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A Bi-Objective Model for Worker Assignment in Cellular Manufacturing System Design

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ABSTRACT

Cellular manufacturing system (CMS) is a manufacturing system that produces families of parts within a cell of machines operated by a worker who plays a crucial role in running the system and determine the quality level. A bi-objective mathematical model is proposed to solve a three-dimensional part-machine-worker assignment problem that improves productivity and efficieny in CMS. The two objectives considered in this model are cost and quality. The costs include the inter- and intra-cell material handling costs as well as the production costs while the quality is calculated as overall percentage. The performance of workers on different machines is measured by the average scrap or defect rate of parts processed on each machine by dedicated workers. The novelty in this model lies in addressing the cell formation problem simultaneously with the layout planning and worker assignment problems. As the proposed problem is NP-hard, a genetic algorithm (GA) is used to effectively solve the problem. Finally, several problems from related literature were used to verify the proposed model. The results are compared to previous researches and demonstrate the advantages of the proposed integrated approach.

***Keywords*--** Cellular Manufacturing System; Cell Formation; Facility Layout; Worker Assignment; Genetic Algorithm; Bi-Objective Optimization

I. INTRODUCTION

Today's significant variation in the design and fluctuation of production volume in addition to seeking more productive and efficient production system is the main motivation toward flexibility in manufacturing. Cellular manufacturing system (CMS) is an application of group technology (GT) philosophy that achieves such flexibility while maintaining high productivity. Based on the GT approach, the production system is divided into several sub-systems called cells in order to facilitate its management. This process is called Cell Formation (CF) in CMSs. The CF process is one of the first and most important steps of the CMS design problem that involves grouping parts into part families and machines into machine cells. In recent years, the CF problem has been extended to include the issues such as facility layout(Forghani et al. 2012;Forghani et al. 2015), production planning(Tavakkoli-Moghaddam et al. 2014; Xing et al. 2014)scheduling(Aryanezhad et al. 2011), supply chain management(Aalaei and Davoudpour 2016)and worker assignment(Bagheri and Bashiri 2014; Egilmez et al. 2014; Dávila and Cesaní 2014; Bootaki et al. 2014).

On the other hand, facility layout problems are found in several types of manufacturing systems. As it has a significant impact on manufacturing costs, work in process, lead times and productivity (Drira et al. 2007). Tompkins et al. (1996)stated that a good placement of facilities could reduce until 50% the total manufacturing costs. Thus, to attain benefits from CMS, its layout should be designed efficiently.

Due to the complexity of CMS design problems, the CF process is performed before the layout designing process in most researches. For instance, Tavakkoli-Moghaddam et al.(2007) proposed a stochastic mathematical model to obtain the machine and cell layouts; i.e., the intra- and inter-cell layouts, respectively. The cell configuration is assumed to be known, and considered as an input to the inter- and intra-cell layout problem. A three stages approach to the CF and its layout has been been addressed in Krishnan et al.(2012).In this approach, the CFis obtained in the first stage. Then, in the second stage, a modified grouping efficiency measure is used to determine the efficiency of grouping. In the third stage, a Genetic Algorithm (GA) is utilized to obtain the cell layout. Forghani et al. (2013) proposed a mathematical model in which the objective is to minimize a weighted sum of total inter- and intra-cell movement costs. They solved this model with different weights in order to find a set of candidate CFs. Then, another mathematical model was used to find the layout of these CFs. Finally, the best configuration in terms of the actual material handling cost is selected. Chang et al. (2013) presented a mathematical model to obtain the CF and cell locations. Then, they used a Tabusearch algorithm to determine the layout of machines within each cell. Applying sequential approaches to solving the

CMS design problems do not necessarily result in an optimal CMS configuration; because, in these approaches, the final CMS design is highly dependent on the CF obtained in the initial steps.

In recent years some researchers have attempted to simultaneously solve the CF and layout problems; for instance, see (Arkat, Farahani, and Hosseini 2012; Mahdavi et al. 2013; Mohammadi and Forghani 2014; Forghani and Mohammadi 2014; Javadi et al. 2014; Mohammadi and Forghani 2016a).Workforce and differences between operators are important issues in the performance of the CMS. In this area, Mahdavi et al. (2012)proposed a mathematical model for the CF problem that depends on a three-dimensional machine-part-worker incidence matrices. The capability of workers in doing jobs on different machines wasre presented by zero or one values. Their objective was to minimize the total number of voids and exceptional elements. Soolaki(2012)developed a CF problem based on production planning and worker assignment in a dynamic environment, where the workers are assigned to the machines according to their skills. The aim of this problem is to minimize several cost components including the hiring, firing and salary costs, production and subcontracting cost, intercellular material handling cost, backorder cost, inventory holding cost, and cell load variation cost. A similar problem considering worker training in a dynamic environment has been considered in Saidi-Mehrabad et al. (2013). Dealing with the interaction interest between workers a bi-objective problem has been proposed in Mahdavi et al. (2014).

Due to the operational autonomy, most CF approaches usually consider the assignment of worker to the whole cell, not to specific machine, since it is assumed that each worker is responsible for the whole cell, and each worker is expected to have mastered a full range of operating skills required by his or her cell. These approaches donot determine which worker could operate which machine. Although, some researcher like; Park et al. (2014) and Norman et al. (2002) were interested with assigning workers to machine they didn't take real measure of how performance of a worker on a machine.. These models do not solve layout problems when assigning workers in CMS. For layout problems, those approaches aim at minimizing the number of inter-cell movements or intra-cell movements, and/or both, instead of minimizing the material handling cost and usually apply unrealistic assumptions such as infinite capacity of machines, equal sizes of machines, single routing of parts...etc.

In this research, a bi-objective mathematical model is developed to solve a three-dimensional part-machine-worker assignment and layout problem in CMSs. The cell formation, layout and assignment are solved simultaneously. Due to different worker involvement and variation in quality level, two objectives are used to model the problem; cost and quality. The first objective is minimizing the total costs which includes the inter- and intra-cell material handling costs as well as production costs. The second objective is maximizing the overall quality percentage. This includes the performance of workers on different machines, which is measured by the average scrap rate or defect rate of parts processed on each machine by the assigned worker. As the proposed problem is NP-hard, a GA is suggested to effectively solve the problem. Finally, numerical examples selected from the related literature are used to verify the proposed model and to demonstrate its advantages. The novel aspect of this model is addressing the CF problem simultaneously with the layout planning and worker assignment problems. Generally, the main contributions of this research can be stated as follows:

- Solve CF, layout and worker assignment in CMS simultaneously,
- Use actual (not assumed) measure of the performance of worker when operating a machine,
- Integrate both the inter- and intra-cell layout problems in the CF process with applicable factors such as scrap rate, part demands, sequence data, and machine dimensions,
- Improve the performance of the CMS such as productivity and efficiency.

II. PROPOSED MODEL

In this section, abi-objective problem is tackled to simultaneously obtain the CF, inter- and intra-cell layouts, process routing of parts and assignment of workers to machines. The layout framework considered in this problem is identical with the one applied in Mohammadi and Forghani(2014).The problem is formulated as a bi-objective mathematical model, where the first objective minimizes the total costs, including the inter- and intra-cell material handling costs and production costs, and the second one maximizes the overall quality percentage.

2.1. Assumptions

The assumptions made in the proposed problem are as follows:

- The set of parts, machines, and workers are known in advance.
- The routings of each part, as well the operation sequence in each routing are pre-determined.
- Only one routing is selected for processing each part.
- The demand and material handling cost of parts, the processing times and production costs on machines, and the available time of machines are known in advance.
- The dimensions of machines and the inter- and intra-cell aisle width are known in advance.
- The number of machines that can be assigned to each cell, as well as the maximum number of cells allowed to be formed, are known.
- Machines within each cell are arranged according to the single line layout.
- Machine duplication is not allowed.

- Workers have the same capability in producing a specific part.
- Workers are not allowed to move between cells.
- Training, hiring and firing of the workers are not allowed.

2.2 Notations

The notations used in this paper are as follows:

Sets:

i part index ($i = 1, \dots, P$, where P is the number of parts)
j route index ($j = 1, \dots, R_i$, where R_i is the number of routings of part i)
m machine index ($i = 1, \dots, M$, where M is the number of machines)
w worker index($i = 1, \dots, W$, where W is the number of workers ($W \leq M$))
c cell index ($i = 1, \dots, C$, where C is the maximum permissible number of cells)

Parameters:

d_i demand of part i (part/year)
c_i^A intra-cell material handling cost of part i per unit distance ($/part)
c_i^E inter-cell material handling cost of part i per unit distance ($/part)
c_{ijm}^O operational cost of part i on machine m in routing j ($/part)
t_{ijm} operation time of part i on machine m routing j (hr/part)
T_m available time of machine m (hr/year)
h_m width of machine m (m)
l_m length of machine m (m)
N_w maximum number of machines allowed to be assigned to worker$w$
N^M maximum number of machines allowed in a cell
d^A aisle width between machines in the same cell (m)
d^E aisle width between the cells (m)
c_{ijm}^S scrap cost of machine m when operating part i at route j ($/part)
$f_{ijmm'}$ = 1 if part i in routings j needs to be transferred between machines m and m'
s_{wm} average scrap rate when worker w is assigned to machine m
AHC total intra-cell material handling cost ($/year)
EHC total inter-cell material handling cost ($/year)
PC total production cost ($/year)
SC total scrap cost ($/year)
TV total variable cost ($/year)
OQ overall quality percentage

Decision variable:

r_{ij} = 1 if part i is processed using routing j; 0 otherwise
z_{mc} = 1 if machine m is assigned to cell c; 0 otherwise
v_{wm} = 1 if worker w is assigned to machine m; 0 otherwise
$\alpha_{mm'}$ = 1 if machine m is placed before machine m' in an identical cell; 0 otherwise
u_m auxiliary positive variable used to produce legal layout sequence
x_m horizontal coordinate of the centroid of machine m
y_c vertical coordinate of the centroid of cell c

2.3 Mathematical model

According to the descriptions given above, the proposed problem is formulated as the following bi-objective mathematical model.

Objective functions:

$$\min TV = AHC + EHC + PC + SC, \tag{1}$$

$$\max OQ = \sum_{m=1}^{M} \sum_{w=1}^{W} v_{wm}(1 - s_{wm}), \tag{2}$$

where

$$AHC = \sum_{i=1}^{P} \sum_{j=1}^{R_i} \sum_{m=1}^{M} \sum_{m'=m+1}^{M} \sum_{c=1}^{C} c_i^A . d_i . r_{ij} . f_{ijmm'} . z_{mc} . z_{m'c} |x_m - x_{m'}|, \tag{1.1}$$

$$EHC = \sum_{i=1}^{P}\sum_{j=1}^{R_i}\sum_{m=1}^{M}\sum_{m'=m+1}^{M}\sum_{c=1}^{C}\sum_{\substack{c'=1\\c'\neq c}}^{C} c_i^E.d_i.r_{ij}.f_{ijmm'}.z_{mc}.z_{m'c'}(|x_m - x_{m'}| + |y_c - y_{c'}|), \quad (1.2)$$

$$PC = \sum_{i=1}^{P}\sum_{j=1}^{R_i}\sum_{m=1}^{M} d_i.r_{ij}.c_{ijm}^O, \quad (1.3)$$

$$SC = \sum_{i=1}^{P}\sum_{j=1}^{R_i}\sum_{m=1}^{M}\sum_{w=1}^{W} d_i.r_{ij}.c_{mij}^S \;.s_{wm}.v_{wm}. \quad (1.4)$$

Constraints:

$$\sum_{j=1}^{R_i} r_{ij} = 1, \qquad i = 1,\dots,P, \quad (3)$$

$$\sum_{c=1}^{C} z_{mc} = 1, \qquad m = 1,\dots,M, \quad (4)$$

$$\sum_{m=1}^{M} z_{mc} \leq N^M, \qquad c = 1,\dots,C, \quad (5)$$

$$\sum_{w=1}^{W} v_{wm} = 1, \qquad m = 1,\dots,M, \quad (6)$$

$$\sum_{m=1}^{M} v_{wm} \leq N_w, \qquad w = 1,\dots,W, \quad (7)$$

$$v_{wm} + v_{wm'} \leq 1 + \sum_{c=1}^{C} z_{mc}.z_{m'c}, \qquad w = 1,\dots,W, \qquad m = 1,\dots,M, \qquad m' = m+1,\dots,M, \quad (8)$$

$$\sum_{i=1}^{P}\sum_{j=1}^{R_i} d_i.r_{ij}.t_{ijm} \leq T_m, \qquad m = 1,\dots,M, \quad (9)$$

$$y_c = \sum_{c'=1}^{c-1} \max_{m=1,..,M}\{(d^E + l_m)z_{mc'}\} + \frac{\max_{m=1,..,M}\{l_m.z_{mc}\}}{2}, \qquad c = 1,\dots,C, \quad (10)$$

$$\alpha_{m'm} + \alpha_{mm'} = \sum_{c=1}^{C} z_{mc}.z_{m'c}, \qquad m = 1,\dots,M, \qquad m' = m+1,\dots,M, \quad (11)$$

$$u_{m'} - u_m \geq 1 + N^M\left(1 - \sum_{c=1}^{C} z_{mc}.z_{m'c}\right), \qquad m = 1,\dots,M, \qquad m' = 1,\dots,M, \quad (12)$$

$$x_m = \sum_{\substack{m'=1\\m'\neq m}}^{M} (d^A + h_m)\alpha_{m'm} + \frac{h_m}{2}, \qquad m = 1,\dots,M, \quad (13)$$

$$0 \leq u_m \leq N^M, \qquad m = 1,\dots,M, \quad (14)$$

$$x_m, y_c \geq 0, \qquad m = 1,\dots,M, \qquad c = 1,\dots,C, \quad (15)$$

$$\alpha_{m'm} \in \{0,1\},, \qquad m = 1,\dots,M, \qquad m' = 1,\dots,M, \quad (16)$$

$$r_{ij}, z_{mc}, v_{wm} \in \{0,1\}, \qquad i = 1,\dots P, \qquad j = 1,\dots,R_i, \qquad m = 1,\dots,M, \qquad c = 1,\dots,C, \qquad w = 1,\dots,W. \quad (17)$$

In the proposed model, there are two objective functions: the first objective function (1) minimizes the total variable costs of the system. The cost components given in Eqs (1.1)–(1.4) respectively stand for the intra- and inter-cell material handling costs, production cost and scrap cost. Objective function (2) maximizes the overall quality percentage. Constraint (3) ensures that only one route is selected for each part type. Constraint (4), ensures that each machine is assigned to one cell. Constraint (5) ensures that no more than N^M machines is assigned to each cell. Constraint (6) represents that each machine is operated by a worker. Constraint (7) prevents the assignment of more than N_w machines to worker$w$. Constraint (8) states that a worker can only be dedicated to the machines in an identical cell; in other words, this constraint prevents the movement of workers between cells. Constraint (9) is the machine capacity constraint. Constraint (10) calculates the vertical coordinate of the centroid of each cell. Constraints (11) and (12) jointly specify the relative position of machines within a cell. Constraint (13) calculates the horizontal coordinate of the centroid of machines. Finally, constraints (14)–(17) shows the type of decision variables.

III. UNIFYING THE OBJECTIVE FUNCTIONS

To unify objective functions (1) and (2) into one objective function, a normalized weighted sum function, TC, is used as shown below (Mohammadi and Forghani 2016a; Mohammadi and Forghani 2016b).

$$\min TC = \beta\left(\frac{TV - TV_L}{TV_U - TV_L}\right) + (1-\beta)\left(\frac{OQ_U - OQ}{OQ_U - OQ_L}\right), \quad (18)$$

subject to: (3)–(17).

Where $\beta (0 \le \beta \le 1)$ is the weighting factor that reflects the relative importance between TV and OQ in the normalized objective function; TV_U and TV_L respectively are the upper and lower boundaries of TV; and OQ_U and OQ_L respectively are the upper and lower boundaries of OQ. To see how these upper and lower boundaries could be estimated refer to (Mohammadi and Forghani 2016a).

IV. THE GENETIC ALGORITHM

According to Garey and Johnson (1979), both the CF and layout problems belong to the class of NP-hard problems. From the other side, in this study we have integrated these problems with the routing selection and worker assignment problems; therefore, the proposed problem would also be NP-hard. In recent years, GAs have been successfully employed to solve this type of problems, see for example (Park et al. 2014; Saeidi et al. 2014; Hosseini et al. 2016; Mohammadi and Forghani 2016b). For these reasons, we use a GA to effectively solve the problem. In the following subsections, the proposed GA is explained.

4.1. Proposed Chromosome encoding

In the GA, each chromosome consists of three sections as given below:

machine section: Based on the information of this section, the assignment of machines to the cells and their layout sequence within each cell is determined. As we have a maximum of C cells, each with a capacity of N^M machines, this section consists of $N^M \times C$ genes. The value of genes in this section involves a combination of the index of all M machines, as well as $N^M \times C - M$ zeroes (the zeros correspond to the unused capacity of cells). To obtain the coordinates of machines and cells (i.e., x_m and y_c) the following algorithm is used.

Algorithm obtain x_m and y_c.
$Y \leftarrow 0$;
For $c = 1$ **to** C **do**
  $X \leftarrow 0$;
  $L \leftarrow 0$;
  For $m' = 1$ **to** N^M **do**
    $m \leftarrow Chr[(c-1)N^M + m']$;
    If $M \neq 0$ **then**
      $x_m \leftarrow X + h_m/2$;
      $X \leftarrow X + d^A + h_m$;
      If $l_m > L$ **then**
        $L \leftarrow l_m$;
      End IF;
    End IF;
  End For;
  $y_c \leftarrow Y + L/2$;
  $Y \leftarrow Y + d^E + L$;
End For;

part section: The part section, which consists of P genes, indicates the routing selected for each part.
worker section: The worker section indicates the assignment of workers to machines; this section includes M genes.

In the initial population, the genes corresponding to the machine and part sections are generated randomly, while the genes of the worker section are generated according to the following procedure:

step 1. Let $S^M := \{1,2,\ldots,M\}$ as the set of machnies, and $S^W := \{1,2,\ldots,W\}$ as the set of workers. Set $R^W \coloneqq \emptyset$ and $\bar{N}_w \coloneqq 0$ for all $w \in S^W$.
step 2. Choose a $m \in S^M$ as an arbitary machine and set $S^M := S^M \setminus \{m\}$. Choose a $w \in S^W$ as an arbitary worker. Set $\bar{N}_w \coloneqq \bar{N}_w + 1$and $S^W := S^W \setminus \{w\}$. IF $\bar{N}_w < N_w$ then set $R^W := R^w \cup \{w\}$. Assign machine m to worker w and go to step 3.
step 3. If $S^W = \emptyset$ then go to step 4, else go to step 2.
step 4. Choose a $m \in S^M$ as an arbitary machine and set $S^M := S^M \setminus \{m\}$. Choose a $w \in R^W$ as an arbitary worker. Set $\bar{N}_w \coloneqq \bar{N}_w + 1$. IF $\bar{N}_w = N_w$ then set $R^W := R^w \setminus \{w\}$. Assign machine m to worker w and go to step 5.
step 5. If $S^M = \emptyset$ then stop, else go to step 4.

To clarify the proposed encoding, an example consisting of 10 parts, 8 machines, 5 workers, and 3 cells is given in Table1. The maximum capacity of the cells (N^M) is assumed to be three machines. According to the machine section, the layout sequence of machines within cells 1, 2 and 3 are as2→3→4, 5→6, and 1→7→8, respectively. The routing information of parts is shown in the part section. For example, the routing selected for part 5 is route 3. Finally, the assignment of workers to the machines is shown in the worker section; for instance, worker 3 is assigned to machines 2 and 8.

Table 1
An examplechromosome

	Machine section									Part section										Worker section							
	Cell									Part										Machine							
Index	1			2			3			1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8
Gene	2	3	4	5	6	0	1	7	8	2	3	2	1	3	2	1	2	2	3	2	3	1	1	5	2	4	3

4.2. GA operators

The operators applied in the proposed GA are as follows:

Selection strategy: After calculating the fitness of chromosomes using Eq. (18), for generating new population, the roulette wheel procedure is applied to select parent chromosomes.

Crossover operators: Due to the multi-section structure of chromosomes, a special crossover operator is needed to be applied to each section. For this purpose, the one-point crossover is applied on the part section. For the machine section, the Partially Mapped Crossover (PMX) is applied (Mohammadi and Forghani 2014). Finally, for the worker section, a Modified Partially Mapped Crossover (MPMX) is applied to prevent violation of constraints (5) and (6). First, the one-point crossover operator is performed on this section. Then, the set of machines assigned to each worker is determined, if the number of machines in this set exceeds the worker's capacity, a random worker having free capacity is chosen and dedicated to one of the machines from the corresponding set. This process is repeated until a feasible solution (chromosome) is derived. For instance, as it is shown in Fig. 1,after performing the one-point crossover on the worker section, in the first child chromosome, i.e., C_1', worker 4 is repeated three times. Now, assume that $N_w = 2$ for all workers. So, it is necessary to replace this worker with one of the workers having free capacity, in this case worker 3.

Section	Part	Machine	Worker
Crossover operator	One-point	PMX	Modified PMX
Cut point	↓ (between genes 5 and 6)	↓ (between genes 4 and 5)	↓ (between genes 3 and 4)
Gene	**1 2 3 4 5 6 7 8 9 10**	**1 2 3 4 5 6 7 8 9**	**1 2 3 4 5 6 7 8**
P_1	2 1 1 2 3 1 2 2 1 1	1 3 4 5 7 0 8 2 6	1 4 2 3 4 5 3 2
P_2	3 2 1 1 1 2 3 3 2 1	1 2 0 6 4 3 5 8 7	3 2 1 4 4 5 3 2
C_1'		1 3 4 5 4 3 5 8 7	1 4 2 4 4 5 3 2
C_2'		1 2 0 6 7 0 8 2 6	3 2 1 3 4 5 3 2
Mapping relation		(4 ↔ 7 ↔ 6); (5 ↔ 8 ↔ 2); (3 ↔ 0)	(3 ↔ 4)
C_1	2 1 1 2 3 2 3 3 2 1	1 0 6 2 4 3 5 8 7	1 3 2 4 4 5 3 2
C_2	3 2 1 1 1 1 2 2 1 1	1 5 3 4 7 0 8 2 6	4 2 1 3 4 5 3 2

Fig. 1. Example of crossover operators

Mutation operators: Similar to the crossover, different types of mutation operators are needed on each section of chromosomes. These operators are given below:

i. Change mutation: This operator is applied on the part section and randomly changes the routing of a randomly selected part.

ii. Swap Mutation: This operator is independently performed on the machine and worker sections. Two random numbers are selected, and the corresponding genes are swapped.

iii. Inverse Mutation: This operator, which is applied to the machine section, places the contents of a randomly selected cell in the reverse order.

iv. Exchange Mutation: This operator is performed on the machine section. Two cells are randomly selected and their contents are swapped with each other.

4.5. Stopping criteria

The GA continues to generate new population until the objective function is not improved for a specified number of generations (Max. No. Generations).

4.6 GA Parameters value

The performance of a GA highly depends on the value of its parameter. To obtain an appropriate value for the GA parameters, we carried out some computational experiments. Based on these experiments, the GA parameters are set as Population size = 150, Max. No. Generations = 150, crossover rate = 0.8 and Mutation rate = 0.2.

V. A NUMERICAL EXAMPLE

A small-sized numerical example is generated and examined to validate the proposed approach. This example includes four machines, four workers, and six parts; where each part has at most two routings. Table 2includes the demand and material handling costs of parts, as well as the processing information of each routing. Table 3shows the dimension and available time of machines, as well as the scrap percent resulting from the assignment of a worker to a machine; in some cases, the scrap percent is assumed100% in order to prevent the corresponding assignment. The other parameters are as $C = 2$, $N^M = 2$, $d^A = 1$, $d^E = 2$, and $\beta = 0.5$.

Table 2

Data related to the parts in the numerical example

Part #	d_i	c_i^A	c_i^E	Route #	Operation sequence: machine(cost, time)
1	100	0.4	0.8	1	1 (2, 0.1)→3 (2.25, 0.3)→2 (3, 0.3)
				2	1 (2, 0.15)→4 (2, 0.32)→2 (3.25, 0.2)
2	150	0.6	0.68	1	1 (1.5, 0.2)→4 (3, 0.3)
				2	1 (1.75, 0.22)→3 (3,0.15)→2 (1.75, 0.32)
3	80	0.7	0.85	1	3 (2.5, 0.2)→2 (2, 0.8)
				2	1 (1,0.14)→3 (2,0.12)→ 4 (2.5, 0.50)
4	130	0.3	0.5	1	3 (4, 0.4)→2 (2, 0.4)
				2	1 (2,0.2)→4 (3.5, 0.2)
5	120	0.2	0.6	1	1 (2.25,0.2)→3 (2.5, 0.12)→2 (2, 0.15)
6	95	0.4	0.66	1	3 (3,0.5)→1 (2, 0.3)→4 (3, 0.5)

Table 3

The data related to the machines and workers in the numerical example

machine\worker	s_{wm} 1	s_{wm} 2	s_{wm} 3	s_{wm} 4	T_m	h_m	l_m
1	0.19	0.30	0.20	0.01	130	3	2.5
2	0.03	0.14	0.05	100	220	2.5	2
3	0.11	0.07	0.07	0.06	180	2	2.5
4	100	0.09	0.03	0.04	200	3	3.5

To be able to evaluate TC, see Eq. (18), the upper and lower bounds on each objective function is assumed to be $TV_U = 6000$, $TV_L = 3000$, $OQ_U = 0.9$ and $OQ_L = 0.5$. The convergence diagram of the GA is depicted in Fig. 2; as it can be seen, the objective value converges to 0.535, at the 27th iteration. The best chromosome in the final population is also shown in Table 4.

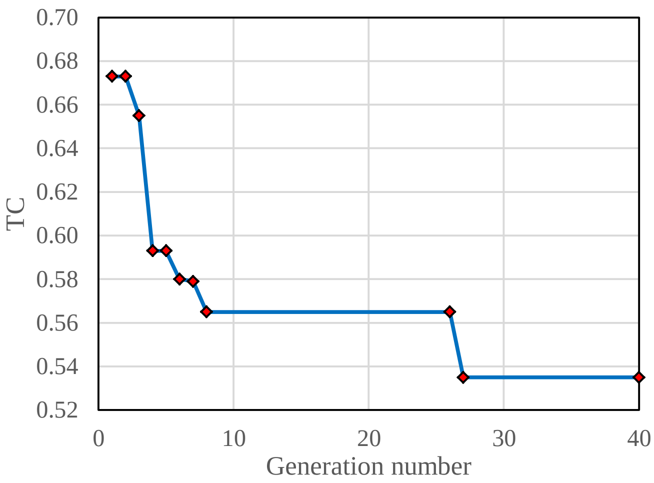

Fig. 2. Convergence diagram for the numerical example

Table 4
The best resultant chromosome for the numerical example

Machine section				Part section						Worker section				Fitness value (TC)	TV	OQ
2	3	4	1	2	1	1	1	1	1	4	1	2	3	0.535	6884	99%

VI. COMPARISON WITH SIMILAR STUDIES

To conduct a comparison between the developed approach and the existing approaches in the literature, four numerical examples are selected from the literature and solved using the proposed GA. For these numerical examples, the incomplete data such as part demands, available time and dimensions of machines, and processing times are randomly generated. Table 5shows the information of the selected numerical examples. In all the cases, it is assumed that$d^A = 1.5$m and$d^E = 2$m; the upper and lower boundaries of the objective functions are calculated according to the explanations given in Section 3;the importance factor (β) is also assumed to be 0.5. Table 6 summarizes the comparison results; for problem 4 there are two alternative solutions found in Chan et al. (2006). From this table, we can see that the developed approach gives better results in terms of the unified objective value compared to the other approaches.

Table5
Information related to the numerical examples used for the comparison*

Problem			Parameters						
No	Source	Size ($W \times P \times M$)	d_i	c_i^A	c_i^E	c_{ijm}^O	T_m	t_{ijm}	l_m and h_m
1	(Kao and Lin 2012)	5 × 10 × 7	Source	0.1	0.15	U(0.5, 3.5)	Source	Source	U(2, 5)
2	(Mohammadi and Forghani 2014)†	7 × 10 × 10	Source	0.1	0.15	U(0.5, 3.5)	U(500, 1500)	U(0.1, 1.5)	U(2, 5)
3	(Chang et al. 2013)	12 × 30×18	100	0.1	0.15	U(0.5, 3.5)	U(500, 1500)	U(0.1, 1.5)	U(2, 5)
4	(Chan et al. 2006)	15 × 20 ×20	100	0.1	0.15	U(0.5, 3.5)	U(500, 1500)	U(0.1, 1.5)	U(2,5)

*In this table, U implies to the uniform distribution.
† The solution for this numerical example has been requested from the respective authors.

Table 6
Comparison results

Problem			Literature solution			Proposed approach			$Imp.$*
No.	C	N^M	TV_{Lit}	OQ_{Lit}	TC_{Lit}	TV_{GA}	QP_{GA}	TC_{GA}	
1	3	3	2166	91	1.153	1941	99	0.0587	94.9%
2	3	4	9870	81	0.517	9976	92	0.4093	20.8%
3	3	7	38641	97	0.4634	36169	99	0.1591	65.7%
4.1	5	5	13032	87	0.4041	10271	92	0.0113	97%
4.2	5	5	11601	77	0.4614	10271	92	0.0113	98%

*$Imp. = 100\,(TC_{Lit} - TC_{GA})/TC_{Lit}$.

VII. CONCLUSION

In order to satisfy the design variation and demand fluctuation, a bi-objective model is proposed to simultaneously solve three problems in cellular manufacturing systems; namely cell formation, cell layout and worker assignment. The bi-objectives in the proposed model are cost and quality. The first objective focuses on minimizing the total costs, including the inter- and intra-cell material handling costs as well as production costs. The second objective focuses on maximizing the overall quality percentage. Since the problem on hand is NP-hard, a genetic algorithm (GA) was adopted to effectively solve the problem. A small-sized numerical example was presented to illustrate and validate the proposed approach. Further numerical benchmark examples, selected from the related literature, were used to verify the performance and to demonstrate the advantages of the proposed approach. The results indicated that the proposed bi-objective approach produced better solutions than the existing approaches in the literature.

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