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Investigation into skill leveled operators in a multi-period cellular manufacturing system with the existence of multi-functional machines

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Multi-period cellular manufacturing system;
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Alternative process routing.

Abstract. Numerous studies published in the field of cellular manufacturing system are based on the assumption that machines are reliable in the entire production line without any breakdown. Since such assumptions are not usually realistic, to contribute to closing this gap between assumption and reality, a new model was proposed that additionally considered machine reliability, alternative process routings, and workforce assignment in a dynamic environment. Given such considerations in this research, the modified problem was defined and formulated and an extended mixed integer multi-period mathematical model was proposed. In order to evaluate the effectiveness and capability of the extended model, some hypothetical numerical instances were generated and computational experiments were carried out using GAMS optimization package. Experimental results demonstrated that the demand value could affect the machine breakdown rate, and a machine with a minimum breakdown rate was implemented more often than others. Moreover, the observed trade-off between the workforce-related costs and cell-formation costs indicated that workforce-related issues had a significant impact on the total efficiency of the system. The proposed model can be quite applicable to medium- and large-scale manufacturing companies.

1. Introduction

Group Technology (GT), known as an effective manufacturing technique, necessitates, as the name suggests, fulfilling similar tasks in the same way. This approach can be viably employed in a competitive production environment, which makes manufacturing systems adapt themselves to the erratic changes and dynamics of production factors such as part demand changes, new product development, machine requirements, etc. Being highly potential and enjoying high performance in manufacturing, Cellular Manufacturing System (CMS) as an application of GT can be implemented at most industrial plants. However, Cell Formation (CF), Inter/intra-Cell Layout (CL), and workforce allocation are the three main sub-problems in designing an efficient CMS. Many researcher have tackled these problems effectively, especially in case of complicated models, in which two or three of the abovementioned problems are simultaneously taken into account. Liu et al. [1], for instance, presented a new model by integrating production planning with facility transfer in a dynamic cellular manufacturing environment in the supply chain. Similarly, Askin [2] reviewed the development of CMS-related organizational issues and options. Accordingly, relevant studies can be categorized in terms of designing and optimization. Among other studies, Ameli and Arkat [3] aimed to solve the

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CF problem and developed a pure integer mathematical model. They also considered issues of machine reliability and Alternative Process Routings (APRs). Bulgak and Bektas [4] conducted another research in which CF problem along with Production Planning was investigated, and reconfiguring the system was simultaneously taken into consideration. Mehdizadeh et al. [5] presented a multi-objective Mixed Integer Programming (MIP) model to simultaneously solve CF and production planning problems. They considered numerous real-world parameters such as alternative plans for processing the part types, flexibility of workers and machines, multi-period production planning, capacity of machines, reconfiguration of dynamic systems, sequence of operations, duplicate machines, time availability of workers, and worker assignment were taken into consideration. Furthermore, Mahdavi et al. [6] extended a dynamic CF considering PP and workforce assignment which aimed to minimize the current inventory, in-process inventory and backlog, inter-cell part trip, reconfiguration of machines, and workforce-related costs. Similarly, Aryanezhad et al. [7] proposed an extended model to address CF and workforce assignment problems while, at the same time, examining the following real-world production factors: flexibility of part routings, machine, and labor enhancement training for mastery of higher skill level. Similarly, Bagheri and Bashiri [8] proposed a comprehensive model in which the dynamic CF problems, including inter-cell layout and workforce assignment problems, were integrated. In fact, in a dynamic environment, they analyzed the learning ability of labors. Javadi et al. [9] introduced a novel model in order to investigate the layout and CF problems simultaneously. Their proposed model attempted to design the material-handling flow path structure and inter/intra-cell layout problem concurrently. Bagheri et al. [10] considered a newfangled model for CMS considering some productoin features comprising reliability of machines with stochastic parameters such as service and arrival times in a dynamic area and APRs. Moreover, they employed a benders decomposition method to overcome the complexity of the mentioned problem. Bayram and Şahin [11] also proposed a mathematical model in which many real-world production factors such as sequences of operations, splitting of lots, changing demands for products, capacities of machines, the products' alternative processing routes, and machine duplication were addressed.

Nowadays, in competitive production systems, the workforce-related issues are of importance. Therefore, it is necessary to review the relevant studies in this domain. Recently, Azadeh et al. [12] applied a novel model to the dynamic CMS in a multi-objective area called MDCMS with emphasis on human factors. Two main objectives including minimizing the inconsistency of the decision-making mode for the workforce in the public manufacturing cells and balancing the workload of the cells with respect to workforce efficacy were emphasized in their research. Moreover, in their research, Liu et al. [13] aimed to develop a combined decision model of production planning and assignment of workers in a dynamic CMS area of fiber connector manufacturing business. In the same manner, Mehdizadeh and Rahimi [14] attempted to develop a joint model to tackle the dynamic CF problem with emphasis on the assignment of workforce and inter/intra cell layout problems in the presence of machine duplication. Similarly, Rafiei and Ghodsi [15] proposed an ant colony optimization to tackle the problem of CF integrated with workforce-related issues. Sakhaii et al. [16] also proposed and applied robust optimization methods to investigate the dynamic CF problem with focus on the concepts of reliability of machines, production planning, allocation of workforce, inter cell layout, and APRs. A comprehensive multi-objective model of the CMS in a dynamic area was extended by Nouri [17] who considered several key cell design factors including designations of machines, inter/intra-cell material handling, allotting of workers, workload balancing and outsourcing according to the operation time, and the operation sequence of parts. However, in this study and other related researches, workforce-related issues were not addressed in detail. In addition, the present study aimed to fill the gap mentioned earlier.

In order to analyze the problem in detail, the most significant factors affecting CMS performance are listed in Table 1.

Table 1. Essential parameters of a Cellular Manufacturing System (CMS) problem.

Factor code	Factor description
1	Process sequence
2	Part trips
2-A	Inter-cell part trip
2-B	Intra-cell part trip
3	Cell formation
4	Machine breakdown
5	Process time/cost
6	Machine time/process capacity
7	Multi-functional machines
8	Cell load variation
9	Operator related issues
9-A	Hiring-firing
9-B	Salary
9-C	Training
9-D	Operator inter-intra cell trips
9-E	Skill level
10	Uncertainty

Based on the factors listed in Table 1, it has been attempted to analyze the recent studies, the obtained results of which are reported in Table 2. According to this table, several vital realistic assumptions such as reliability of machines, APRs, and workforce learning-forgetting effect have been neglected by a number of previous studies. In the following, however, an optimization problem will be introduced and generalized by emphasizing the APRs and workforce-related issues while multi-functional machines are available and machines are not reliable. The generalized problem is presented with the aim of reducing the inter-cell part trips and minimizing machine breakdown and workforce-related costs. In fact, the proposed model is an extended version of the research conducted by Bagheri and Bashiri [8], to which many other realistic factors such as APRs, machine reliability, and workforce learning-forgetting effect are added.

In the following, a Mixed Integer Non-Linear Mathematical Programming (MINLP) model will be proposed which is in line with the mentioned objectives. Then, a linearization technique was implemented to convert the model into an MIP form. Section 3 analyzes the effectiveness of the presented model which is verified through giving some numerical examples followed by the conclusion and some suggestions for future research in the last section.

2. The optimization model

2.1. Problem explanation and mathematical formulation

A majority of the previous approaches are based on an unrealistic assumption that machines are reliable in the whole production horizon without any breakdown. In fact, in industrial environments, machines are unreliable and their breakdown costs should be considered in order to enhance the efficiency of CMS. To this end, this paper proposes a framework to consider the costs of machine breakdown, i.e., repairing and installation-uninstallation costs. Consequently, exponential distribution should be considered with a given breakdown (failure) rate of machine reliability in its operating time:

$$R = \exp(-\lambda t), \tag{1}$$

where R is the machine reliability at time t. The breakdown rate λ is also given in the planning horizon; therefore, the mean time among the failures called MTBF is determined through Eq. (2):

$$MTBF = \frac{1}{\lambda}. \tag{2}$$

To determine the total machine breakdown cost within its production horizon, the total production time is divided by its MTBF and then, the obtained value is multiplied by machine-failure unit cost.

Other basic assumptions considered in modeling the problem are described as follows:

1. Some features are already given and fixed over the planning horizon such as the number of cells, demand of each part type in each period, and lower/upper bounds of cell capacity;
2. There are machine tools that can be installed on the predefined machines. Each tool can be used to machine a specific operation of a part;
3. Workforce can be assigned to the responsibility of more than one tool or machine according to their skill level;
4. Training the operators is allowed; in other words, workforce could be taught to work with a particular machine by paying a teaching cost. However, the trained workforce can be applied in other periods without any extra training cost. Besides, according to a predefined forgetting rate, workforce may forget working with a tool.

2.2. Notations

Indices:

m	The number of machines, $m' = 1, ..., M$
g	Machine tools, $g' = 1, ..., G$
$i = 1, ..., I$	The number of parts
c	The number of machine cells that should be constructed, $c' = 1, ..., C$
$j = 1, ..., O$	The number of operations for each part type
$t = 1, ..., T$	The number of manufacturing cycles (term)
$k = 1, ..., K$	The number of available workforce
$l = 1, ..., L$	Workforce skill level

Input parameters:

MC_i	Inter-cell part trip cost
SM	Machine install/uninstall cost in a cell
SG	Tool install/uninstall cost on a machine
Ψ_{ijg}	Tool consumption cost
B_m	The repairing cost of machine "m"
$mcaptime_m$	The maximum time of processing by machine "m"
u_m, l_m	The maximum and minimum numbers of tools that can be installed on machine "m"
u_c, l_c	The maximum and minimum numbers of machines that could be assigned to cell "c"
q	The percentage of cell load variation
$MTBF = \frac{1}{\lambda_m}$	The average time of the machine "m" breakdowns

Table 2. Literature review

Author's name	**Year**	**F1**	**F2**		**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**F9**					**F10**
			F2-B	**F2-A**							**F9-E**	**F9-D**	**F9-C**	**F9-B**	**F9-A**	
Bayram and Şahin [10]	2016	*	–	*	*	–	–	–	–	*	–	–	–	–	–	–
Nouri [16]	2016		*	*	*	–	–	–	–	*	–	–	–	–	*	–
Liu, et al. [12]	2016	*	–	–	*	–	–	*	–	–	*	–	*	–	–	–
Deep and Singh [17]	2015	*	*	*	*	–	*	*	–	–	–	–	–	–	–	–
Renna and Ambrico [18]	2015	*	–	*	*	–	*	*	–	–	–	–	–	–	–	*
Esmailnezhad, et al. [19]	2015	*	–	–	–	*	*		–	–	–	–	–	–	–	*
Wu and Suzuki [20]	2015	*	–	*	–	–	*	*		*	–	–	–	–	–	–
Alhourani [21]	2015	*	*	*	–	*	*	*	–	–	–	–	–	–	–	–
Ulutas [22]	2015	*	–		–	–	*		–	–	–	–	–	–	–	–
Nouri[23]	2015	*	*	*	–	–	*	–	–	*	–	*	–	*	*	–
Kumar and Sharma [24]	2015	*	–	*	–	*	–	*	–	–	–	–	–	–	–	–
Sakhaii, et al. [25]	2015	*	*	*	*	*	–		–	–	–	–	*		*	*
Niakan, et al. [26]	2015	*	*	*	*	–	*	*	–	–	–	–	–	*	*	*
Erozan, et al. [27]	2015	*	–	–	–	–	*	–	–	*	–	–	–	–	–	–
Brusco [28]	2015	*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Won and Logendran [29]	2015	*	–	–	–	–	*	*	–	*	–	–	–	–	–	–
Halat and Bashirzadeh [30]	2015	*	–	*	–	–	*	–	–	–	–	–	–	–	–	–
Yadollahi, et al. [31]	2014	*	*	*		*	–	*	–	–	–	–	–	–	–	–
Egilmez, et al. [32]	2014	*	–	–	–	–	*	–	–	–	–	–	–	–	–	*
Park, et al. [33]	2014		–	–	–	–	–	–	–	–	–	*	–	–	–	–
Sharifi, et al. [34]	2014	*	–	*	*	–	*	*	–	–	–	–	–	–	–	–
Baykasoglu and Gorkemli [35]	2014	*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Mohammadi and Forghani [36]	2014	*	*	*	–	–	*	*	–	–	–	–	–	–	–	–
Bootaki, et al [37]	2014	*	–	–	–	–	–	–	–	–		*	–	–	–	–
Jabal-Ameli and Moshref-Javadi [28]	2014	*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Raja and Anbumalar [39]	2014	*	–	*	–	–	–	–	–	–	–	–	–	–	–	–
Kao and Chen [40]	2014	*	–	–	–	–	–	–	*	–	–	–	–	–	–	–
This paper	2016	*	*	*	*	*	*	*	*	*	*	*	*	*	*	–

H, F	Workforce hiring/firing cost
SA_l	The salary of the workforce with the skill level l
$movek$	The workforce trip cost of cells
$a_{kg}^{t=1}$	1 if workforce k can work with tool g at the start time of planning horizon
aw_g	The minimum skill level to work with tool "g"
∂_l	Skill level boundary
w_1, w_2	Increase and decrease in workforce skill level
D_i^t	The demand value for the i-th part in the t-th manufacturing term
$dis_{cc'}$	The distance between the two candidate locations c and c'
$time_{ijgm}$	The processing time of operation j on machine type m for part type i with tool g
$MINEM$	The least number of workforce sufficient to be hired in each manufacturing term
$Opcaptime$	The maximum time of working for each workforce
α_{ijg}^t	1 if operation j of part type i can be processed by tool g in production period t; 0 otherwise
β_{gm}^t	1 if tool g can be installed on machine m in production period t; 0 otherwise

Decision variables:

$$x_{mc}^t = \begin{cases} 1; & \text{If machine } m \text{ in period } t \text{ is designated to cell } c \\ 0; & \text{Otherwise} \end{cases}$$

$$y_{gm}^t = \begin{cases} 1; & \text{If tool } g \text{ in period } h \text{ is installed on machine } m \\ 0; & \text{Otherwise} \end{cases}$$

$$p_{ijg}^t = \begin{cases} 1; & \text{If operation } j \text{ of part type } i \text{ in period } t \text{ is processed with tool } g \\ 0; & \text{Otherwise} \end{cases}$$

$$b_k^t = \begin{cases} 1; & \text{If operator } k \text{ is working in period } t \\ 0; & \text{Otherwise} \end{cases}$$

$$h_k^t = \begin{cases} 1; & \text{If operator } k \text{ is hired in period } t \\ 0; & \text{Otherwise} \end{cases}$$

$$w_{kg}^t = \begin{cases} 1; & \text{If operator } k \text{ is working with machine tool } g \text{ in period } t \\ 0; & \text{Otherwise} \end{cases}$$

$$le_{kl}^t = \begin{cases} 1; & \text{If operator } k \text{ is in skill level of } l \text{ in period } t \\ 0; & \text{Otherwise} \end{cases}$$

$$a_{kg}^{t\geq 2} = \begin{cases} 1; & \text{Ifoperator } k \text{ can work with tool } g \text{ in period } t \\ 0; & \text{Otherwise} \end{cases}$$

2.3. The objective function

The proposed MINLP model for the CMS design is offered as Eqs. (3) to (11):

$$\min \ \text{Model 1}:$$

$$\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{O_i}\sum_{g,g'=1}^{G}\sum_{m,m'=1}^{M}\sum_{c,c\neq c'} x_{mc}^t \times y_{gm}^t \times p_{ijg}^t \times x_{m'c'}^t \times y_{g'm'}^t \times p_{i(j+1)g'}^t \times D_i^t \times dis_{c,c'} \times MC_i, \quad (3)$$

$$+\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{O_i}\sum_{g,g'=1}^{G}\sum_{c=1}^{C}\sum_{m,m'\neq m} x_{mc}^t \times y_{gm}^t \times p_{ijg}^t \times x_{m'c}^t \times y_{g'm'}^t \times p_{i(j+1)g'}^t \times D_i^t \times MC_i, \quad (4)$$

$$+\sum_{t=1}^{T-1}\sum_{m=1}^{M}\sum_{c,c\neq c'} x_{mc}^t \times x_{mc'}^{t+1} \times dis_{c,c'} \times SM, \quad (5)$$

$$+\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{j=1}^{O_i}\sum_{g=1}^{G} y_{gm}^t \times p_{ijg}^t \times D_i^t \times \Psi_{ijg}, \quad (6)$$

$$+\sum_{t=1}^{T-1}\sum_{g=1}^{G}\sum_{m,m\neq m'} y_{gm}^t \times y_{gm'}^{t+1} \times SG, \quad (7)$$

$$+\sum_{t=1}^{T}\sum_{m=1}^{M}\frac{\sum_{i=1}^{I}\sum_{j=1}^{O_i}\sum_{g=1}^{G} p_{ijg}^t \times y_{gm}^t \times time_{ijgm} \times D_i^t}{MTBF_m} \times B_m, \quad (8)$$

$$\sum_{k=1}^{K}(h_k^1 \times H) + \sum_{t=2}^{T}\sum_{k=1}^{K}(h_k^t \times H + (1-b_k^t) \times F), \quad (9)$$

$$+\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{g,g'}\sum_{m,m'}\sum_{c,c\neq c'} w_{kg}^t \times w_{kg'}^t \times y_{gm}^t \times x_{mc}^t \times y_{g'm'}^t \times x_{m'c'}^t \times dis_{c,c'} \times movek, \quad (10)$$

$$+\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{g=1}^{G}\sum_{i=1}^{I}\sum_{j=1}^{O_i}\sum_{m=1}^{M}\sum_{c=1}^{C} p_{ijg}^t \times y_{gm}^t$$

$$\times x^t_{mc} \times time_{ijgm} \times D^t_i \times w^t_{kg} \times le^t_{lk} \times SA_l, \quad (11)$$

Subjected to:

$$\sum_{c=1}^{C} X^t_{mc} = 1 \quad \forall m, t; \quad (12)$$

$$\sum_{g=1}^{G} P^t_{ijg} = 1 \quad \forall i, j, t; \quad (13)$$

$$\sum_{m=1}^{M} Y^t_{gm} \leq 1 \quad \forall g, m, t; \quad (14)$$

$$P^t_{ijg} \leq \alpha^t_{ijg} \quad \forall i, j, g, t; \quad (15)$$

$$Y^t_{gm} \leq \beta^t_{gm} \quad \forall g, m, t; \quad (16)$$

$$\sum_{c=1}^{C}\sum_{m=1}^{M} Y^t_{gm} \times X^t_{mc} \leq \sum_{i=1}^{I}\sum_{j=1}^{O_i} P^t_{ijg} \quad \forall g, t; \quad (17)$$

$$\sum_{c=1}^{C}\sum_{m=1}^{M} Y^t_{gm} \times X^t_{mc} \geq P^t_{ijg} \quad \forall i, j, g, t; \quad (18)$$

$$\sum_{m=1}^{M} X^t_{mc} \leq u_c \quad \forall c, t; \quad (19)$$

$$\sum_{m=1}^{M} X^t_{mc} \geq l_c \quad \forall c, t; \quad (20)$$

$$\sum_{g=1}^{G} Y^t_{gm} \leq u_m \quad \forall m, t; \quad (21)$$

$$\sum_{g=1}^{G} Y^t_{gm} \geq l_m \quad \forall m, t; \quad (22)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{O_i}\sum_{g=1}^{G} P^t_{ijg} \times Y^t_{gm} \times time_{ijgm} \times D^t_i \leq mcaptime \quad \forall m, t; \quad (23)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{O_i}\sum_{g=1}^{G} X^t_{mc} \times Y^t_{gm} \times P^t_{ijg} \times time_{ijgm} \times D^t_i \geq \frac{q}{C}\sum_{c=1}^{C}\sum_{i=1}^{I}\sum_{j=1}^{O_i}\sum_{g=1}^{G} X^t_{mc} \times Y^t_{gm} \times P^t_{ijg} \times time_{ijgm} \times D^t_i \quad \forall c, t; \quad (24)$$

$$b^1_k = h^1_k \quad \forall k; \quad (25)$$

$$b^{t+1}_k (1 - b^t_k) = h^{t+1}_k \quad \forall k, t; \quad (26)$$

$$h^{t+1}_k \leq 1 - b^t_k \quad \forall t = 1, ..., T-1 \quad \forall k; \quad (27)$$

$$\sum_{k=1}^{K} b^t_k \geq \min EM \quad \forall t; \quad (28)$$

$$w^t_{kg} \leq b^t_k \quad \forall k, g, t; \quad (29)$$

$$\sum_{k=1}^{K} w^t_{kg} = \sum_{m=1}^{M} y^t_{gm} \quad \forall g, t; \quad (30)$$

$$\sum_{g=1}^{G} w^t_{kg} \geq b^t_k \quad \forall k, t; \quad (31)$$

$$w^t_{kg} \times aw_g \leq a^t_{kg} \quad \forall k, g, t; \quad (32)$$

$$a^{t+1}_{kg} = b^t_k \times a^t_{kg} + w^t_{kg} \times \omega_1 \sum_{i=1}^{I}\sum_{j=1}^{O_i} \eta^t_g + (1 - b^t_k) \max (a^t_{kg} - \omega_2, 0) \quad \forall k, gt; \quad (33)$$

$$\sum_{l=1}^{L-1} \partial_l \times le^t_{(l+1)k} \leq \frac{\sum_{g=1}^{G} a^t_{kg}}{G} \leq \sum_{l=1}^{L} \partial_l \times le^t_{lk} \quad \forall k, t; \quad (34)$$

$$\sum_{l=1}^{L} le^t_{lk} = 1 \quad \forall k, t; \quad (35)$$

$$\sum_{t=1}^{T}\sum_{g=1}^{G}\sum_{i=1}^{I}\sum_{j=1}^{O_i}\sum_{m=1}^{M}\sum_{c=1}^{C} p^t_{ijg} \times y^t_{gm} \times x^t_{mc} \times time_{ijgm} \times D^t_i \times w^t_{kg} \leq opcaptime \times b^t_k \quad \forall\ k, t; \quad (36)$$

$$w^t_{kg},\ h^t_k,\ b^t_k,\ le^t_{kl} \in \{0, 1\} \qquad a^t_{kg} \geq 0,$$

$$X^t_{mc},\ Y^t_{gm},\ P^t_{ijg} \in \{0, 1\}. \quad (37)$$

The proposed model aims to minimize two main target groups: Group (1) includes the part and machine-related costs and Group (2) includes the workforce-related costs. The first term of the objective function, i.e., 3, aims to minimize the trips of inter-cell parts. Of note, an inter-cell part trip is determined based on inter-cell distances. The function of Part 4 is to minimize the intra-cell part trips. In addition, Part 5 minimizes the total cost of system reconfiguration. The dynamic nature of the production systems, i.e., demand, process routings, and machine characteristics variation, causes the machine to move among cells between two consecutive periods. This cost includes the uninstallation, movement, and installation of the machines among the cells. Part 6 minimizes the total consumption costs of tools. Moreover, Part 7 minimizes the installation/uninstallation costs of tools on different machines. Part 8 minimizes the overall machine breakdown cost. This cost is determined according to the total processing time of a machine and its breakdown rate. The function of Part 9 is to minimize the workforce hiring/firing costs. Part 10 takes control over the workforce among cells trips. Moreover, workforce salary cost is minimized using Part 11.

Constraint (12) guarantees that any type of machine is accurately assigned to a given cell. Eq. (13) ensures that the operation of each part can be performed by only one tool. It is assumed that a tool can be installed on only one machine. This constraint is guaranteed by Relation (14). Therefore, the presence of unused tools in a production period is possible. Relations (15) and (16) ensure that each operation and tool can be assigned to a tool and machine, respectively, with the capability of that installation. Constraints (17) and (18) ensure that the unused tool in a production period cannot be installed on any machine. The maximum and minimum numbers of machines for a cell are represented by Constraints (19) and (20), respectively, which are in the cell size range. Moreover, the allocated number of tools to each machine are presented by Constraints (21) and (22), respectively. The maximum amount of time that each machine consumes is eliminated by Constraint (23). Moreover, Constraint (24) balances the load variations of each cell during a production period. In the 1st period, if a worker is hired, he/she should be assigned to working with a machine. This issue is guaranteed by Constraint (25). The workforce hiring/firing balance between two consecutive periods is shown in Constraints (26) and (27). Constraint (28), in each manufacturing term, specifies the least number of workforce that should be hired. Workforce can work with a tool only if that workforce is implemented in a production period. Constraint (29) guarantees this point. Constraint 30 states that for a tool, workforce should be hired in a production period. Furthermore, if a workforce is hired, he/she should be assigned to some tools (machines) (Constraint (31)). Based on Constraint (32), workforce with a minimum skill value can be selected to work with a machine tool. The workforce learning-forgetting effect is assumed according to Constraints (33) and (34). Based on these two constraints, workforce skill level must be updated in each production period. Constraint (35) emphasizes that workforce should be ranked and given a skill level according to his/her abilities. Workforce time capacity for working in a production period is limited by Constraint (36). Finally, Constraints (37) defines the types of model variables.

2.4. Linearization

Since the presented MINLP model owing to the existence of nonlinearities in terms 3, 4, 5, 6, 7, 8, 10, and 11 and Constraints (17), (18), (23), (24), (26), and (33) is a nonlinear one, here, it was transformed into a linear MIP model using three linearization techniques.

Proposition 1. Consider the pure quadratic 0-1 variable $Z = X_1 \times X_2 \times ... \times X_n$, where X_i $(i = 1, .., n)$ is a binary variable. The amount of variable Z is obviously 1 if and only if all other variables are 1; otherwise 0 [8]. The mentioned mathematical view is formulated below by utilizing some new supplementary limitations.

$$Z \leq X_i \quad \forall i = 1, .., n, \qquad Z \geq \sum_{i=1}^{n} X_i - (n-1).$$

Proposition 2. Consider the variable $Z = X \times Y$ in which X and Y are binary and integer positive variables, respectively. Utilizing some new auxiliary constraints transforms the model into a linear form. The needed limitations are mentioned as follows:

$$Z \leq M \times X; \qquad Z \leq Y;$$

$$Z \geq Y - (1 - X)\, M; \qquad Z \geq 0 \text{ and int.}$$

Proposition 3. Consider the term:

$$\min \quad T,$$

$$\text{St}:$$

$$T = \max\, (X, a),$$

where X is a variable. By introducing some new auxiliary constraints, the mentioned nonlinear term could be converted into a linear one. The needed limitations are mentioned as follows:

$$T \geq X, \qquad T \geq a.$$

Accordingly, new variables are defined as follows:

$$PXY1^t_{ijgmc} = x^t_{mc} y^t_{gm} p^t_{ijg} x^t_{m'c'} y^t_{g'm'} p^t_{i(j+1)g'}, \tag{38}$$

$$PXY2^t_{ijgmc} = x^t_{mc} y^t_{gm} p^t_{ijg} x^t_{m'c} y^t_{g'm'} p^t_{i(j+1)g'}, \tag{39}$$

$$XX^t_{mcc'} = x^t_{mc} x^{t+1}_{mc'}, \tag{40}$$

$$YX^t_{gmc} = y^t_{gm} x^t_{mc}, \tag{41}$$

$$PY^t_{ijgm} = p^t_{ijg} y^t_{gm}, \tag{42}$$

$$PXY^t_{ijgmc} = p^t_{ijg} x^t_{mc} y^t_{gm}, \tag{43}$$

$$YY^t_{gmm'} = y^t_{gm} y^{t+1}_{gm'}, \tag{44}$$

$$WW^t_{kgg'} = w^t_{kg} w^t_{kg'}, \tag{45}$$

$$WL^t_{kgl} = w^t_{kg} le^t_{lk}, \tag{46}$$

$$B_k^t = b_k^{t+1} \times (1 - b_k^t), \tag{47}$$

$$Z = \max(a_{kg}^t - \omega_2, 0), \tag{48}$$

$$BA_{kg}^t = b_k^t \times a_{kg}^t, \tag{49}$$

$$BZ_k^t = (1 - b_k^t) \times Z. \tag{50}$$

The following supplementary limitations should be considered along with the previous model:

$$PXY1_{ijgmc}^t \geq YX_{gmc}^t + p_{ijg}^t + YX_{g'm'c'}^t + p_{i(j+1)g'}^t - 3, \tag{51}$$

$$PXY1_{ijgmc}^t \leq YX_{gmc}^t, \tag{52}$$

$$PXY1_{ijgmc}^t \leq p_{ijg}^t, \tag{53}$$

$$PXY1_{ijgmc}^t \leq YX_{g'm'c'}^t, \tag{54}$$

$$PXY1_{ijgmc}^t \leq p_{i(j+1)g'}^t, \tag{55}$$

$$PXY2_{ijgmc}^t \geq YX_{gmc}^t + p_{ijg}^t + YX_{g'm'c}^t + p_{i(j+1)g'}^t - 3, \tag{56}$$

$$PXY2_{ijgmc}^t \leq YX_{gmc}^t, \tag{57}$$

$$PXY2_{ijgmc}^t \leq p_{ijg}^t, \tag{58}$$

$$PXY2_{ijgmc}^t \leq YX_{g'm'c}^t, \tag{59}$$

$$PXY2_{ijgmc}^t \leq p_{i(j+1)g'}^t, \tag{60}$$

$$XX_{mcc'}^t \geq x_{mc}^t + x_{mc'}^{t+1} - 1, \tag{61}$$

$$XX_{mcc'}^t \leq x_{mc}^t, \tag{62}$$

$$XX_{mcc'}^t \leq x_{mc'}^{t+1}, \tag{63}$$

$$YX_{gmc}^t \geq y_{gm}^t + x_{mc}^t - 1, \tag{64}$$

$$YX_{gmc}^t \leq y_{gm}^t, \tag{65}$$

$$YX_{gmc}^t \leq x_{mc}^t, \tag{66}$$

$$PY_{ijgm}^t \geq p_{ijg}^t + y_{gm}^t - 1, \tag{67}$$

$$PY_{ijgm}^t \leq p_{ijg}^t, \tag{68}$$

$$PY_{ijgm}^t \leq y_{gm}^t, \tag{69}$$

$$PXY_{ijgm}^t \geq x_{mc}^t + PY_{ijgm}^t - 1, \tag{70}$$

$$PXY_{ijgm}^t \leq PY_{ijgm}^t, \tag{71}$$

$$PXY_{ijgm}^t \leq x_{mc}^t, \tag{72}$$

$$WPXY_{ijkgm}^t \leq w_{kg}^t + PXY_{ijgm}^t - 1, \tag{73}$$

$$WPXY_{ijkgm}^t \geq w_{kg}^t, \tag{74}$$

$$WPXY_{ijkgm}^t \geq PXY_{ijgm}^t, \tag{75}$$

$$YY_{gmm'}^t \geq y_{gm}^t + y_{gm'}^{t+1} - 1, \tag{76}$$

$$YY_{gmm'}^t \leq y_{gm}^t, \tag{77}$$

$$YY_{gmm'}^t \leq y_{gm'}^{t+1}, \tag{78}$$

$$WW_{kgg'}^t \geq w_{kg}^t + w_{kg'}^t - 1, \tag{79}$$

$$WW_{kgg'}^t \leq w_{kg}^t, \tag{80}$$

$$WW_{kgg'}^t \leq w_{kg'}^t, \tag{81}$$

$$WL_{kgl}^t \geq w_{kg}^t + le_{lk}^t - 1, \tag{82}$$

$$WL_{kgl}^t \leq w_{kg}^t, \tag{83}$$

$$WL_{kgl}^t \leq le_{lk}^t, \tag{84}$$

$$WLPXY_{ijkgml}^t \geq WL_{kgl}^t + PXY_{ijgm}^t - 1, \tag{85}$$

$$WLPXY_{ijkgml}^t \leq WL_{kgl}^t, \tag{86}$$

$$WLPXY_{ijkgml}^t \leq PXY_{ijgm}^t, \tag{87}$$

$$WYX_{kgg'mm'cc'}^t \geq WW_{kgg'}^t + YY_{gmm'}^t + XX_{mcc'}^t - 2, \tag{88}$$

$$WYX_{kgg'mm'cc'}^t \geq WW_{kgg'}^t, \tag{89}$$

$$WYX_{kgg'mm'cc'}^t \geq YY_{gmm'}^t, \tag{90}$$

$$WYX_{kgg'mm'cc'}^t \geq XX_{mcc'}^t, \tag{91}$$

$$B_k^t \geq b_k^{t+1} + (1 - b_k^t) - 1, \tag{92}$$

$$B_k^t \leq b_k^{t+1}, \tag{93}$$

$$B_k^t \leq (1 - b_k^t), \tag{94}$$

$$Z \geq a_{kg}^t - \omega_2, \tag{95}$$

$$Z \geq 0, \tag{96}$$

$$BA_{kg}^t \geq a_{kg}^t - M_\infty(1 - b_k^t), \tag{97}$$

$$BA_{kg}^t \leq a_{kg}^t, \tag{98}$$

$$BA_{kg}^t \leq M_\infty \times b_k^t, \tag{99}$$

$$BZ_k^t \geq Z - M_\infty[1 - (1 - b_k^t)], \tag{100}$$

$$BZ_k^t \leq Z, \tag{101}$$

$$BZ_k^t \leq M_\infty \times (1 - b_k^t). \tag{102}$$

Therefore, the linear version of the MIP model can also be considered.

min Model 2 =

$$\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{O_i}\sum_{g,g'=1}^{G}\sum_{m,m'=1}^{M}\sum_{c,c\neq c'}$$

$$PXY1_{ijgmc}^t \times D_i^t \times dis_{c,c'} \times MC_i, \tag{103}$$

$$+\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{O_i}\sum_{g,g'=1}^{G}\sum_{c=1}^{C}\sum_{m,m\neq m'} PXY2_{ijgmc}^t \times D_i^t, \tag{104}$$

$$+\sum_{t=1}^{T-1}\sum_{m=1}^{M}\sum_{c,c\neq c'} XX_{mcc'}^t \times dis_{c,c'} \times SM, \tag{105}$$

$$+\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{j=1}^{O_i}\sum_{g=1}^{G} PY_{ijgm}^t \times D_i^t \times \psi_{ijg}, \tag{106}$$

$$+\sum_{t=1}^{T-1}\sum_{g=1}^{G}\sum_{m,m\neq m'} YY_{gmm'}^t \times SG, \tag{107}$$

$$+\sum_{t=1}^{T}\sum_{m=1}^{M}\frac{\sum_{i=1}^{I}\sum_{j=1}^{O_i}\sum_{g=1}^{G} PY_{ijgm}^t \times time_{ijgm} \times D_i^t}{MTBF_m} \times B_m, \tag{108}$$

$$\sum_{k=1}^{K}(h_k^1 \times H) + \sum_{t=2}^{T}\sum_{k=1}^{K}\left(h_k^t \times H + (1 - b_k^t) \times F\right), \tag{109}$$

$$\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{g,g'}\sum_{m,m'}\sum_{c,c'\neq c} WYX_{kgg'mm'cc'}^t \times dis_{c,c'}, \tag{110}$$

$$+\sum_{m=1}^{M}\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{g=1}^{G} WLPXY_{ijkgml}^t \times time_{ijgm}$$

$$\times D_i^t \times SA_l. \tag{111}$$

The above model is conditional on the unaltered set of Constraints (12)–(17), (19)–(22), (25), (27)–32), (34), (35) and the new auxiliary Constraints (51)–(92).

Moreover, the set of Constraints (17), (18), (23), (24), (26), and (33) is replaced by:

$$\sum_{c=1}^{C}\sum_{m=1}^{M} YX_{gmc}^t \leq \sum_{i=1}^{I}\sum_{j=1}^{O_i} P_{ijg}^t \qquad \forall g, t; \tag{112}$$

$$\sum_{c=1}^{C}\sum_{m=1}^{M} YX_{gmc}^t \geq P_{ijg}^t \qquad \forall i, j, g, t; \tag{113}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{O_i}\sum_{g=1}^{G} PY_{ijgm}^t \times time_{ijgm} \times D_i^t \leq captime$$

$$\forall m, t; \tag{114}$$

$$B_k^t = h_k^{t+1} \qquad \forall k, t; \tag{115}$$

$$a_{kg}^{t+1} = \omega_1 \sum_{i=1}^{I}\sum_{j=1}^{O_i} WPXY_{ijkgm}^t + BZ_k^t + BA_{kg}^t$$

$$\forall k, g, t; \tag{116}$$

and the last set of constraint, i.e., Constraint (36) is replaced by:

$$w_{kg}^t, h_k^t, b_k^t, le_{kl}^t, B_k^t, p_{ijg}^t, WW_{kgg'}^t, WL_{kgl}^t, x_{mc}^t, y_{gm}^t,$$

$$PY_{ijgm}^t, PXY_{ijgmc}^t, PXY1_{ijgmc}^t, PXY2_{ijgmc}^t,$$

$$WPXY_{ijkgm}^t, WLPXY_{ijkgml}^t, WYX_{kgg'mm'cc'}^t,$$

$$XX_{mcc'}^t, YX_{gmc}^t, YY_{gmm'}^t \in \{0,1\}\, BA_{kg}^t,$$

$$BZ_k^t, z, a_{kg}^t \geq 0. \tag{117}$$

3. Computational experience

In the following, the experiments conducted to evaluate the capability of solving the CMS problem through the presented model and applied approach are presented. Three instances were randomly generated. Experiments were performed on the implemented and solved model on a Core i5 PC with 1 GB of RAM using GAMS 23.5. The input data of generated instances are given in Tables 3–5. According to Bagheri and Bashiri [8], to obtain an optimal solution, two problems of CF and workforce assignment should be simultaneously solved. To this end, the present paper aims to separate and solve these two problems in three modes, namely the

Table 3. Numerical assumptions of different instances

Instance	Number of machines	Number of parts	Number of time periods	Number of cells	Number of operators	Number of machine tools
Instance 1	3	2	3	2	4	5
Instance 2	4	4	3	2	6	7
Instance 3	3	4	3	2	8	10

Table 4. Numerical assumptions of different instances.

Machine breakdown rate	Machine repairing cost	Tool consumption cost	Inter-cell trips		Demand value	Inter-cell distances	Machining time per operation (seconds)
(Integer uniform)	(Integer uniform)	(Integer uniform)	Machines	Parts	(Integer uniform)	(Integer uniform)	(Integer uniform)
$[0.01, 0.05]$	$[35, 37]$	$[10, 17]$	20	$[12, 16]$	$[10, 14]$	$[3, 5]$	$[0.09, 0.11]$

Table 5. Numerical assumptions of different instances.

Minimum number of required operators per period	Number of machines in each cell		Number of tools on each machine		Maximum time capacity		Learning rate	Forgetting rate
	Max	**Min**	**Max**	**Min**	**Machine**	**Operator**		
3	4	1	4	2	50	11	0.015	0.005

Table 6. A comparison of hierarchical and simultaneous approaches.

Instance	Model 1	Model 2	Hierarchical approach	Simultaneous approach
Instance 1	3216	102	3319	**3319**
Instance 2	2884	166	3050	**3050**
Instance 3	1646	209	1855	**1796**

solo, hierarchical, and simultaneous modes. The two separated models are as presented below:

Model 1 (CF)	**Model 2 (OS)**
Min 3–8	*Min 9–11*
Subjected to:	*Subjected to:*
12–24, 37	25–37

First, the generated instances are solved through Model 1. Then, the obtained results are introduced to Model 2 as input parameters; Model 2 is consequently implemented to solve the workforce assignment problem. The second model is also solved in isolation. Finally, the simultaneous model is implemented to compare the results. Table 6 reports the obtained results. As observed in Table 6, increasing the size of problem results in a better performance of the simultaneous model. Compared to the hierarchical mode, this model can reach more optimal solutions, especially in the case of large-scale problems. Moreover, the schematic view of Instance 3 is illustrated in Figure 1. Of note, this figure only demonstrates the solutions of periods 1 and 2.

It is evident from Table 6 that the CF problem solution has a stronger effect on the final solution than that of the OS problem. Therefore, these two problems cannot be compared in such a condition. In order to overcome this obstacle, the LP-metric approach was implemented.

Generally, the LP-metric techniques prepare an extensive approach to solving MCDM problems while objectives are incommensurable and they are in contrast with each other. These techniques transform m objectives (criteria) into one objective by utilizing the summation of normalized objectives; then, non-dominated optimal answers could be achieved by utilizing the mentioned single-objective function. Normalizing is required as the objective (criterion) is incongruity dimension.

In fact, LP-metric can be used to achieve commensurate *units of objective functions.*

$$D = \left(\sum_{i=1}^{n} \lambda_i \left(\frac{f_i^* - f_i(x)}{f_i^* - f_i^-} \right)^p \right)^{\frac{1}{p}}, \qquad p = 1, 2, ... \tag{118}$$

In the above equation, $f_i(x)$, $f_i^*(x)$, and $f_i^-(x)$ are objective function, ideal objective function, and anti-ideal objective function, respectively. In addition, λ_i is the weight given due the importance of the $f_i(x)$.

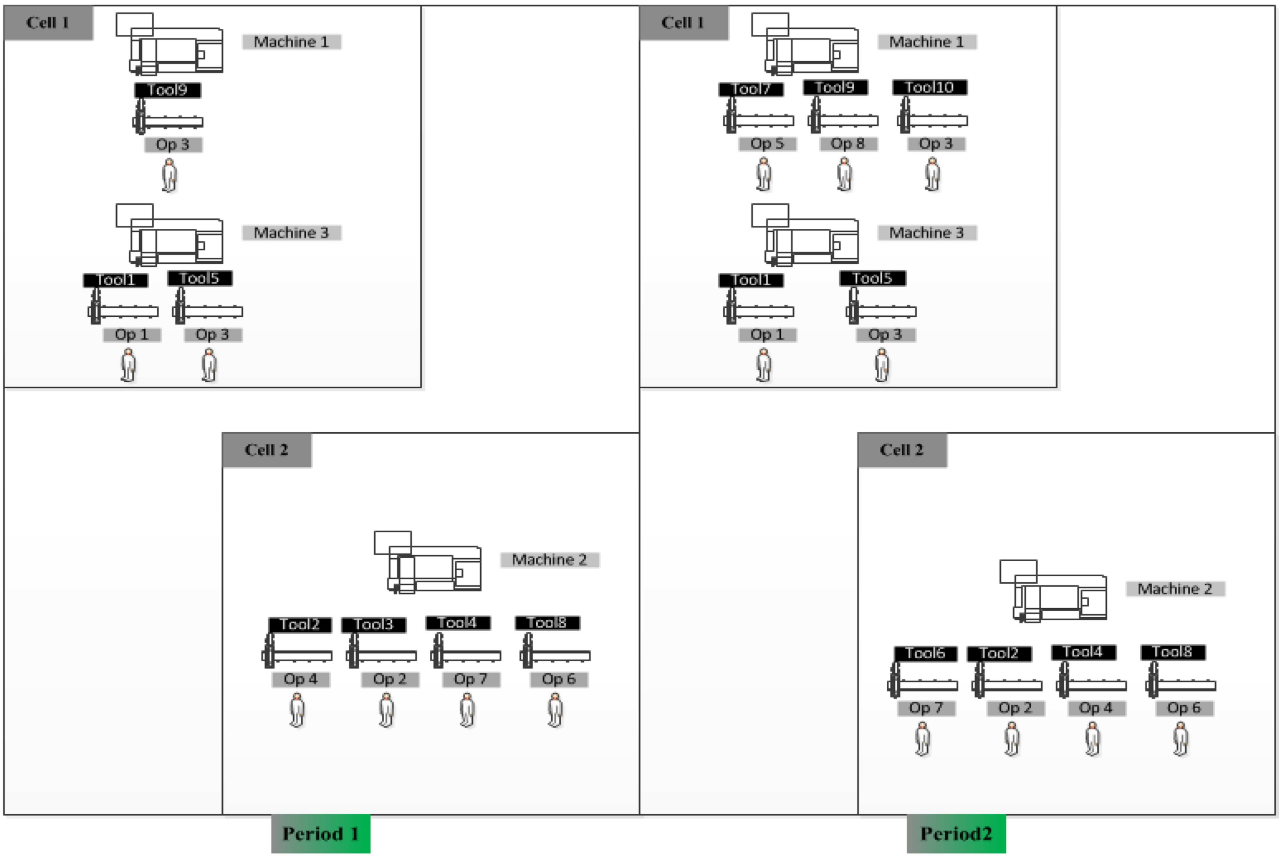

Figure 1. The schematic view of the solution to Instance 3.

Table 7. The trade-off matrix of Cell Formation (CF) and OS problems.

	Positive ideal solutions		**Negative ideal solutions**	
	f_1	f_2	f_1	f_2
f_1	$f_1^* = 1569.979$	273	$f_1^- = 17968.82$	271
f_2	13156.49	$f_2^* = 209.484$	10634.63	$f_2^- = 549.491$

Attempts were made to minimize the distance between the ideal and anti-ideal pursuant to the constraints and discover the non-dominated solution. Therefore, in Eq. (118), LP-metric represents the distance between $F(x)$ and $F^*(x)$.

Based on this approach, the trade-off matrix can be generated, as shown in Table 7.

By changing the λ_i value, which represents the weight considered for each of the aforementioned problems, the Pareto optimal solution can be obtained, as shown in Figure 2.

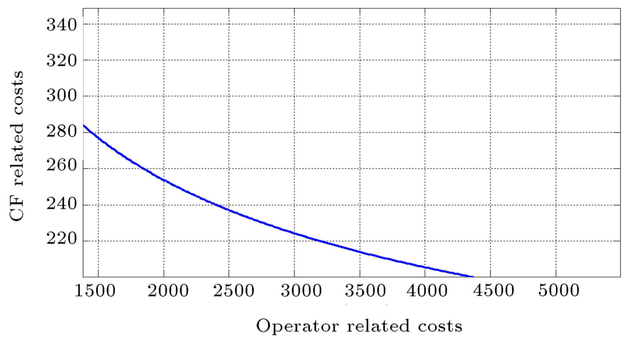

Figure 2. The pareto solution to Cell Formation (CF) and OS problems.

As observed in this figure, workforce-related costs have a significant impact on the CF solution. In order to analyze the OS problem in detail, expert workforce who worked only with a machine tool without any training cost was carefully supervised. The salary of this workforce was naturally higher than that of others. In this situation and based on the results, workforce with a lower skill level was selected to be trained how to work with that machine tool. With a decrease in the salary of the expert workforce, he/she was selected as a machine tool workforce.

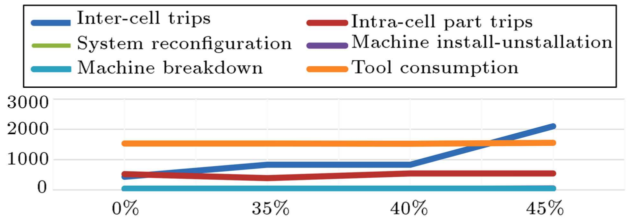

Figure 3. Cost sensitivity analysis versus demand rate.

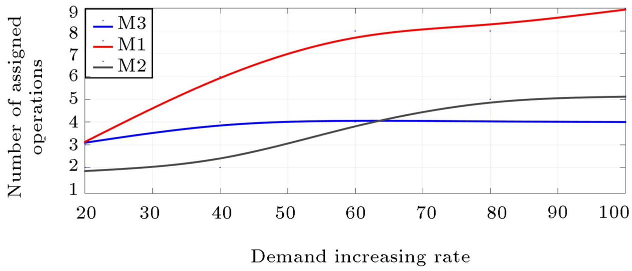

Figure 4. The increasing rate of demand vs. the number of operations assigned to a machine (period 1) Instance).

In addition, it can be concluded that any change in the demand value might significantly affect the essential cost terms, shown in Figure 3. According to this Figure, with an increase in the demand value, the inter-cell part trip cost has exponentially increased. Hence, a decision-maker should control the demand value to avoid extra inter-cell part trip costs. Moreover, a meticulous maintenance plan can decrease the rate of machine breakdown in high-demand companies.

Machines are the second main manufacturing resources required to be analyzed in detail. Machine breakdown and demand rate are of considerable significance in machine implementation in a manufacturing company. Figure 4 illustrates the increasing rate of demand on the total number of operations assigned to a machine in a production period (Instance 1).

According to this Figure 4, Machine 3 can process a maximum number of 4 operations in a production period. As mentioned earlier, a machine cannot be interrupted while processing a task. According to the input data, the rate of breakdown in machine 3 is higher than that in the other two machines. Therefore, it is preferable that this machine would process only 3 operations, even in a high-demand situation.

To adjust real-world cellular production system models, it is required to add more variables and limitations to the model, which will demand a lot of time to solve such models by time, memory, and processing power. As a result, nowadays, modern methods are applied to a Genetic Algorithm (GA). A GA is part of random search techniques that are used to solve NP-complete problems, such as cell-system production models.

In this section, MATLAB software (GA tool-Genetic algorithm GUI) was utilized to solve the complexities of the hierarchical and simultaneous model with the GA to evaluate the performance of the models in vaster dimensions. In Table 8, the dimensions of 4 numerical instances are solved using GA. The obtained results are given in both Table 9 and Figure 5. Of note, the simulation model has achieved a better result than the hierarchical model. By developing a variety of the dimensions of the models, the deviation of the optimum values obtained in the two models becomes more significant than ever.

Due to the lack of a similar article and a real case study in Iran, the sensitivity analysis of one of the examined examples mentioned in the paper was performed to validate the model. For instance, in Instance 4, by assuming that the dimensions of the model were

Table 8. Numerical assumptions of instance.

Instance	Number of machines	Number of parts	Number of time periods	Number of cells	Number of operators	Number of machine tools
Instance GA 1	10	20	3	2	13	2
Instance GA 2	15	25	3	3	14	3
Instance GA 3	20	27	3	3	15	5
Instance GA 4	25	30	3	5	16	6

Table 9. A comparison of hierarchical and simultaneous approaches (genetic algorithm).

Instance	Model 1	Model 2	Hierarchical approach	Simultaneous approach
Instance GA 1	7560	1003	8563	**8294**
Instance GA 2	8640	2845	11485	**9869**
Instance GA 3	10380	5004	15384	**10384**
Instance GA 4	15230	9384	24614	**17974**

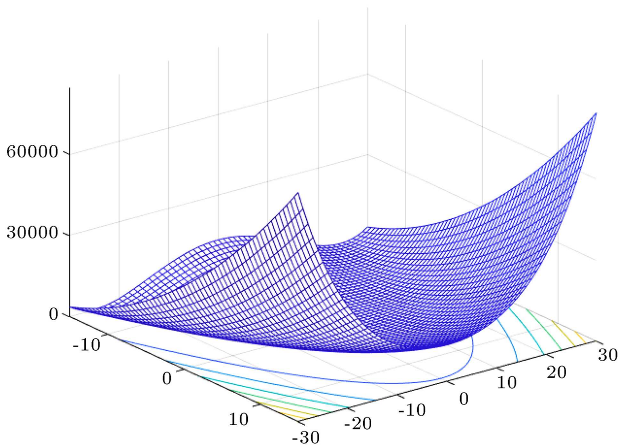

Figure 5. Functional behavior in the genetic algorithm.

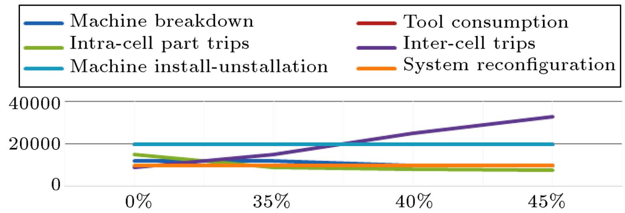

Figure 6. Cost sensitivity analysis versus demand rate in the genetic algorithm.

constant, the sensitivity of the model parameters was analyzed. For example, the sensitivity analysis of the demand parameter that changed all decision variables and optimal values is shown in Figure 6. Some quantities were not significantly different in costs such as the cost of installing machines and cellular configurations. In other cases, the breakdown of machines and cost of intercellular mobility were considerably high; therefore, the resulting changes seem reasonable.

4. Conclusion

The present paper proposed a new-fangled model to design an efficient Cellular Manufacturing System (CMS). The basic assumptions of the proposed model were the incorporation of machine tools, machine breakdown, and the workforce learning-forgetting effect. To the best of the authors' knowledge, only a few researchers have focused on such real-world parameters. In terms of both computational time and optimality, the experimental results verified the efficiency of the proposed approach. Moreover, analytical experiments were performed to assess the sensitivity of the presented model and it could be concluded that the machine failure played a key role in elevating the performance of CMS, especially in companies of high demands. In addition, workforce-related costs were found to have a strong impact on the cell formation solution. Another sensitivity analysis of the proposed model revealed the impact of changing demand on the rate of machine utilization. In other words, by increasing the demand value, the machine with the minimum breakdown cost value was implemented more often than other ones. Besides, nowadays, in the competitive atmosphere of the world, the workforce represents the main production resources. Hence, analyzing and proposing new models is essential to optimally solve OS problems. In this paper, some workforce-related issues including hiring, firing, their salary, training, and the workforces' learning-forgetting effect were taken into account. Given all these considerations, the developed mathematical model could be employed for factories with the capability of having a cellular design. In fact, numerous industrial factories such as car manufacturers with a rich diversity in their product types and fluctuations in the demand value can employ the proposed model with the aim of designing an optimal CMS via the minimum amount of costs. The main objective of this research was to consider some real-world production elements to be applied to many factories.

As a guideline for future studies, it would be motivating to develop some solution approaches to optimally solve the model. Moreover, incorporating other real-world industrial factors such as intra-cell GL and machine duplication in providing a framework can be of great value for future research. Additionally, the concept of uncertainty can be considered in the provided framework. As an instance, uncertainty in the demand value or the processing time is one of the main issues in real world application and thus, it can be explored in more detail in future studies.

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References

1. Liu, C., Wang, J., and Leung, J.Y.T. "Integrated bacteria foraging algorithm for cellular manufacturing in supply chain considering facility transfer and production planning", *Applied Soft Computing*, **62**, pp. 602–618 (2018).
2. Askin, R.G. "Contributions to the design and analysis of cellular manufacturing systems", *International Journal of Production Research*, **51**, pp. 6778–6787 (2013).
3. Ameli, M.S.J. and Arkat, J. "Cell formation with alternative process routings and machine reliability consideration", *The International Journal of Advanced Manufacturing Technology*, **35**, pp. 761–768 (2008).
4. Bulgak, A.A. and Bektas T. "Integrated cellular manufacturing systems design with production planning and

dynamic system reconfiguration", *European Journal of Operational Research*, **192**, pp. 414–428 (2009).

5. Mehdizadeh, E., Niaki S.V.D., and Rahimi, V. "A vibration damping optimization algorithm for solving a new multi-objective dynamic cell formation problem with workers training", *Computers & Industrial Engineering*, **101**, pp. 35–52 (2016).
6. Mahdavi, I., Aalaei, A., Paydar, M.M., and Solimanpur, M. "Designing a mathematical model for dynamic cellular manufacturing systems considering production planning and worker assignment", *Computers & Mathematics with Applications*, **60**, pp. 1014–1025 (2010).
7. Aryanezhad, M.B., Deljoo, V., and Mirzapour Al-e-Hashem, S. "Dynamic cell formation and the worker assignment problem: a new model", *The International Journal of Advanced Manufacturing Technology*, **41**, pp. 329–342 (2009).
8. Bagheri, M. and Bashiri M. "A new mathematical model towards the integration of cell formation with workforce assignment and inter-cell layout problems in a dynamic environment", *Applied Mathematical Modelling*, **38**, pp. 1237–1254 (2014).
9. Javadi, B., Jolai, F., Slomp, J., Rabbani, M., and Tavakkoli- Moghaddam, R. "An integrated approach for the cell formation and layout design in cellular manufacturing systems", *International Journal of Production Research*, **51**, pp. 6017–6044 (2013).
10. Bagheri, M., Sadeghi, S., and Saidi-Mehrabad, M. "A benders' decomposition approach for dynamic cellular manufacturing system in the presence of unreliable machines", *Journal of Optimization in Industrial Engineering*, **17**, pp. 37–49 (2015).
11. Bayram, H. and Şahin, R. "A comprehensive mathematical model for dynamic cellular manufacturing system design and linear programming embedded hybrid solution techniques", *Computers & Industrial Engineering*, **91**, pp. 10–29 (2016).
12. Azadeh, A., Ravanbakhsh, M., Rezaei-Malek, M., Sheikhalishahi, M., and Taheri-Moghaddam, A. "Unique NSGA-II and MOPSO algorithms for improved dynamic cellular manufacturing systems considering human factors", *Applied Mathematical Modelling*, **48**, pp. 655–672 (2017).
13. Liu, C., Wang, J., and Leung, J.Y.T. "Worker assignment and production planning with learning and forgetting in manufacturing cells by hybrid bacteria foraging algorithm", *Computers & Industrial Engineering*, **96**, pp. 162–179 (2016).
14. Mehdizadeh, E. and Rahimi, V. "An integrated mathematical model for solving dynamic cell formation problem considering workforce assignment and inter/intra cell layouts", *Applied Soft Computing*, **42**, pp. 325–341 (2016).
15. Rafiei, H. and Ghodsi, R. "A bi-objective mathematical model toward dynamic cell formation considering labor utilization", *Applied Mathematical Modelling*, **37**, pp. 2308–2316 (2013).
16. Sakhaii, M., Tavakkoli-Moghaddam, R., Bagheri, M., and Vatani, B. "A robust optimization approach for an integrated dynamic cellular manufacturing system and production planning with unreliable machines", *Applied Mathematical Modelling*, **40**, pp. 169–191 (2016).
17. Nouri, H. "Development of a comprehensive model and BFO algorithm for a dynamic cellular manufacturing system", *Applied Mathematical Modelling*, **40**, pp. 1514–1531 (2016).

Biographies

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