An Investigation into Skill Leveled Operators in a Multi-Period Cellular Manufacturing System with the Existence of Multi-Functional Machines

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Abstract

Many works published in the area of cellular manufacturing system are based on the assumption that machines are reliable in the whole production horizon without any break down. As such assumptions often are not realistic, to contribute to closing this gap to reality, the model has been modified by additionally including machine reliability, alternative process routings and workforce assignment in a dynamic environment. In this research to integrate this aspects, the modified problem has been defined and formulated and an extended mixed integer multi-period mathematical model has been proposed.

In order to evaluate the effectiveness and capability of the extended model, some hypothetical numerical instances are generated and computational experiment are carried out using Gams optimization package. Experimental results demonstrate that the demand value can affect the machine breakdown rate, and a machine with a minimum breakdown rate is implemented more often than others. Moreover, the observed trade-off between the workforce-related costs and the cell-formation costs indicates that workforce-related issues have a significant impact on the total efficiency of the system. The proposed model can be implemented in medium- and large-scale manufacturing companies.

Keywords: multi-period cellular manufacturing system, machine reliability, workforce learning-forgetting effect, alternative process routing.

1. Introduction

Group Technology (GT), as an effective manufacturing technique, implies that similar tasks should be done in the same way. This approach can be applied usefully in a competitive production environment, which makes manufacturing systems adapt themselves to the erratic changes of production factors such as part demand changes, development of new products, machine requirements and the like. Cellular Manufacturing System (CMS) as an application of GT can be implemented in most industrial plants with the capability of being a high-performance producer. However, Cell Formation (CF), Inter/intra-Cell Layout (CL), and workforce allocation are the three main sub-problems in designing an efficient CMS. Many researches have been performed so as to tackle these problems effectively, especially in the case of complicated models, in which two or three of the abovementioned problems are taken into account simultaneously. Liu, et al. [1], for instance, have presented a new model with integration of
production planning and facility transfer in dynamic cellular manufacturing environment on the supply chain. In the same vein, Askin [2] has reviewed the developments in CMS-related organizational issues and options. Accordingly, the relevant research studies can be categorized in terms of both designing and optimizing aspects. Among other studies, with the goal of solving the CF problem, Ameli and Arkat [3] developed a pure integer mathematical model. They’ve also considered issues of machine reliability and Alternative Process Routings (APR). In another study, Bulgak and Bektas [4] have conducted a research which in CF problem with Production Planning (PP) have been investigated, simultaneously reconfiguring the system has been considered in their work. Meh dizadeh, et al. [5] presented a multi-objective mixed integer programming (MIP) model to simultaneously solve CF and production planning problems. Many real world parameters such as alternative plans for processing of part types, flexibility of workers and machines, multi-period production planning, capacity of machines, reconfiguration of dynamic systems, sequence of operations, duplicate machines, the workers’ time availability, as well as assignment of workers are taken into consideration in this study. Furthermore, Mahdavi, et al. [6] have extended a dynamic CF considering PP and workforce assignment which aims at minimizing the current inventory, in-process inventory and backlog, inter-cell part trip, reconfiguration of machines, as well as 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 many real-world production factors including the existence of flexibility in part routing, machine as well as labor progression to higher skill level. In a similar vein, Bagheri and Bashiri [8] have proposed a comprehensive model in which the dynamic CF problem including inter-cell layout and workforce assignment problems have been integrated. In fact, in a dynamic environment, they have analyzed the learning ability of labors in a dynamic environment. Javadi, et al. [9] extended a novel model in order to deal with the layout and CF problems, simultaneously. Their proposed model attempts to concurrently design the material-handling flow path structure and inter/intra-cell layout problem. Bagheri et al. [10] considered a newfangled model for CMS considering some productin features comprising reliability of machines with stochastic parameters such as service and arrival times in a dynamic area and alternative process routings. Also, they employed a Benders decomposition (BD) method to overcome this problem’s complexity. Bayram and Şahin [11] have also proposed a mathematical model in which many real-world production factors such as sequences of operations, splitting of lots, the products changing demands, capacities of machines, the products’ alternative processing routes, as well as machine duplication are addressed.

Nowadays, in competitive production systems, the workforce-related issues are more important. Hence, it is necessary to review the relevant studies carried out in this domain. Recently, Azadeh, et al. [12] presented a novel model for the dynamic CMS in a multi-objective area called MDCMS, taking into account human factors. Two main objectives, namely minimizing the inconsistency of the decision-making mode for the workforce in the public manufacturing cells, and balancing the cells’ workload regarding the workforces’ efficacy, have been targeted in their research. Moreover, Liu et al. [13] have aimed their research at developing a combined decision model of production planning and assignment of workers in a dynamic CMS area of fiber connector manufacturing business. In the same vein, the aim of the study conducted by Meh dizadeh and Rahimi [14] is to develop a joint model to tackle the dynamic CF problem taking the assignment of workforce and inter/intra cell layouts problems into account in the presence of machine duplication. Similarly, Rafiei and Ghodsi [15] have proposed an ant colony optimization (ACO) to tackle the problem of cell formation integrated with workforce
related issues. Sakhaii, et al. [16] have also proposed and applied robust optimization methods to cope with the dynamic CF problem focusing on the concepts of reliability of machines, production planning, allocation of workforce, inter cell layout, as well as alternative process routings. A comprehensive multi-objective model of the CMS in a dynamic area is extended by Nouri [17] considering several key cell design factors like designations of machines, inter/intra-cell material handling, allotting of workers, workload balancing and outsourcing according to the operation time, and the parts’ operation sequence. However, in this study and other related researches, workforce-related issues are not addressed in a detailed and comprehensive way, a gap which is aimed to be filled in the present study.

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

[Insert Table 1 Here]

Drawing on the factors listed in Table 1, we have attempted to analyze the recent studies, the obtained results of which are reported in Table 2. According to this table, many studies haven’t considered some vital realistic assumption like reliability of machines, routings of alternative process and the workforce learning-forgetting effect. In the following, however, an optimization problem is introduced and generalized by assuming alternative process routings and workforce-related issues while multi-functional machines are available and machines are not reliable. The generalized problem is presented which aims at the reduction of inter-cell part trips and minimizing machine breakdown and workforce-related costs. In fact, the proposed model is an extended version of the work done by Bagheri and Bashiri [8], to which many other realistic factors like APRs, Machine reliability, and the workforce learning-forgetting effect are added to be considered.

[Insert Table 2 Here]

The remainder of the presented research continues with proposing a mixed integer non-linear mathematical programming (MINLP) model which is in line with the mentioned objectives. Then, a linearization technique is used 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 & Mathematical Formulation

Most previous approaches assumed that machines are reliable in the whole production horizon without any breakdown which is not a realistic assumption. Actually, in industrial environments, machines are unreliable and the breakdown costs should be considered in order to elevate the efficiency of CMS. In this paper, a framework for considering cost of machine breakdown is proposed, cost of machine breakdown is known and includes repairing costs and also installation-uninstallation costs. Consequently, the exponential distribution could be taken into account with a given breakdown (failure) rate for reliability of machine in its operating time:
\[ R = \exp\left(-\lambda t\right) \]  

Where \( R \) is machine reliability at time \( t \). The breakdown rate \( \lambda \) is also given over the planning horizon, so the mean time between failures called MTBF is determined by Equation 2.

\[ MTBF = \frac{1}{\lambda} \]  

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

Other basic assumptions taken into account in modeling the problem can be described as follows:

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

2.2 Notations

Indices:

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

Input parameters:

\( MC_i \) \quad \text{Inter-cell part trip cost}

\( SM \) \quad \text{Machine install/uninstall cost in a cell.}

\( SG \) \quad \text{Tool install/uninstall cost on a machine}

\( \psi_{jg} \) \quad \text{Tool consumption cost}

\( B_m \) \quad \text{The repairing cost of machine “m”}

\( m\text{c}ap\text{time}_m \) \quad \text{The maximum time of processing on machine “m”}

\( u_m, l_m \) \quad \text{The maximum and minimum number of tools that can be installed on machine “m”}

\( u_c, l_c \) \quad \text{The maximum and minimum number of machines that could be assigned to cell “c”}

\( q \) \quad \text{The percentage of cell load variation}

\( MTBF = \frac{1}{\lambda_m} \) \quad \text{The average time between the breakdowns of machine “m”}

\[ \alpha'_{jg} = \begin{cases} 1; & \text{if operation j of part type i can be processed by tool g in production period t} \\ 0; & \text{else} \end{cases} \]

\[ \beta'_{gm} = \begin{cases} 1; & \text{if tool g can be installed on machine m in production period t.} \\ 0; & \text{else} \end{cases} \]

\( H, F \) \quad \text{Workforce hiring/firing cost}

\( S\text{A}_l \) \quad \text{The salary of the workforce with the skill level l}

\( m\text{ove}k \) \quad \text{The workforce trip cost between cells}

\( a_{kg}^{t=1} \) \quad \text{1 if workforce k can work with tool g at the start time of planning horizon}

\( a\text{w}_g \) \quad \text{The minimum skill level to work with tool “g”}

\( \sigma_l \) \quad \text{Skill level boundary}
\[ w_1, w_2 \quad \text{Increasing and decreasing in workforce skill level} \]

\[ D^t_i \quad \text{The demand value for i-th part in t-th manufacturing term} \]

\[ \text{dis}_{cc'} \quad \text{The distance between the two candidate locations } c \text{ and } c' \]

\[ \text{time}_{jgm} \quad \text{The operation } j \text{'s processing time on machine type } m \text{ for part type } i \text{ with tool } g \]

\[ \text{MINEM} \quad \text{The least number of workforces which are sufficient to be hired in each manufacturing term} \]

\[ \text{Opcaptime} \quad \text{the maximum time of working for each workforce} \]

Decision variables:

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

\[ y^t_{gm} = \begin{cases} 1; & \text{If tool } g \text{ in period } h \text{ is installed on machine } m \\ 0; & \text{Otherwise} \end{cases} \]

\[ p^t_{ijg} = \begin{cases} 1; & \text{If operation } j \text{'s } i \text{ in period } t \text{ is processed with tool } g \\ 0; & \text{Otherwise} \end{cases} \]

\[ b^t_k = \begin{cases} 1; & \text{If operator } k \text{ is working in period } t \\ 0; & \text{Otherwise} \end{cases} \]

\[ h^t_k = \begin{cases} 1; & \text{If operator } k \text{ is hired in period } t \\ 0; & \text{Otherwise} \end{cases} \]

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

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

\[ a^t_{kg} = \begin{cases} 1; & \text{If operator } k \text{ can work with tool } g \text{ in period } t \\ 0; & \text{Otherwise} \end{cases} \]

2.3 **The objective function**

The proposed MINLP model for the CMS design is offered as Eqs. (3) to (11):
\[
\begin{align*}
\text{min } & \quad \text{Model 1} = \\
& \quad \sum_{t=1}^{T} \sum_{l=1}^{I} \sum_{g=1}^{G} \sum_{m=1}^{M} \sum_{c=1}^{C} x'_{mc} \times y'_{gm} \times p'_{ijg} \times x'_{m'c} \times y'_{g'm} \times p'_{l(j+1)g} \times D'_{i} \times \text{dis}_{c,c'} \times MC_{i} \\
& \quad + \sum_{t=1}^{T} \sum_{l=1}^{I} \sum_{g=1}^{G} \sum_{c=1}^{C} x'_{mc} \times y'_{gm} \times p'_{ijg} \times x'_{m'c} \times y'_{g'm} \times p'_{l(j+1)g} \times D'_{i} \times MC_{i} \\
& \quad + \sum_{t=1}^{T-1} \sum_{m=1}^{M} \sum_{c=1}^{C} x'_{mc} \times x'_{mc} \times \text{dis}_{c,c'} \times SM \\
& \quad + \sum_{t=1}^{T} \sum_{l=1}^{I} \sum_{g=1}^{G} \sum_{m=1}^{M} y'_{gm} \times p'_{ijg} \times D'_{i} \times \Psi_{ijg} \\
& \quad + \sum_{t=1}^{T-1} \sum_{g=1}^{G} \sum_{m=1}^{M} y'_{gm} \times y'_{gm} \times SG \\
& \quad + \sum_{t=1}^{T} \sum_{l=1}^{I} \sum_{g=1}^{G} \sum_{m=1}^{M} \sum_{c=1}^{C} p'_{ijg} \times y'_{gm} \times \text{time}_{ijgm} \times D'_{i} \\
& \quad + \sum_{t=1}^{T} \sum_{m=1}^{M} \sum_{c=1}^{C} \sum_{k=1}^{K} \left( h_{k} \times H \right) + \sum_{t=2}^{T} \sum_{k=1}^{K} \left( h_{k} \times H + (1-b_{k}) \times F \right) \\
& \quad + \sum_{t=1}^{T} \sum_{k=1}^{K} \sum_{l=1}^{L} \sum_{g=1}^{G} \sum_{m=1}^{M} \sum_{c=1}^{C} w'_{kg} \times w'_{kg} \times y'_{gm} \times x'_{mc} \times y'_{g'm} \times x'_{m'c} \times \text{dis}_{c,c'} \times \text{movek} \\
& \quad + \sum_{t=1}^{T} \sum_{k=1}^{K} \sum_{l=1}^{L} \sum_{g=1}^{G} \sum_{m=1}^{M} \sum_{c=1}^{C} p'_{ijg} \times y'_{gm} \times x'_{mc} \times \text{time}_{ijgm} \times D'_{i} \times w'_{kg} \times le'_l \times SA_l \\
\text{Subjected to:} \\
& \quad \sum_{c=1}^{C} X'_{mc} = 1 \quad \forall m,t; \\
& \quad \sum_{g=1}^{G} P'_{ijg} = 1 \quad \forall i,j,t; \\
& \quad \sum_{m=1}^{M} Y'_{gm} \leq 1 \quad \forall g,m,t; \\
& \quad P'_{ijg} \leq \alpha'_{ijg} \quad \forall i,j,g,t; \\
& \quad Y'_{gm} \leq \beta'_{gm} \quad \forall g,m,t; 
\end{align*}
\]
\[
\sum_{c=1}^{M} \sum_{m=1}^{G} \sum_{i=0}^{L} \sum_{j=1}^{I} P_{ijg} \leq \sum_{c=1}^{M} \sum_{m=1}^{G} \sum_{i=1}^{L} \sum_{j=1}^{I} P_{ijg} \quad \forall g, t; \\
\sum_{c=1}^{M} \sum_{m=1}^{G} \sum_{i=1}^{L} \sum_{j=1}^{I} Y_{gm} \times X_{mc} \geq P_{ijg} \quad \forall i, j, g, t; \\
\sum_{m=1}^{M} X_{mc} \leq u_c \quad \forall c, t; \\
\sum_{m=1}^{M} X_{mc} \geq l_c \quad \forall c, t; \\
\sum_{g=1}^{G} Y_{gm} \leq u_m \quad \forall m, t; \\
\sum_{g=1}^{G} Y_{gm} \geq l_m \quad \forall m, t; \\
\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{g=1}^{G} P_{ijg} \times Y_{gm} \times \text{time}_{ijgm} \times D_{ij} \leq mc\text{aptime} \quad \forall m, t; \\
\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{g=1}^{G} X_{mc} \times Y_{gm} \times \text{time}_{ijgm} \times D_{ij} \geq \frac{C}{G} \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{g=1}^{G} X_{mc} \times Y_{gm} \times \text{time}_{ijgm} \times D_{ij} \quad \forall c, t; \\
b^t_k = h^t_k \quad \forall k; \\
b^{t+1}_k(1-b^t_k) = h^{t+1}_k \quad \forall k, t; \\
h^{t+1}_k \leq 1-b^t_k \quad \forall t = 1,...,T-1, \forall k; \\
\sum_{k=1}^{K} b^t_k \geq \min EM \quad \forall t; \\
w^t_{kg} \leq b^t_k \quad \forall k, g, t; \\
\sum_{k=1}^{K} w^t_{kg} = \sum_{m=1}^{M} Y_{gm} \quad \forall g, t; \\
\sum_{g=1}^{G} w^t_{kg} \geq b^t_k \quad \forall k, t; \\
w^t_{kg} \times aw_{g} \leq a^t_{kg} \quad \forall k, g, t;
The proposed model is aimed at minimizing two indicated 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 at minimizing the trips of inter-cell parts. The notable point is that an inter-cell part trip is determined based on inter-cell distances. The part 4 is to minimize intra-cell part trips. Also, the part 5 aims at minimizing the trips of inter-cell parts. The dynamic nature of the production system, i.e., demand, process routings and machine characteristics variation cause machine movements between cells which occur between two consecutive periods. This cost includes the uninstallation, movement and installation of the machines between the cells. 6 minimizes the total tools consumption costs. Also, 7 is to minimize the installation/uninstallation costs of tools on different machines. 8 minimizes the overall machine breakdown cost. This cost is according to the total processing time of a machine and its breakdown rate. The part 9 is to minimize the workforce hiring/firing costs. 10 controls the workforce between cells trips. Moreover, workforce salary cost is minimized using 11.

12 guarantees that any type of machine is assigned to a given cell. Eq. 13 is to ensure that each part operation can be performed with only one tool. It is assumed that a tool can be installed on only one machine. This constraint is guaranteed with 14. So, it is possible that there will be unused tools in a production period. 15 and 16 are to ensure that each operation and tool can be assigned, respectively, to a tool and machine with the capability of that installation. 17 and 18 ensure that the unused tool in a production period can’t be installed on any machine. The maximum and the minimum number of machines for a cell are constrained respectively by 19 and 20 to stand in the cell size range. Also, the allocated number of tools to each machine are constrained by 21 and 22, respectively. The maximum amount of time which each machine can use is eliminated by 23. Moreover, 24 balances the load variations of each cell in a production period. In the 1st period, if a worker is hired he/she should be assigned to work with a machine. This issue is guaranteed by 25. The workforce hiring/firing balance between two consecutive periods is constrained by 26 and 27. Constraint 28, in each manufacturing term,
specify the least number of workforces that should be hired. A workforce can work with a tool only if that workforce is implemented in a production period. 29 guarantees this point. 30 states that for a tool, a workforce should be hired in a production period. Also, if a workforce is hired, he/she should be assigned to some tools (machines) (31). Based on 32, a workforce with a minimum skill value can be selected to work with a machine tool. The workforce learning-forgetting effect is assumed according to 33 and 34. Based on these two constraints, a workforce skill level must be updated in each production period. 35 emphasizes that a workforce should be ranked and given a skill level according to his/her abilities. A workforce time capacity for working in a production period is limited by 36. Finally, 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 the constraints of 17, 18, 23, 24, 26 and 33 is a nonlinear one, here, we have transformed it into a linear MIP model using three linearization techniques.

Proposition 1. Take the pure quadratic 0-1 variable \( Z = X_1 \times X_2 \times \ldots \times X_n \) into account, where \( X_i \) \((i = 1, \ldots, n)\) is a binary variable. The variable \( Z \) can be obviously 1 if and only if the all variables are 1; otherwise 0 (Bagheri and Bashiri [8]). Application of mentioned mathematical view is formulated as below by utilizing some new supplementary limitations.

\[
Z \leq X_i \quad \forall i = 1, \ldots, n
\]

\[
Z \geq \sum_{i=1}^{n} X_i - (n - 1)
\]

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 transform the model to a linear form. The needed limitations are mentioned in this manner:

\[
Z \leq M \times X
\]

\[
Z \leq Y
\]

\[
Z \geq Y - (1 - X)M
\]

\[
Z \geq 0 \text{ and } \text{int.}
\]

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.

\[ T \geq X \]
\[ T \geq a \]

Accordingly, let’s define new variables as follows.

\[ PXY_{ijgmc}^1 = x_{mc}^t y_{gm}^t p_{ijg}^t x_{mc}^t y_{gm}^t p_{(i,j+1)g}^t \quad 38 \]
\[ PXY_{ijgmc}^2 = x_{mc}^t y_{gm}^t p_{ijg}^t x_{mc}^t y_{gm}^t p_{(i,j+1)g}^t \quad 39 \]
\[ XX_{mc}^t = x_{mc}^t x_{mc}^{t+1} \quad 40 \]
\[ YY_{gmc}^t = y_{gm}^t x_{mc}^t \quad 41 \]
\[ PY_{ijgm}^t = p_{ijg}^t y_{gm}^t \quad 42 \]
\[ PXY_{ijgmc}^1 = p_{ijg}^t x_{mc}^t y_{gm}^t \quad 43 \]
\[ YY_{gm}^t = y_{gm}^t y_{gm}^{t+1} \quad 44 \]
\[ WW_{kg}^t = w_{kg}^t w_{kg}^t \quad 45 \]
\[ WL_{kg}^t = w_{kg}^t l_{e_{lk}} \quad 46 \]
\[ B_k^t = b_k^{t+1} \times (1 - b_k^t) \quad 47 \]
\[ Z = \max(a_{kg}^t - a_k^t, 0) \quad 48 \]
\[ BA_{kg}^t = b_k^t \times a_{kg}^t \quad 49 \]
\[ BZ_k^t = (1 - b_k^t) \times Z \quad 50 \]

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

\[ PXY_{ijgmc}^1 \geq YY_{gmc}^t + p_{ijg}^t + YY_{gmc}^t + p_{(i,j+1)g}^t - 3 \quad 51 \]
\[ PXY_{ijgmc}^1 \leq YY_{gmc}^t \quad 52 \]
\[ PXY_{ijgmc}^1 \leq p_{ijg}^t \quad 53 \]
\[ PXY_{ijgmc}^1 \leq YY_{gmc}^t x_{mc}^t y_{gm}^t p_{ijg}^t \quad 54 \]
\[ PXY_{ijgmc}^1 \leq p_{(i,j+1)g}^t \quad 55 \]
\[ PXY_{ijgmc}^2 \geq YY_{gmc}^t + p_{ijg}^t + YY_{gmc}^t + p_{(i,j+1)g}^t - 3 \quad 56 \]
\[ PXY_{ijgmc}^2 \leq YY_{gmc}^t \quad 57 \]
\[ PXY_{ijgmc}^2 \leq p_{ijg}^t \quad 58 \]
\[ PXY_{ijgmc}^2 \leq YY_{gmc}^t x_{mc}^t y_{gm}^t \quad 59 \]
\[ PXY_{ijgmc}^2 \leq p_{(i,j+1)g}^t \quad 60 \]
\[XX_{mcc}^t \geq x_{mc}^t + x_{mc}^{t+1} - 1\]

\[XX_{mcc}^t \leq x_{mc}^t\]

\[XX_{mcc}^t \leq x_{mc}^{t+1}\]

\[YX_{gmc}^t \geq y_{gm}^t + x_{mc}^t - 1\]

\[YX_{gmc}^t \leq y_{gm}^t\]

\[YX_{gmc}^t \leq x_{mc}^t\]

\[PY_{ijgm}^t \geq p_{iig}^t + y_{gm}^t - 1\]

\[PY_{ijgm}^t \leq p_{iig}^t\]

\[PY_{ijgm}^t \leq y_{gm}^t\]

\[PXY_{ijgm}^t \geq x_{mc}^t + PY_{ijgm}^t - 1\]

\[PXY_{ijgm}^t \leq PY_{ijgm}^t\]

\[PXY_{ijgm}^t \leq x_{mc}^t\]

\[WPXY_{ijkmgm}^t \leq w_{kg}^t + PXY_{ijgm}^t - 1\]

\[WPXY_{ijkmgm}^t \leq w_{kg}^t\]

\[WPXY_{ijkmgm}^t \leq PXY_{ijgm}^t\]

\[YY_{gmm}^t \geq y_{gm}^t + y_{gm}^{t+1} - 1\]

\[YY_{gmm}^t \leq y_{gm}^t\]

\[YY_{gmm}^t \leq y_{gm}^{t+1}\]

\[WW_{kg}^{i+1} \geq w_{kg}^t + w_{kg}^t - 1\]

\[WW_{kg}^t \leq w_{kg}^t\]

\[WW_{kg}^{i+1} \leq w_{kg}^t\]

\[WL_{kg}^t \geq w_{kg}^t + le_{ik}^t - 1\]

\[WL_{kg}^t \leq w_{kg}^t\]

\[WL_{kg}^{i+1} \leq le_{ik}^t\]

\[WLPXY_{ijkmgm}^t \geq w_{kg}^{i+1} + PXY_{ijgm}^t - 1\]

\[WLPXY_{ijkmgm}^t \leq w_{kg}^{i+1}\]

\[WLPXY_{ijkmgm}^t \leq PXY_{ijgm}^t\]

\[WXY_{kkgm}\[c\]_{cc}^t \geq WW_{kg}^{i+1} + YY_{gmm}^t + XX_{mcc}^{t+1} - 2\]

\[WXY_{kkgm}\[c\]_{cc}^t \geq WW_{kg}^{i+1}\]

\[WXY_{kkgm}\[c\]_{cc}^t \geq YY_{gmm}^t\]

\[WXY_{kkgm}\[c\]_{cc}^t \geq XX_{mcc}^t\]
\[B'_k \geq b'_{k+1} + (1 - b'_k) - 1\]  
\[B'_k \leq b'_{k+1}\]  
\[B'_k \leq (1 - b'_k)\]

\[Z \geq \alpha'_{k_0} - \omega_z\]  
\[Z \geq 0\]

\[BA'_{k_0} \geq \alpha'_k - M_\infty (1 - b'_k)\]  
\[BA'_{k_0} \leq \alpha'_k\]  
\[BA'_{k_0} \leq M_\infty \times b'_k\]  
\[BZ'_k \geq Z - M_\infty [1 - (1 - b'_k)]\]

\[BZ'_k \leq Z\]

\[BZ'_k \leq M_\infty \times (1 - b'_k)\]

Thus, the linear version of the MIP model could be considered in this manner.

\[
\begin{align*}
\text{min} & \quad \text{Model 2 } = \\
& \quad \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{g=1}^{G} \sum_{m=1}^{M} \sum_{c=1}^{C} PXY'_{ijgm} \times D'_i \times \text{dis}_{c,c'} \times MC_i \\
& \quad + \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{g=1}^{G} \sum_{c=1}^{C} \sum_{m=1}^{M} PXY'_{ijgm} \times D'_i \\
& \quad + \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{g=1}^{G} \sum_{c=1}^{C} \sum_{m=1}^{M} XX'_{mcce'} \times \text{dis}_{c,c'} \times SM \\
& \quad + \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{g=1}^{G} \sum_{c=1}^{C} \sum_{m=1}^{M} PY'_{ijgm} \times D'_i \times \psi_{ijg} \\
& \quad + \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{g=1}^{G} \sum_{c=1}^{C} \sum_{m=1}^{M} YY'_{gmm} \times SG \\
& \quad + \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{g=1}^{G} \sum_{c=1}^{C} \sum_{m=1}^{M} PY'_{ijgm} \times \text{time}_{ijgm} \times D'_i \\
& \quad + \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{g=1}^{G} \sum_{c=1}^{C} \sum_{m=1}^{M} \frac{MTBF_m}{\text{MTBF}_m} \times B_m \\
& \quad \sum_{k=1}^{K} (h_k' \times H) + \sum_{t=2}^{T} \sum_{k=1}^{K} (h_k' \times H + (1 - b'_k) \times F) 
\end{align*}
\]

13
\[ \sum_{i=1}^{T} \sum_{k=1}^{K} \sum_{g=g'}^{m} \sum_{m'=m'}^{c} \sum_{c'=c}^{e} WYX^t_{kgg'm'm'c'} \times dis_{c,c'} \]

\[ + M \sum_{m=1}^{M} \sum_{r=1}^{T} \sum_{k=1}^{K} \sum_{l=1}^{L} \sum_{g=1}^{G} WLPXY^t_{ijklg} \times time_{ijgm} \times D'_i \times SA_i \]

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

Moreover, the set constraints 17, 18, 23, 24, 26 and 33 are replaced by

\[ \sum_{c=1}^{C} \sum_{m=1}^{M} YX^t_{gmc} \leq \sum_{i=1}^{I} \sum_{j=1}^{O_i} P^t_{ijg} \quad \forall g, t; \]

\[ \sum_{c=1}^{C} \sum_{m=1}^{M} YX^t_{gmc} \geq P^t_{ijg} \quad \forall i, j, g, t; \]

\[ \sum_{i=1}^{I} \sum_{j=1}^{O_i} G \times P^t_{ijgm} \times time_{ijgm} \times D'_i \leq \text{captime} \quad \forall m, t; \]

\[ B'_k = h'_k \quad \forall k, t; \]

\[ a^t_{kg} = \alpha \sum_{i=1}^{I} \sum_{j=1}^{O_i} WPXY^t_{ijkgm} + BZ'_k + BA'_k \quad \forall k, g, t; \]

and the last set constraint 36 is replaced by

\[ \{ W'_k, h'_k, B'_k, \lambda'_c, \lambda'_l, B'_k, P'_ijg, WW'_kg, WL'_kg, X'_mc, Y'_gm, PW'_ijgm, PXY'_ijgm, PXY'_ijgm, WLPXY'_ijklg, WYX^t_{kgg'm'm'c'} \triangleq \{0, 1\} \]

3. Computational experience

In the following, experiments to evaluate the capability of solving the CMS problem by means of presented model and applied approach have been conducted. Randomly, three instances are generated. Experiments have been performed with model implemented and solved on a Core i5 PC with 1 GB of RAM by using GAMS 23.5. The input data of generated instances are illustrated in Table 3- Table 5.
To attain an optimal solution, according to the study conducted by Bagheri and Bashiri [8], the two problems of cell formation and workforce assignment should be solved simultaneously. As an investigation of this claim, the present paper has aimed to separate and solve these two problems in three modes, namely the solo mode, the hierarchical mode, and the simultaneous mode. The two separated models are as presented below.

**Model 1 (CF)**

\[
\text{Min } 3-8 \\
\text{Subjected to:} \\
12 - 24, 37
\]

**Model 2 (OS)**

\[
\text{Min } 9-11 \\
\text{Subjected to:} \\
25 - 37
\]

At first, the generated instances are solved using model 1. Then, the obtained results are given to model 2 as input parameters and model 2 is 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 it could be observed in Table 6, increasing the problem size results in a better performance of the simultaneous model. This model can reach more optimal solutions than the hierarchical mode, especially in the case of large-scale problems. Moreover, the schematic view of instance 3 is illustrated in Figure 1. It has to be noted that 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 can’t be compared in this condition. In order to overcome this obstacle, the LP-Metric approach was implemented.

Generally speaking, the LP-metric techniques prepare an extensive approach of accordance to solve MCDM problems while objectives are incommensurable and they are in contrast together. These techniques transform m objectives (criteria) into one objective via 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 (criteria) are incongruity dimension.

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

\[
D = \left( \sum_{i=1}^{n} \lambda_i \left( \frac{f_{i}^- - f_{i}(x)}{f_{i}^* - f_{i}^-} \right)^p \right)^{\frac{1}{p}}, \quad p = 1, 2, \ldots
\]
In the equation above, \( f_i(x) \), \( f_i^*(x) \) and \( f_i^-(x) \) are objective function, ideal objective function and anti-ideal objective function respectively. Also \( \lambda_i \) is the weight given for the importance of the \( f_i(x) \). The ultimate target is aimed at minimizing the distance between ideal and anti-ideal pursuant to the constraints then to discover the non-dominated solution. Thus in equation 118 LP-metric describe the distance between \( F(x) \) and \( F^*(x) \).

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

By changing the \( \lambda_i \) value, which represents the weight considered for each of the aforementioned problems, the Pareto optimal solution can be obtained as Figure 2.

As can be observed in this figure, workforce-related costs have a significant impact on the cell formation solution. In order to analyze the OS problem in more detail, we can consider an expert workforce, working only with a machine tool without any training cost. This workforce’s salary is naturally higher than that of the others. In this situation and based on the results, an workforce with a lower skill level is selected to be trained and work with that machine tool. With a decrease in the salary of the expert workforce, he/she is selected as a machine tool workforce.

In addition, it turns out that any change in the demand value can significantly affect the essential cost terms Figure 3 It can be inferred from this figure that, 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 cost. Moreover, a meticulous maintenance plan can decrease the rate of machine breakdown in high demand companies.

Machines are the second main manufacturing resource to be analyzed in more detail. Machine breakdown and demand rate are of paramount importance 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, machine 3 can process a maximum number of 4 operations in a production period. As already mentioned, a machine can’t be interrupted while it is processing a job. According to the input data, the rate of breakdown in machine 3 is higher than that of the other two machines. Therefore, it is preferable that this machine process only 3 operations even in a high demand situation.

To adjust real-world cellular production system models, we need to add more variables and limitations to the model, which will require a lot of time to solve such models by time, memory, and processing power. As a result, nowadays, modern methods apply 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) has tried to solve the model of the hierarchical and simultaneous model with the genetic algorithm to evaluate the performance of the models in larger dimensions. In Table 8 dimensions of 4 numerical instances are solved using GA. The obtained results are demonstrated in table 9 and Fig. 5. As it is notable, the simulation model has obtained a better answer than the hierarchical model. By increasing the dimensions of the models, the deviation of the optimum values obtained in the two models is more significant.

To validate the model due to the lack of a similar article and the lack of a real case study in the country, we act to analyze the sensitivity analysis in one of the examined examples in the paper. For instance, in Example 4, assuming the dimensions of the model are constant, we have analyzed the sensitivity of the model parameters. As an example, sensitivity analysis of the demand parameter that changes all decision variables and optimal values is shown in Fig. 6. In some quantities are not noted significantly different in Costs such as the cost of installing machines and cellular configurations. In other cases, as the breakdown of machines and the cost of intercellular mobility is quite tangible that the resultant changes seem reasonable.

[Please insert Tables 8 and 9 about here]

[Please insert Figs. 5 and 6 about here]

4. Conclusion

In the present paper, a new-fangled model was presented to design an efficient cellular manufacturing system (CMS). The basic assumption of the proposed model is the incorporation of machine tools, machine breakdown and the workforce learning/forgetting effect. To the best of the authors’ knowledge, only rare researches have focused their consideration on such real-world parameters, so far. In terms of both computational time and optimality, the experimental results verified the efficiency of the proposed approach. Moreover, analytical experiment to assess the sensitivity of presented model has observed that considering the machine failure play a vital rule to elevate the performance of cellular manufacturing system, especially in companies with 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 is implemented more often than other machines. Besides, nowadays in competitive atmosphere of the world, the workforces are 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. With all these considerations, it can be claimed that the developed mathematical model could be employed in factories with the capability of having a cellular design. In fact, many 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 goal of designing an optimal CMS by the minimum amount of costs. The main goal of this research was considering some real-world production elements to be applied in 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 can be explored in more detail in future studies.

**Acknowledgement**

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**References**


Biography of authors

Manuscript Title: Skill leveled operators’ consideration in a multi-period cellular manufacturing system in presence of multi-functional machines

Majid Rafiee received his B.Sc. degree in Industrial Engineering from Isfahan University, Isfahan, Iran, in 2003, and his M.Sc. and Ph.D. degrees in Industrial Engineering from Sharif University of Technology, Tehran, Iran, in 2006 and 2013, respectively.

In 2013, he joined the Department of Industrial Engineering at Sharif University of Technology, Tehran, Iran, as Assistant Professor. Dr. Rafiee’s research interests include Stochastic Programming, Operations Research, Mathematical Programming, Quality Management, and Quality Control.

Atye Mohammadi-Talab received his B.Sc. degree in Industrial Engineering from Sharif university of Technology, Tehran, Iran, and his M.Sc. degree in Mathematics from University of Tehran, Tehran, Iran, in 2013 and 2016, respectively.

Her main areas of interest are integer programming, mathematical modeling and optimization.
Figure 1. The schematic view of instance 3 solution

Figure 2. The Pareto Solution for CF and OS Problems
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-Instance1)
Figure 5. Functional behavior in the Genetic Algorithm

Figure 6. Cost Sensitivity Analysis versus Demand Rate in the Genetic Algorithm
### Table 1. Essential parameters of a CMS problem

<table>
<thead>
<tr>
<th>Factor code</th>
<th>Factor description</th>
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<td>Inter-cell part trip</td>
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<td>2-B</td>
<td>Intra-cell part trip</td>
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<td>Cell formation</td>
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### Table 2. Literature review

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**Table 3. Numerical assumptions of different instances**

**Table 4. Numerical assumptions of different instances**
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<th>Inter-cell distances</th>
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**Table 5. Numerical assumptions of different instances**

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<th>Maximum time capacity</th>
<th>Learning rate</th>
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**Table 6. A comparison of hierarchical and simultaneous approaches**

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**Table 7. The trade-off matrix of CF and OS problems**

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<td>$f_1^*$ = 1569.979</td>
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**Table 8. Numerical assumptions of instance**

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<th>Number of machines</th>
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<th>Number of cells</th>
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### Table 9. A comparison of hierarchical and simultaneous approaches (Genetic Algorithm)

<table>
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<tr>
<th>Example</th>
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