.

Cells	cu_c	Machine		Parts			Output Information	
		Type	Quantity	Part 1	Part 2	Part 3		
Cell 1	0.9736842	2	2	2	1,3		Best Objective	20685.3
Cell 2	0.6833333	1	1	1			Obj. Bound	20685.3
		4	1		2		Gap %	0 %
Cell 3	0.6762295	1	1			1	ou	0.7931472
		3	1			2		

TABLE 5. Solution of the First Test Problem Considering Only the Third Objective Function.

Cells	cu_c	Machine		Parts			Output Information	
		Type	Quantity	Part 1	Part 2	Part 3		
Cell 1	0.6231884	2	1		1		Best Objective	274.909
		4	1	1				
Cell 2	0.6223958	1	2			1,2	Obj. Bound	0
		2	1	2				
Cell 3	0.625	1	1		3		ou	0.6233333
		4	1		2			

The second example is a small-sized problem considering M = 4, P = 3, and C = 3 to produce parts, in which each product must be processed under 3 operations and some operations can be done on 2 alternative machines with different processing times. Moreover, all relative weights for each objective function have the same importance and are equal to 1. In fact, this problem is solved as integrated form with the presence of all objectives. Table 6 shows the input data required for instance 2. Table 7 illustrates solutions of the second example.

The third example is a medium-sized problem considering M = 5, P = 6, and C = 3 to produce parts, in which each product must be processed under three operations and some operations can be done on two alternative machines with different processing times. The whole data set is based on Table 8. In this example, the global optimal solution has been reached and the objective function is equal to 538763 that is the same as the objective bound. Table 9 shows the related results and values.

6. CONCLUSION

In this paper, we have proposed a new multi-objective cell formation model as a mixed-integer nonlinear programming to minimize manufacturing costs, maximize the overall utilization of machinery, and balance the average workload among cells simultaneously by integrating the objectives into a complex cost-based objective
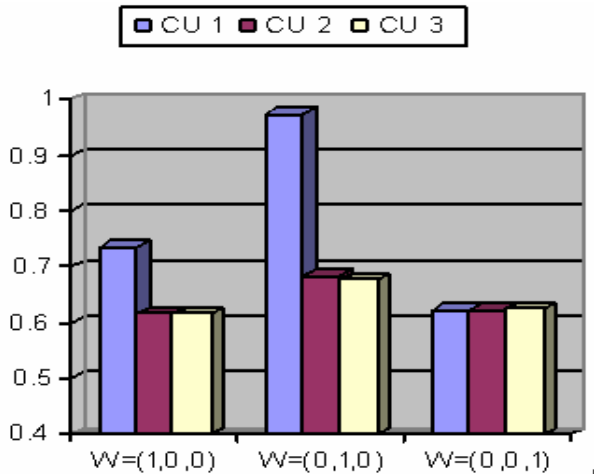
Figure 2. Utilization of each cell with regards to the presence of each objective function value.
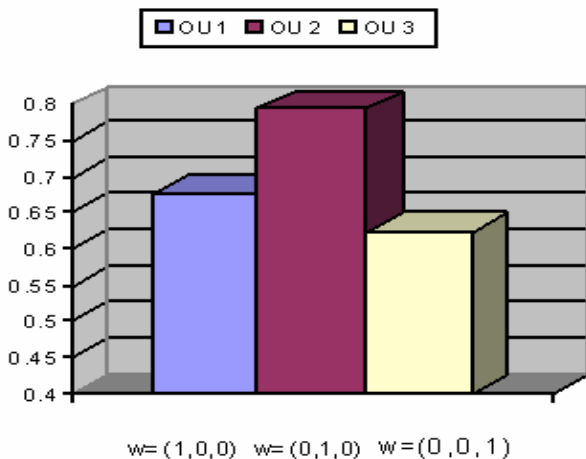

Figure 3. Overall utilization of machinery with regards to the presence of each objective function value.

function. The main advantages of our proposed model are to form part families and machine cells simultaneously, and to determine the best processing route for each part type.

This model also considers the alternative routing, alternative process plan, operation sequence, machine duplication, inter-cell material handling into batches. We have solved an example and verified that the approach can determine the optimal cellular configuration for planning horizon. The proposed model cannot be solved within a

reasonable time even for small-sized problems, due to the NP-completeness of the model; thus, the use of meta-heuristics for solving such a hard problem, and to obtain solutions that are more efficient and also is suggested for future research.

7. ACKNOWLEDGEMENT

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TABLE 6. Input Data for the Second Test Problem.

Cell Info.			Part Info.	D_p	240			280			290		
	UB	10		D_p	240			280			290		
	LB	2		γ_p	32			28			30		
	C	3		B_P	14			15			12		

Machine info.				t_{jpm}	p_1			p_2			p_3		
β_m	α_m	M_m	T_m		j_1	j_2	j_3	j_1	j_2	j_3	j_1	j_2	j_3
6	20000	210	2800	m_1	7		9		5	7	6	7	
5	18000	360	3400	m_2	6	8		10		10			
5	22000	340	2900	m_3		5		6				9	6
6	19000	290	3300	m_4			8		8		8		7

TABLE 7. Solution of the Second Test Problem Considering Same Importance (i.e., one) for Each Objective Function.

Cells	cu_c	Machine		Parts			Output Information	
		Type	Quantity	Part 1	Part 2	Part 3		
Cell 1	0.7108955	2	1				Best Objective	397614
		4	1	3				
Cell 2	0.8787640	1	1		2,3	2	Obj. Bound	396614
		4	1			1		
Cell 3	0.8 213	1	1	1			*ou*	0.835436
		3	1	2	1	3		

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TABLE 8. Input Data for the Second Test Problem.

Cell Info.			Part Info.	D_p	250			275			310			220			290			320		
	UB	10																				
	LB	2		γ_p	25			32			37			31			29			28		
	C	3		B_P	12			15			14			16			12			19		

Machine Info.				t_{jpm}	P_1			P_2			P_3			P_4			P_5			P_6		
β_m	α_m	M_m	T_m		j_1	j_2	j_3	j_1	j_2	j_3	j_1	j_2	j_3	j_1	j_2	j_3	j_1	j_2	j_3	j_1	j_2	j_3
6	20000	220	2200	m_1	6		8	4			7			5		9	4			9		
5	18000	400	3600	m_2		4		7		5	8		7	7				8		8		7
5	22000	350	3200	m_3			7	9					8	3		6		8		4		
6	19000	390	3300	m_4	8					8	9			8								8
4	21000	370	3500	$m5$		5		9					9			3	9	9			8	

TABLE 9. Solution of the Second Third Test Problem Considering Same Importance (i.e., one) for Each Objective Function.

Cells	cu_c	Machine Type	Quantity	P_1	P_2	P_3	P_4	P_5	P_6	Output Information	
Cell 1	0.9578196	1	1	1	2			1		Best Objective	538763
		2	2		1,3				1,3		
		3	1			2				Obj. Bound	538763
Cell 2	0.9585015	2	1				2				
		5	1				3	2,3			
Cell 3	0.9588529	2	1	2	1,3					*ou*	0.9584035
		3	1	3			1		2		

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