# A New Mathematical Model for Cell Layout Problem considering Rotation of Unequal Dimensions of Cells and Machines 

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#### Abstract

One of the main concepts in group technology (GT) is the cellular manufacturing system (CMS) with three main problems of cell formation (CF), cell layout (CL), and cell scheduling (CS). This paper studies the cell layout problem (CLP), aiming to find the optimal layout of machines within each cell (intracellular layout) and the optimal layout of cells in each workshop (intercellular layout). To adapt to reality, the dimensions of the cells and machines (inside each cell) were considered unequal, and also the cells and machines could rotate. We believe that a cellular layout that assumes unequal dimensions of the cells and machines can be used for batch production. This kind of production has a wide variety of low to medium demand. Furthermore, a cellular layout can be applied in CMSs and also in noncontinuous industries that have a job shop layout. Our main contribution is considering the possibility of rotating the cells and machines inside the cells. For this purpose, a mixed nonlinear programming model was developed to solve the CLP with the minimum cost of intracellular and intercellular material flows. The proposed nonlinear model was first converted into a linear model, and then a problem was generated and solved with GAMS software to validate the resulting linear model. This model finds the best layout of cells within the workshop and the best layout of machines inside each cell. Then, because of the NP-hardness of the CLP and the fact that even exact methods cannot solve large-scale examples in an acceptable computational time, an imperialist competitive algorithm (ICA) was designed and used to solve the problem. To evaluate the efficiency of the proposed algorithm, its numerical results in small dimensions were compared with the results of GAMS software. In large dimensions, 30 random problems were created, and the results of ICA were compared with the results of the particle swarm optimization (PSO) algorithm and genetic algorithm (GA). Finally, the parameters of the three meta-heuristic algorithms were set by the Taguchi method. Numerical results indicated that ICA was superior to both the PSO algorithm and GA. It could also achieve efficient solutions in a shorter computational time.


## 1. Introduction

One of the main purposes of manufacturing systems is to convert raw materials, capital, information, labor, and other resources into more value-added goods or services. Manufacturing systems consist of several specifically organized machines to construct different kinds of products. They have different types based on facility layout, flow shop system, job shop system, fixed position layout, and cellular manufacturing system (CMS). In a flow shop system, production facilities are set sequentially. Examples of this flow are metal production industries, refineries, and
petrochemical industries. In a job shop production system, similar machines are located next to each other as in automotive and home appliance industries. In fixed position layout, the product is fixed, and each department performs the essential processes. Examples of such systems are aircraft, ship building, and construction industries. The last type of production system, i.e., CMS, is an application of group technology (GT) and comparing to other types of manufacturing systems like the flow shop system, has higher flexibility in the production of different types of products. Also comparing to job shop production system, which is used only for low production volume with high production
and storage cost, CMS enjoys good efficiency with a higher production rate [1].

A cell may contain a group of similar machines in which the components must have the maximum movement within each cell and the minimum movement relating to other cells. This advantage causes in the reduction of material handling costs, process and setup times, and inventory, which ultimately leads to better quality, customer satisfaction, and on-time delivery of the product. For the effective implementation of CMS, there are three important tasks:
(1) Grouping of parts with similar design features or processes in the family of parts, and grouping of machines into machine cells, which is called cell formation (CF).
(2) Finding the optimal layout of machines within each cell (intracellular layout) and the optimal layout of cells in the workshop (intercellular layout), which is collectively called cell layout problem (CLP).
(3) Determining the order of part families in each cell and the order of tasks in each part family, which is called cell scheduling (CS) [2].

The main objective of this paper is to develop a new mixed nonlinear mathematical model for CLP while the cells and machines have unequal dimensions and can rotate. The main questions of the paper are: "How to extend a new mixed nonlinear mathematical model for CLP?" and "How to solve it due to the Np-hardness of the model?" Accordingly, the main contributions of this research can be outlined as follows:
(i) Unlike previous research findings implying that do not rotate, using the model developed in this research, cells and machines can rotate in different directions.
(ii) In order to conform to the reality, unequal dimensions for cells and machines have been considered in this study.
(iii) The main application of cellular layout is in the automotive industries like the Toyota manufacturing industry.
(iv) In the present study, a new mixed nonlinear mathematical model has been proposed for CLP.
The following phases have been done in the present study. The related literature is reviewed in Section 2. Problem statement is explained in Section 3. A mathematical model of the problem is presented in Section 4 to minimize the intercellular and intracellular material flow. Since CLP is very complex and its computational time increases extremely as the size of the problem increases, exact algorithms for solving large-size problems lose their efficiencies; therefore, Section 5 compares the results of ICA with those of (PSO) and (GA). Finally, conclusions, study limitations, and future works presented in Section 6.

## 2. Literature Review Related to CLPs

CLPs are generally divided into three types: intercellular layout, intracellular layout, and intra- and inter-cellular layout. In the first case, only the layout of cells in the workshop or intercellular layout is considered. The objective function, in this case, is to minimize the cost of material flow between the cells in the workshop. In the second case, the cells' location is already known, and only the layout of machines within each cell or intracellular layout is considered. The objective function of this type of problem is to minimize the cost of material flow between the machines inside the cells. In the third case, the layout of cells in the workshop and the layout of machines inside the cells are considered, which is called intra- and inter-cellular layout. The objective function, in this case, is to minimize the cost of material flow between the cells and the cost of material flow between the machines within each cell. In the following, almost all the work done in the field of CLPs are reviewed. Some studies considered intra- and inter-cellular layout problems under dynamic situations and assumed equal dimensions for cells and machines. Others considered intracellular layout problems. The third group of studies mentioned intercellular layout problems with similar dimensions for cells and machines. Then a mathematical model and a solution method are proposed for the mentioned problems, and numerical results are presented.

Rosenblatt [3] studied factory layout problems under dynamic conditions and equal dimensions for machines. Vakharia and Wemmerlov [4] considered the problem of intracellular layout with equal dimensions and used a coefficient to assess the similarity of parts and the formation of a family of parts and cells. Two years later, Venugopal and Narendran [5] proposed the problem of cell formation (CF) to minimize the intercellular movements of parts, balance the capacity of cells, and solve the problem using GA. Meanwhile, Jajodia et al. [6] developed a new method for intracellular and intercellular layout problems with the equal dimensions for cells and machines. Arvindh and Irani [7] proposed the idea of designing a CMS in intracellular and intercellular layout with equal dimensions for cells and machines and used the production flow technique as a solution. Kim and Kim [8] assumed a model in which the shape of the machine was regular or irregular, its dimensions were fixed, the material handling system was based on an open field, and the objective function had a single criterion.

Vakharia and Cheng [9] developed the CF problem in an intercellular layout. The solution method was based on simulated annealing (SA) and tabu search (TS) algorithms. Consequently, Liang and Zolfaghari [10] proposed a problem for grouping machines with equal dimensions under uncertain and static conditions. Wang et al. [11] proposed a model for solving equipment layout problems in CMSs in which the demand rates changed over the product's life cycle. Lozano et al. [12] developed machine grouping and intercellular layout problems and considered a mathematical programming model to minimize the cost of intercellular
translocation. Solimanpur et al. [13] developed intercellular layout problems as a quadratic assignment. Anders and Lozano [14] proposed CF and intercellular layout problems by assuming a criterion for grouping machines in cells and used PSO algorithm to solve them. Tavakkoli-Moghaddam et al. [15] addressed intracellular and intercellular layout problems by assuming the possible demands and considered the fuzzy linear integer programming model. Hu et al. [16] inspected the intercellular layout problem and developed a model to minimize the cost of intercellular material flow. Chan et al. [17] proposed intercellular and intracellular layout problems by assigning machines within cells and considering equal dimensions for cells and machines. Tavakkoli-Moghaddam et al. [18] considered the problem of dynamic CF and intercellular layout under dynamic conditions. Mahdavi et al. [19] concentrated on the problem of intercellular and intracellular movements and CF in CMS. The following year, Rafiee et al. [20] proposed a CMS considering intracellular and intercellular layout problems in dynamic conditions. Ariafar et al. [21] applied intracellular and intercellular layout problems to CMS. Mahdavi et al. [22] developed a mathematical model for the simultaneous combination of CF and intracellular and intercellular layout. Shiyas and Pillai [1] considered the problem of intercellular layout and used a mathematical model to design manufacturing cells. Asl and Wang [23] developed an intracellular layout problem under uncertain and probabilistic conditions to minimize material flow costs. Mehdizadeh and Rahimi [24] proposed an integrated mathematical model for solving the dynamic CF problem, considering operator allocation and intracellular and intercellular layout problems. Ghosh et al. [25] considered the problem of intercellular layout and proposed a quadratic assignment planning model for such problems. Derakhshan Asl and Wang [26] developed the problem of intracellular layout in static and dynamic conditions, supposing unequal machine dimensions and the possibility of machine rotation. Rabbani et al. [27] hypothesized the problems of CF and intracellular and intercellular layout simultaneously in dynamic conditions and grouping of machines and parts. Feng et al. [28] investigated the CL and CF problems simultaneously and used GA and SA to solve them. Golmohammadi et al. [29] developed intracellular and intercellular layout problems and assumed machines, cells, parts, and batch sizes for transporting parts.

Mahmoodian et al. [30] developed a "smart" PSO algorithm for CLPs. Danilovic and Illic [31] worked on a hybrid algorithm to solve CLPs. Paramasamy et al. [32] developed a GA to form families of machine parts and cells and solved CLPs.

Rahimi et al. [33] considered CF, intercellular layout, and cell scheduling problems for CMSs. Zhao et al. [34] proposed a new layout methodology for the multifloor linear cellular manufacturing layout and a mathematical model. Neufeld et al. [35] pointed out several characteristics that specify the distinctiveness of cell scheduling. Golmohammadi et al. [36] developed a biobjective optimization model to integrate CF and intercellular or intracellular layouts. Rostami et al. [37] presented a multiobjective mathematical model for the simultaneous integration of virtual cellular manufacturing with the
supply chain and new product development. Ayough et al. [38] integrated job assignment and job rotation scheduling problems and presented a novel multiperiod nonlinear mixed integer model.

Goli et al. [39] designed a fuzzy mixed-integer linear programming model for CF problems in CMS. Salimpour et al. [40] developed CF, intracellular and intercellular layout problems, and machines of unequal dimensions. Golmohammadi et al. [41] considered the problem of facility layout by integrating CF in continuous space and intercellular and intracellular layouts. Mondal et al. [42] hypothesized the problems of intercellular layout and CF in CMS and offered a model for minimizing cell load variation and reducing intercellular movements. Razmjoei et al. [43] hypothesized an intercellular layout in CMS. Hazarika [44] proposed an intercellular layout in CMS and surveyed the problem of machine CF. Mansour et al. [45] studied cellular manufacturing and intracellular and intercellular layout problems at the same time. Fakhrzad et al. [46] simultaneously addressed CF and intercellular layout problems in terms of scheduling, labor assignment, and limited financial resources. Finally, Forghani and Fatemi Ghomi [47] addressed CF and group layout problems and proposed a mixed integer programming model. A summary of the results of the above works are presented in Table 1.

As shown in Table 1, the current research was conducted on CLPs, including intracellular and intercellular layouts where the dimensions of cells and machines are considered unequal and rotation of cells and machines are allowed. However, in the previous research studies, these six factors were not considered simultaneously.
2.1. Research Gap. As explained above, a comprehensive review of the literature within the last three decades clarifies that no research has examined CLPs under unequal dimensions of cells and machines within each cell and the possibility of rotation of cells and machines. Hence, this study was designed to examine these types of problems.

## 3. Problem Statement

In CLP problem, to find the layout of cells in the workshop and that of machines within each cell, first the number of cells and machines and then the dimensions of the workshop, cells, and machines are determined. Next, the number of machines inside each cell is specified. Lastly, the material flow between the cells and between the machines is determined. For example, assume we have three cells and ten machines. The cells are positioned in a workshop ( 1.5 m in length and 1.5 m in width). The length of the first cell is 50 cm and its width is 45 cm , and the length of the second cell is 45 cm and its width is 40 cm . The length and width of the third cell are both 40 cm , and the dimensions of the machines are also known. The first, second, third, and fourth machines are inside the first cell, the fifth, sixth, and seventh machines are inside the second cell, and the eighth, ninth, and tenth machines are inside the third cell. There is a material flow between the first, second, and third cells
Table 1: Results of literature review.

| Author/Year | Intracellular | Intercellular | Unequal dimension of cells | Unequal dimension of machines | Cells rotation | Machines rotation |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Rosenblatt (1986) [3] | $\bullet \longrightarrow$ |  |  |  |  |  |
| Vakharia and Wemmerlov (1990) [4] | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |  |
| Venugopal and Narendran (1992) [5] |  | $\bullet \longrightarrow$ |  |  |  |  |
| Jajodia et al. (1992) [6] | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |  |
| Arvindh and Irani (1994) [7] | $\longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |  |
| Kim and Kim (1995) [8] | $\bullet \longrightarrow$ |  |  | $\bullet \longrightarrow$ |  | $\bullet \longrightarrow$ |
| Vakharia and Chang (1997) [9] |  | $\bullet \longrightarrow$ |  |  |  |  |
| Liang and Zolfaghari (1999) [10] |  | $\bullet \longrightarrow$ |  |  |  |  |
| Wang et al. (2001) [11] | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |
| Lozano et al. (2002) [12] |  | $\bullet \longrightarrow$ |  |  |  |  |
| Solimanpur et al. (2004) [13] |  | $\bullet \longrightarrow$ |  |  |  |  |
| Anders and Lozano (2006) [14] |  | $\bullet \longrightarrow$ |  |  |  |  |
| Tavakkoli-Moghaddam et al. (2007) [48] | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |  |
| Hu et al. (2007) [16] |  | $\bullet \longrightarrow$ |  |  |  |  |
| Chan et al. (2008) [17] | - $\longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |  |
| Tavakkoli-Moghaddam et al. (2008) [18] |  | $\bullet \longrightarrow$ |  |  |  |  |
| Mahdavi et al. (2010) [19] | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ |  | $\bullet \longrightarrow$ |  |  |
| Rafiee et al. (2011) [20] | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |  |
| Ariafar et al. (2011) [21] | $\longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |  |
| Mahdavi et al. (2013) [22] | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ |  |  |
| Shiyas and Pillai (2014) [1] | $\longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |  |
| Asl and Wong (2015) [23] | $\longrightarrow$ |  |  | $\bullet \longrightarrow$ |  | $\bullet \longrightarrow$ |
| Mehdizadeh and Rahimi (2016) [24] | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |  |
| Ghosh et al. (2016) [25] |  | $\bullet \longrightarrow$ |  |  |  |  |
| Derakhshan Asl, Wong (2017) [26] | $\bullet \longrightarrow$ |  |  | $\bullet \longrightarrow$ |  | $\bullet \longrightarrow$ |
| Rabbani et al. (2016) [27] | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |  |
| Feng et al. (2018) [28] |  | $\bullet \longrightarrow$ |  | $\bullet \longrightarrow$ |  |  |
| Golmohammadi et al. (2019) [29] | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |  |
| Rahimi et al. (2020) [33] |  | $\bullet \longrightarrow$ |  |  |  |  |
| Mahmoodian et al. (2019) [30] | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |  |
| Danilovich and Illich (2019) [31] | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |  |
| Paramasamy (2019) [32] | $\longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |  |
| Zhao et al. (2020) [34] | - $\longrightarrow$ |  |  | $\bullet \longrightarrow$ |  |  |
| Neufeld et al. (2020) [35] |  | $\bullet \longrightarrow$ |  |  |  |  |
| Golmohammadi et al. (2020) [36] | - $\longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |  |
| Rostami et al. (2020) [37] |  | $\bullet \longrightarrow$ |  |  |  |  |
| Ayough et al. (2020) [38] | $\bullet \longrightarrow$ |  |  |  |  |  |
| Salimpour et al. (2021) [40] | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ |  |  |
| Golmohammadi et al. (2021) [41] | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ |  |  |  |  |
| Goli et al. (2021) [39] |  | $\bullet \longrightarrow$ |  |  |  |  |
| Mondal et al. (2021) [42] |  | $\bullet \longrightarrow$ |  |  |  |  |
| Razmjoei et al. (2021) [43] |  | $\bullet \longrightarrow$ |  |  |  |  |
| Hazarika (2022) [44] |  | $\bullet \longrightarrow$ |  |  |  |  |

Table 1: Continued.

| Author/Year | Intracellular | Intercellular | Unequal dimension of cells | Unequal dimension of machines | Cells rotation | Machines rotation |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Mansour et al. (2022) [45] | $\longrightarrow$ | $\bullet \longrightarrow$ |  | $\bullet \longrightarrow$ |  |  |
| Fakhrzad et al. (2022) [46] |  | $\longrightarrow$ |  |  |  |  |
| Forghani et al. (2022) [49] | $\longrightarrow$ | $\longrightarrow$ | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ |  |  |
| Present research | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ | $\bullet \longrightarrow$ |

called intercellular material flow. There is also a material flow between the machines inside each cell, called intracellular material flow. The layout of the first, second, and third cells in the workshop area is called intercellular layout, and the machine's layout inside each cell is called intracellular layout. It is also possible to rotate all machines and cells. Figure 1 schematically displays an integrated intercellular and intracellular layout.

This study examines CLPs when the cells are located in the workshop and do not go beyond the workshop area, and the machines are located inside the cells and do not go outside. In addition, the cells and machines should not overlap. As you know, in the real world, cells and machines have unequal dimensions; so, in this study, in order to get closer to reality, the dimensions of cells and machines inside each cell have been considered to be unequal. Another considered aspect in this research is that, unlike previous studies where cells and machines did not rotate, here, they can rotate in different directions. The present study suggests a new mixed nonlinear mathematical model for CLPs. Because the proposed model is nonlinear, to solve small CLPs using GAMS software, the model was linearized, and the results were compared with the ICA results.

Since CLPs are NP-hard, we used ICA and other metaheuristic algorithms like PSO and GA to solve large-scale problems. Finally, the results of ICA were compared with the results of the two other algorithms (PSO and GA).
3.1. Assumptions. In this research, a new mixed nonlinear mathematical programming model is proposed to solve intracellular and intercellular layout problems with unequal dimensions for cells and machines. The assumptions of the proposed mathematical model are as follows:
(1) Manufacturing cells should be enclosed inside the workshop with exact dimensions.
(2) Location of the cells inside the workshop is not predetermined.
(3) Dimensions of the cells and machines are known and not equal (i.e., it is not an assignment problem).
(4) The cells are not located over each other and do not overlap.
(5) The machines used to produce various parts are enclosed inside the cells.
(6) The machines are not located over each other and do not overlap.
(7) Structural cells can rotate.
(8) Machines can also rotate.
(9) Material entry and exit points are always in the center of the cells and machines.

### 3.2. Notations

### 3.2.1. Indices

$i, k$ : Cell index
$j, p$ : Machine index


Figure 1: Integrated inter-cellular and intracellular layout for three cells and ten machines.

### 3.2.2. Parameters

$W$ : Length of the workshop
$H$ : Width of the workshop
$N$ : Number of cells
$w_{i}$ : Length of the $i^{\text {th }}$ cell $i=\{1, \ldots, N\}$
$h_{i}$ : Width of the $i^{\text {th }}$ cell $i=\{1, \ldots, N\}$
$w_{\mathrm{ij}}^{\prime}$ : Length of the $j^{\text {th }}$ machine in the $i^{\text {th }}$ cell $i=\{1, . ., N\}, j=\{1, \ldots, M\}$
$h_{\mathrm{ij}}^{\prime}$ : Width of the $j^{\text {th }}$ machine in the $i^{\text {th }}$ cell $i=\{1, . ., N\}, j=\{1, \ldots, M\}$
$M_{i}$ : Number of the machines in the $i^{\text {th }}$ cell $i=\{1, . ., N\}$ $f_{\mathrm{ik}}$ : Material flow between the $i^{\text {th }}$ and $k^{\text {th }}$ cells $i=\{1, . ., N\}, k=\{1, \ldots, N\}, i \neq k$
$f_{\mathrm{ijp}}$ : Material flow between the $j^{\text {th }}$ and $p^{\text {th }}$ machines in cell $i i=\{1, . ., N\}, j=\{1, \ldots, M\}, p=\{1, \ldots, M\}, j \neq p$

### 3.2.3. Decision Variables

$x_{i}$ : Center coordinates of the $i^{\text {th }}$ cell along the $x$-axis $i=\{1, \ldots, N\}$
$y_{i}$ : Center coordinates of the $i^{\text {th }}$ cell along the $y$-axis $i=\{1, \ldots, N\}$
$x_{\mathrm{ij}}^{\prime}$ : Center coordinates of the $j^{\text {th }}$ machine in the $i^{\text {th }}$ cell along the $x$-axis $i=\{1, . ., N\}, j=\{1, \ldots, M\}$
$y_{\mathrm{ij}}^{\prime}$ : Center coordinates of the $j^{\text {th }}$ machine in the $i^{\text {th }}$ cell along the $y$-axis $i=\{1, . ., N\}, j=\{1, \ldots, M\}$
$d_{\mathrm{ik}}$ : Rectilinear distance between $i$ and $k$ cells, a function of $x_{i}$ and $y_{i} i=\{1, . ., N\}, k=\{1, \ldots, N\}, i \neq k$
$d_{\mathrm{ijp}}$ : Rectilinear distance between $j$ and $p$ machines, a function of $x_{\mathrm{ij}}^{\prime}$ and $y_{\mathrm{ij}}^{\prime} i=\{1, . ., N\}, j=\{1, \ldots, M\}, p=$ $\{1, \ldots, M\}, j \neq p$
$r_{i}=\left\{\begin{array}{l}1, \text { if cell } i \text { direction changes compared to its original direction } \\ 0, \text { otherwise }\end{array}\right.$
$i=\{1, \ldots, N\}$
$r_{\mathrm{ij}}^{\prime}=\left\{\begin{array}{l}1, \text { if machine } j \text { direction in cell } i \text { changes compared to its original direction } \\ 0, \text { otherwise }\end{array}\right.$
$i=\{1, . ., N\}, j=\{1, \ldots, M\}$
3.3. Preliminaries. This model aims to find the best layout of cells in the workshop and the best layout of machines inside each cell.
3.4. Mixed Nonlinear Programming Model. Based on the above information, the mixed nonlinear programming model for intracellular and intercellular layout problems is as follows:

$$
\begin{align*}
& f_{1}=\operatorname{Min}\left(\sum_{i=1}^{N} \sum_{k=1}^{N} f_{\mathrm{ik}} d_{\mathrm{ik}}\right)  \tag{1}\\
& =\operatorname{Min}\left(\sum_{i=1}^{N} \sum_{k=1}^{N} f_{i k}\left(\left|x_{i}-x_{k}\right|+\left|y_{i}-y_{k}\right|\right)\right), \\
& f_{2}=\operatorname{Min}\left(\sum_{i=1}^{N}\left(\sum_{j=1}^{M_{i}} \sum_{p=1}^{M_{i}} f_{\mathrm{ijp}}\left(\left|x_{\mathrm{ij}}^{\prime}-x_{\mathrm{ip}}^{\prime}\right|+\left|y_{\mathrm{ij}}^{\prime}-y_{\mathrm{ip}}^{\prime}\right|\right)\right)\right),  \tag{2}\\
& \min Z=f_{1}+f_{2} \\
& =\operatorname{Min}\left(\sum_{i=1}^{N} \sum_{k=1}^{N} f_{\mathrm{ik}}\left(\left|x_{i}-x_{k}\right|+\left|y_{i}-y_{k}\right|\right)+\sum_{i=1}^{N}\left(\sum_{j=1}^{M_{i}} \sum_{p=1}^{M_{i}} f_{\mathrm{ijp}}\left(\left|x_{\mathrm{ij}}^{\prime}-x_{\mathrm{ip}}^{\prime}\right|+\left|y_{\mathrm{ij}}^{\prime}-y_{\mathrm{ip}}^{\prime}\right|\right)\right)\right),  \tag{3}\\
& \frac{w_{i}}{2}\left(1-r_{i}\right)+\frac{h_{i}}{2} r_{i} \leq x_{i} \leq W-\left(\frac{w_{i}}{2}\left(1-r_{i}\right)+\frac{h_{i}}{2} r_{i}\right) i=1,2, \ldots, N,  \tag{4}\\
& \frac{h_{i}}{2}\left(1-r_{i}\right)+\frac{w_{i}}{2} r_{i} \leq y_{i} \leq H-\left(\frac{h_{i}}{2}\left(1-r_{i}\right)+\frac{w_{i}}{2} r_{i}\right) i=1,2, \ldots, N,  \tag{5}\\
& \frac{w_{\mathrm{ij}}^{\prime}}{2}\left(1-r_{\mathrm{ij}}^{\prime}\right)+\frac{h_{\mathrm{ij}}^{\prime}}{2} r_{\mathrm{ij}}^{\prime} \leq x_{\mathrm{ij}}^{\prime} \leq w_{i}-\left(\frac{w_{\mathrm{ij}}^{\prime}}{2}\left(1-r_{\mathrm{ij}}^{\prime}\right)+\frac{h_{\mathrm{ij}}^{\prime}}{2} r_{\mathrm{ij}}^{\prime}\right) i=1,2, \ldots, N, \quad j=1,2, \ldots, M_{i},  \tag{6}\\
& \frac{h_{\mathrm{ij}}^{\prime}}{2}\left(1-r_{\mathrm{ij}}^{\prime}\right)+\frac{w_{\mathrm{ij}}^{\prime}}{2} r_{\mathrm{ij}}^{\prime} \leq y_{\mathrm{ij}}^{\prime} \leq h_{i}-\left(\frac{h_{\mathrm{ij}}^{\prime}}{2}\left(1-r_{\mathrm{ij}}^{\prime}\right)+\frac{w_{\mathrm{ij}}^{\prime}}{2} r_{\mathrm{ij}}^{\prime}\right) i=1,2, \ldots, N, \quad j=1,2, \ldots, M_{i},  \tag{7}\\
& \left|x_{i}-x_{k}\right|+\left|y_{i}-y_{k}\right| \geq\left(\frac{w_{i}}{2}\left(1-r_{i}\right)+\frac{h_{i}}{2} r_{i}+\frac{w_{k}}{2}\left(1-r_{k}\right)+\frac{h_{k}}{2} r_{k}\right)  \tag{8}\\
& +\left(\frac{h_{i}}{2}\left(1-r_{i}\right)+\frac{w_{i}}{2} r_{i}+\frac{h_{k}}{2}\left(1-r_{k}\right)+\frac{w_{k}}{2} r_{k}\right) i, k=1,2, \ldots, N, \quad i \neq k, \\
& \left|x_{\mathrm{ij}}^{\prime}-x_{\mathrm{ip}}^{\prime}\right|+\left|y_{\mathrm{ij}}^{\prime}-y_{\mathrm{ip}}^{\prime}\right| \geq\left(\frac{w_{\mathrm{ij}}^{\prime}}{2}\left(1-r_{\mathrm{ij}}^{\prime}\right)+\frac{h_{\mathrm{ij}}^{\prime}}{2} r_{i j}^{\prime}+\frac{w_{\mathrm{ip}}^{\prime}}{2}\left(1-r_{\mathrm{ip}}^{\prime}\right)+\frac{h_{\mathrm{ip}}^{\prime}}{2} r_{\mathrm{ip}}^{\prime}\right)  \tag{9}\\
& +\left(\frac{h_{\mathrm{ij}}^{\prime}}{2}\left(1-r_{\mathrm{ij}}^{\prime}\right)+\frac{w_{\mathrm{ij}}^{\prime}}{2} r_{\mathrm{ij}}^{\prime}+\frac{h_{\mathrm{ip}}^{\prime}}{2}\left(1-r_{\mathrm{ip}}^{\prime}\right)+\frac{w_{\mathrm{ip}}^{\prime}}{2} r_{\mathrm{ip}}^{\prime}\right) i=1,2, \ldots, N, j, p=1,2, \ldots, M_{i}, \quad j \neq p, \\
& x_{i} \geq 0 i=1,2, \ldots, N,  \tag{10}\\
& y_{i} \geq 0 i=1,2, \ldots, N,  \tag{11}\\
& x_{\mathrm{ij}}^{\prime} \geq 0 i=1,2, \ldots, N, j=1,2, \ldots, M,  \tag{12}\\
& y_{\mathrm{ij}}^{\prime} \geq 0 i=1,2, \ldots, N, j=1,2, \ldots, M,  \tag{13}\\
& r_{i} \in\{0,1\} i=1,2, \ldots, N, \tag{14}
\end{align*}
$$

$$
\begin{equation*}
r_{\mathrm{ij}}^{\prime} \in\{0,1\} i=1,2, \ldots, N, j=1,2, \ldots, M \tag{15}
\end{equation*}
$$

In the proposed model, the objective function consists of two parts. The first part shows minimizing the cost of material flow between cells, and the second part states minimizing the cost of material flow between machines located inside the cell. Equation (1) indicates minimizing the sum of material flow costs between cells, and equation (2) represents minimizing the sum of material flow costs between machines. In equations (1) and (2), the cost is considered one per unit distance. Equation (3) indicates intracellular and inter-cellular cost minimization. Inequalities (4) and (5) show that each cell is enclosed inside the workshop along the $x$ - and $y$-axes. Inequalities (6) and (7) express that the machines of each cell are enclosed in the corresponding cell along the $x$ - and $y$-axes. Inequality (8) indicates the nonoverlap of cells, while Inequality (9) expresses the nonoverlap of machines inside the cells. Inequalities (10) and (11) express that the center coordinates of
the $i^{\text {th }}$ cell along the $x$ - and $y$-axes are equal to or greater than 0 . Inequalities (12) and (13) indicate that the center coordinates of the $j^{\text {th }}$ machine located in the $i^{\text {th }}$ cell, along the $x$ - and $y$-axes, are equal to or greater than 0 . Constraints (14) and (15) ensure that the decision variables, $r_{i}$ and $r_{\mathrm{ij}}^{\prime}$ are binary variables.

### 3.5. Linearization of the Mixed Nonlinear Programming

 Model. Since the proposed model is nonlinear, we should linearize the model. For this purpose, the following variables were changed in the objective function and constraints as shown in Table 2.After applying the changes in the above variables, the objective function and model constraints were transformed into equations (16)-(21):

$$
\begin{align*}
f_{1}= & \sum_{i=1}^{N} \sum_{k=1}^{N} f_{\mathrm{ik}} d_{\mathrm{ik}}=\sum_{i=1}^{N} \sum_{k=1}^{N} f_{\mathrm{ik}}\left(Z 1_{\mathrm{ik}}+Z 2_{\mathrm{ik}}+Z 3_{\mathrm{ik}}+Z 4_{\mathrm{ik}}\right),  \tag{16}\\
f_{2}= & \sum_{i=1}^{N}\left(\sum_{j=1}^{M_{i}} \sum_{p=1}^{M_{i}} f_{\mathrm{ijp}}\left(Z 5_{\mathrm{ijp}}+Z{6_{\mathrm{ijp}}}+Z 7_{\mathrm{ijp}}+Z 8_{\mathrm{ijp}}\right)\right),  \tag{17}\\
\min \mathrm{Z}= & f_{1}+f_{2},  \tag{18}\\
Z 1_{\mathrm{ik}}-Z 2_{\mathrm{ik}}+Z 3_{\mathrm{ik}}-Z 4_{\mathrm{ik}} \geq & \left(\frac{w_{i}}{2}\left(1-r_{i}\right)+\frac{h_{i}}{2} r_{i}+\frac{w_{k}}{2}\left(1-r_{k}\right)+\frac{h_{k}}{2} r_{k}\right)  \tag{19}\\
& +\left(\frac{h_{i}}{2}\left(1-r_{i}\right)+\frac{w_{i}}{2} r_{i}+\frac{h_{k}}{2}\left(1-r_{k}\right)+\frac{w_{k}}{2} r_{k}\right) i, k=1,2, \ldots, N, \quad i \neq k, \\
Z 5_{\mathrm{ijp}}-Z 6_{\mathrm{ijp}}+Z 7_{\mathrm{ijp}}-Z 8_{\mathrm{ijp}} \geq & \left(\frac{w_{\mathrm{ij}}^{\prime}}{2}\left(1-r_{\mathrm{ij}}^{\prime}\right)+\frac{h_{\mathrm{ij}}^{\prime}}{2} r_{\mathrm{ij}}^{\prime}+\frac{w_{\mathrm{ip}}^{\prime}}{2}\left(1-r_{\mathrm{ip}}^{\prime}\right)+\frac{h_{\mathrm{ip}}^{\prime}}{2} r_{\mathrm{ip}}^{\prime}\right) i=1,2, \ldots, N j, p=1,2, \ldots, M_{i}, \quad j \neq p,  \tag{20}\\
& Z 1_{\mathrm{ik}}, Z 2_{\mathrm{ik}}, Z 3_{\mathrm{ik}}, Z 4_{\mathrm{ik}}, Z 5_{\mathrm{ijp}}, Z 6_{\mathrm{ijp}}, Z 7_{\mathrm{ijp}}, Z 8_{\mathrm{ijp}} \geq 0 . \tag{21}
\end{align*}
$$

3.6. Solution Method. Ballakur and Steudel [50] described that CLPs are complex and increase in complexity when the cells and machines are unequally sized. For this reason, exact methods cannot solve the problems explained above during an acceptable computational time. Therefore, to test our proposed model, meta-heuristic algorithms should be used. To our knowledge, ICA has not been used until now in CLPs. Hence, this algorithm was implemented on CLPs, and its numerical results were compared with the numerical results of PSO and GA.

ICA creates an initial set of random solutions, known as chromosomes in GA, as particles in PSO, and as countries in ICA. Convergence rates and achieving near-optimal solutions are other advantages of ICA [51, 52].
3.6.1. Implementation of ICA to Solve the Problem. ICA was first introduced by Atashpaz-Gargari and Lucas in 2007 [51]. It is designed based on population. The original population is generated randomly, each member of which is known as a country. It steadily improves the initial answers (countries), and finally, creates the suitable answer to the optimization problem (optimal country). In the concept of optimization, some of the best members of the population that have the lowest cost are selected as imperialist countries, and the rest of the population is allocated as a colony to the imperialist country. Colonies in the original population are divided between the imperialist countries based on their power. The power of any imperialist is inversely related to the fitness (cost) of that country. Colonies and imperialist

Table 2: Changes of variables for linearization.

| Changing the variables <br> applied to the | Changing the variables <br> applied to the <br> objective function |
| :--- | ---: |
| $x_{i}-x_{k}=Z 1_{\mathrm{ik}}-Z 2_{\mathrm{ik}}$ | $x_{i}-x_{k}=Z 1_{\mathrm{ik}}+Z 2_{\mathrm{ik}}$ |
| $y_{i}-y_{k}=Z 3_{\mathrm{ik}}-Z 4_{\mathrm{ik}}$ | $y_{i}-y_{k}=Z 3_{\mathrm{ik}}+Z 4_{\mathrm{ik}}$ |
| $x_{\mathrm{ij}}^{\prime}-x_{\mathrm{ip}}^{\prime}=Z 5_{\mathrm{ijp}}-Z 6_{\mathrm{ijp}}$ | $x_{\mathrm{ij}}^{\prime}-x_{\mathrm{ip}}^{\prime}=Z 5_{\mathrm{ijp}}+Z 6_{\mathrm{ijp}}^{\prime}$ |
| $y_{\mathrm{ij}}^{\prime}-y_{\mathrm{ip}}^{\prime}=Z 7_{\mathrm{ijp}}-Z 8_{\mathrm{ijp}}$ | $y_{\mathrm{ij}}^{\prime}-y_{\mathrm{ip}}^{\prime}=Z 7_{\mathrm{ijp}}+Z 8_{\mathrm{ijp}}$ |

countries form empires $[53,54]$. The steps to implementation of ICA are as follows.
(1) Creating Initial Solutions and Forming Empires. ICA is implemented in four phases, and each phase is executed to the maximum number of repetitions. In each iteration, the amount of material flow cost is calculated for all population members and selected as the number of empires from the countries with the lowest material flow cost, as imperialist countries. The selection of the best countries in our case was made using Roulette's wheel method [55]. The remaining countries were then assigned as colonies to the imperialist country, and primary empires were created.
(2) Solution Representation. Previous studies have shown that displaying solutions as continuous is efficient and provides better solutions in terms of facility layout [23]. Therefore, in the present study, solutions were displayed in a continuous and linear manner. To implement the algorithm, in displaying shadow solutions for each decision variable, a number between 0 and 1 was mentioned. Four parts were used to represent the solution. The first part consists of 9 numbers; the first three of which are the shadow of the center coordinates of the cells along the $x$-axis
$\left(\widehat{x}_{i}, i=1, \ldots, N\right)$, the second three are the shadow of the center coordinates of the cells along the $y$-axis $\left(\widehat{y}_{i}, i=1, \ldots, N\right)$, and the last three numbers show the shadow of rotation or nonrotation of the cells in relation to their original direction $\left(\widehat{r}_{i}, i=1, \ldots, N\right)$. The second part contains the next 15 numbers; the first five numbers in this section are the shadow of the center coordinates of the machines in the first cell along the $x$-axis ( $\hat{x}_{j}, j=1, \ldots, M$ ), the second five numbers are the shadow of the center coordinates of the machines in the first cell along the $y$-axis ( $\hat{y}_{j}, j=1, \ldots, M$ ), and the last five numbers are the shadow of rotation or nonrotation of the machines in the first cell $\left(\widehat{r}_{j}, j=1, \ldots, M\right)$. The third part includes the next 12 numbers; the first four numbers in this section are the shadow of the center coordinates of the machines in the second cell along the $x$-axis ( $\hat{x}_{j}, j=1, \ldots, M$ ), the second four numbers are the shadow of the center coordinates of the machines in the second cell along the $y$-axis $\left(\hat{y}_{j}, j=1, \ldots, M\right)$, and the last four numbers are the shadow of the orientation of the machines in the second cell $\left(\widehat{r}_{j}, j=1, \ldots, M\right)$. The fourth part comprises the numbers 36 to 45 ; the first three numbers in this section are the shadow of the center coordinates of the machines in the third cell along the $x$-axis $\left(\hat{x}_{j}, j=1, \ldots, M\right)$, the second three numbers are the shadow of the center coordinates of the machines in the third cell along the $y$-axis $\left(\hat{y}_{j}, j=1, \ldots, M\right)$, and the last three numbers are the shadow of the orientation of the machines in the third cell $\left(\hat{r}_{j}, j=1, \ldots, M\right)$. Then, by inserting the obtained shadow coordinates in equations (22)-(24), we can determine the center coordinates of the machines along the $x$-axis $\left(\widehat{x}_{j}\right)$, the center coordinates of the machines along the $y$-axis ( $\widehat{y}_{j}$ ) in the corresponding cell, and their orientation relative to their original direction $\left(\hat{r}_{j}\right)$ :

$$
\begin{align*}
& x_{j}=x \min _{j}+\left(x \max _{j}-x \min _{j}\right) \widehat{x}_{j} \longrightarrow\left\{\begin{array}{l}
x \min _{j}=\frac{w_{j}}{2}\left(1-r_{j}\right)+\frac{h_{j}}{2} r_{j}, \\
x \max _{j}=W-\left(\frac{w_{j}}{2}\left(1-r_{j}\right)+\frac{h_{j}}{2} r_{j}\right),
\end{array} j=1, \ldots, M,\right.  \tag{22}\\
& y_{j}=y \min _{j}+\left(y \max _{j}-y \min _{j}\right) \hat{y}_{j} \longrightarrow\left\{\begin{array}{l}
y \min _{j}=\frac{h_{j}}{2}\left(1-r_{j}\right)+\frac{w_{j}}{2} r_{j}, \\
y \max _{j}=H-\left(\frac{h_{j}}{2}\left(1-r_{j}\right)+\frac{w_{j}}{2} r_{j}\right),
\end{array} j=1, \ldots, M,\right.  \tag{23}\\
& r_{j}=\left\{\begin{array}{ll}
0, & 0 \leq \widehat{r}_{j} \leq 0.5 \text { اکی, }, \\
1, & 0.5 \leq \widehat{r}_{j} \leq 1 \text { کا, }
\end{array} j=1, \ldots, M .\right. \tag{24}
\end{align*}
$$

In this type of solution representation, a matrix with 1 row and $3 \times \mathrm{M}$ columns is applied. The above process is also used to display the solution for the cells. For example, in displaying the solution for three cells and 12 machines,
a matrix with one row and 45 columns is utilized. Figure 2 displays the shadow of the center coordinates of machines and cells, while Figure 3 displays their actual center coordinates.


Figure 2: Displaying the shadow of the center coordinates of cells, machines, and their orientations.

| 27.449 | 21.949 | 21.949 | 16.949 | 31.349 | 25.849 | 25.849 | 31.349 | 25.849 | 0 | 40.174 | 40.174 | 40.174 | 25.693 | .. |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 83.193 | 55.693 | 0 | 0 | 1 | 27.449 | 0 | 1 | 1 | 0 | 25.906 | 25.906 | 18.906 | 18.906 | .. |
| 21.884 | 16.228 | 21.884 | 15.884 | 0 | 0 | 1 | 0 | 20.707 | 12.207 | 16.707 | 8.308 | 8.308 | 8.308 | .. |


| 1 | 1 | 1 |
| :--- | :--- | :--- |

Figure 3: Displaying the actual center coordinates of cells, machines, and their orientations.
(3) Improving the Solution Space. At this phase, the position of the imperialist countries is changed using the absorption operator. By using the revolution operator, random changes are made in the material flow cost of the imperialist and colony countries to attain better and more diverse solutions. The movement of the colonies towards the imperialist country (following a policy of absorption) is done using the following equation:

$$
\begin{equation*}
x^{\prime}=x+\beta(t-x) \tag{25}
\end{equation*}
$$

where $x^{\prime}$ is the secondary position of the colony, $x$ is the primary position of the colony, $\beta$ is the simulation coefficient, $t$ is the value of the imperialist or the objective value, and $0 \leq \beta \leq 2$. The absorption policy about colonies is shown in Figure 4.
(4) Replacement of the Colony and the Imperialist with Each Other in case of Meeting Relevant Conditions. Next, the material flow cost of the colonies is compared with the relevant imperialist country, and if the material flow cost of the colony is better than the material flow cost of the imperialist, the position of the colony and the imperialist country will be changed (the intragroup competition).

## (5) Transfer of Colonies and Imperialists to Another Empire in

 case of Meeting Relevant Conditions. At this step, empires are first evaluated using equation (26) in order to obtain the index for each empire:$$
\begin{equation*}
f(\text { Empires })=f(\text { imperialist })+\xi \operatorname{Mean}(f(\text { colonies })) \tag{26}
\end{equation*}
$$

where $f$ (imperialist) refers to the value of the imperialist objective function, Mean ( $f$ (colonies)) denotes the average value of the objective function for the colonies, and $\xi$ is the zeta coefficient, the value of which is set by parameter setting.


Figure 4: Application of absorption policy in the case of colonies.

The weakest colony is removed from the weakest empire, and accidently, moved to a more powerful empire (intergroup or inter-empire competition). If the weakest empire has no colony, the imperialist, as a colony, is transferred to another empire. Then the value of the objective function of the empires is updated, and the same process is repeated.
(6) Reporting the Best Solution Found. In this section, the best solution found in the output of MATLAB software is shown.
(7) Checking the Stop Condition. Although there are several conditions for stopping the algorithm, in this paper, reaching a certain number of iterations or reaching the maximum iteration (MaxIt) in implementing the ICA is considered a stop condition. The pseudocode of the proposed ICA is presented in Figure 5.

## 4. Results

4.1. Computational Results. Here, numerical examples as well as the results of running them with GAMS (win32 24.1.3) and MATLAB R2015 are presented.
4.1.1. Solving a Small-Scale Problem to Assess the Proposed Model's Validity. To evaluate the model's validity, a smallscale problem was solved with GAMS software. The data of this example were taken from the Asl and Wong article [23].

```
Step 1: generating the primary countries and calculating the material flow cost of the countries.
Step 2: Selecting the countries with the lowest cost as imperialists and assigning other countries to them (creation
of primary empires).
Step 3: Movement of the colonies to the imperialist country using the absorption or simulation operator follows:
x'=x+\beta(t-x)
Step 4: Applying random changes to the material flow costs of countries using the revolution operator.
Step 5: Comparing the cost of the colony countries with the cost of the respective imperialist country and
changing the status of the colony country with the imperialist country if the material flow cost of the colony
country is better than that of the imperialist country.
Step 6: Evaluating the empires using the following equation:
f}(\mathrm{ empires) =f(imperialist) + Y Mean (f (colonies))
Step 7: Removing the weakest colony from the weakest empire and transferring it to the strongest empire.
Step 8: Eliminating the powerless empires.
Step 9: If there is just one empire, go to Step 10; otherwise, go to Step 3.
Step 10: Reporting the best solution found.
Step 11: Checking the stop condition.
```

Figure 5: Pseudocode of the imperialist competitive algorithm.

This example comprised three cells and 12 machines. The cells were set in a 100 cm wide $\times 100 \mathrm{~cm}$ long workshop. Other parameters of the problem are presented in Tables 3-9.

The small-scale problem was solved by the above model in GAMS software. Since CLPs are very complex and exact solution methods cannot solve them in a reasonable computational time, we solved them using ICA, and the results were compared with those of GAMS software as shown in Table 10. The layout of cells in the workshop and the layout of machines inside each cell are shown in Figure 6.

### 4.2. Parameter Setting for Meta-Heuristic Algorithms Using

 the Taguchi Method. In meta-heuristic algorithms, several parameters must be set. Parameter setting is important because better solutions can be created using the right parameter setting. In this paper, parameter setting for ICA, PSO, and GA was performed using the Taguchi method [56]. In the Taguchi method, the factors and parameters of each algorithm are categorized into two groups of controllable and uncontrollable, and the effect of uncontrollable factors is minimized. Then, the parameters of the assumed algorithms are adjusted by considering the output of the Taguchi method, which is the main effects plot for the signal-to-noise ratios.4.2.1. Parameter Setting for the ICA. ICA has two operators and eight parameters. The following symbols are used to set the parameters of this algorithm: MaxIt, npop, nEmp, alpha, beta, PRevolution, $m u$, and zeta, where MaxIt is the highest number of iterations, $n p o p$ is the population size, $n E m p$ is the number of empires, alpha is selection pressure, beta is similarity coefficient, PRevolution is the probability of revolution operator, $m u$ is the revolution operator rate, and zeta is the average cost factor of colonies. The parameters of ICA are set according to Figures 7 and 8, and the results are presented in Table 11.
4.2.2. Parameter Setting for PSO. There are five parameters for PSO, and MaxIt, nPop, $C_{1}, C_{2}$, and $W$ symbols are applied to regulate its parameters: MaxIt is the highest number of iterations, $n P o p$ is the number of particles, $C_{1}$ is the

Table 3: Length and width of machines.

| Machines | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Length of machine $\left(w_{j}^{\prime}\right)$ | 5 | 7 | 6 | 4 | 6 | 5 | 10 | 7 | 6 | 5 | 5 | 6 |
| Width of machine $\left(h_{j}^{\prime}\right)$ | 4 | 5 | 5 | 4 | 6 | 4 | 7 | 5 | 5 | 5 | 5 | 4 |

Table 4: Length and width of manufacturing cell.

| Cells | Cell 1 | Cell 2 | Cell 3 |
| :--- | :---: | :---: | :---: |
| Length of cell $\left(w_{i}\right)$ | 35 | 30 | 25 |
| Width of cell $\left(h_{i}\right)$ | 35 | 30 | 25 |

Table 5: Number of machines inside each cell.

| Cell number | Machine number |
| :--- | :---: |
| 1 | $3-5-9-10-11$ |
| 2 | $2-4-6-7$ |
| 3 | $1-8-12$ |

Table 6: Material flow between cells.

| Intercellular material flow | 1 | 2 | 3 |
| :--- | :--- | :--- | :--- |
| 1 | 0 | 5 | 7 |
| 2 | 0 | 0 | 0 |
| 3 | 0 | 9 | 0 |

Table 7: Material flow between machines in the first cell.

| Machines | 3 | 5 | 9 | 10 | 11 |
| :--- | :---: | :---: | :---: | :---: | :---: |
| 3 | 0 | 0 | 10 | 20 | 0 |
| 5 | 20 | 0 | 0 | 10 | 0 |
| 9 | 0 | 10 | 0 | 0 | 20 |
| 10 | 20 | 0 | 20 | 0 | 0 |
| 11 | 0 | 0 | 0 | 10 | 0 |

acceleration coefficient of the best personal answer, $C_{2}$ is the acceleration coefficient of the best overall answer, and $W$ is the inertia weight coefficient. The results are presented in Table 12.

Table 8: Material flow between machines in the second cell.

| Machines | 2 | 4 | 6 | 7 |
| :--- | :---: | :---: | :---: | :---: |
| 2 | 0 | 15 | 25 | 0 |
| 4 | 40 | 0 | 0 | 15 |
| 6 | 0 | 0 | 0 | 40 |
| 7 | 10 | 40 | 15 | 0 |

Table 9: Material flow between machines in the third cell.

| Machines | 1 | 8 | 12 |
| :--- | :---: | :---: | :---: |
| 1 | 0 | 0 | 80 |
| 8 | 35 | 0 | 0 |
| 12 | 0 | 55 | 0 |

Table 10: Results of solving the mathematical model with GAMS and the ICA.

| Objective <br> function of <br> ICA | Computational <br> time of ICA | Objective <br> function of <br> GAMS | Computational <br> time of GAMS |
| :--- | :---: | :---: | :---: |
| 3880.0012 | 79.601018 | 3880.0012 | 3101.61 |



Figure 6: Layout of cells in the workshop and layout of machines inside each cell.
4.2.3. Parameter Setting for GA. GA has five parameters, and MaxIt, nPop, Pc, Pm, and Mu symbols are used to adjust these parameters: MaxIt is the highest number of iterations, $n P o p$ is the population size, $P c$ is the percentage of intersection operator for population, Pm is the percentage of mutation operator for population, and Mu is the percentage of mutation rate for selected chromosomes. The results are presented in Table 13.
4.3. Generating Random Problems. To evaluate the mixed nonlinear programming model and meta-heuristic algorithms, 30 random problems were designed in MATLAB

R2015 software and solved by (ICA), (PSO), and (GA). Then, the results were statistically analyzed using analysis of variances. The mean values of the objective function related to three meta-heuristic algorithms are shown in Figure 9 and Table 14.
4.3.1. Results of Running Random Problems. After designing the random problems, we executed them and the center coordinates of cells in the workshop and the center coordinates of machines inside each cell for the $30^{\text {th }}$ random problem after implementation of ICA, PSO, and GA were determined, and the results are shown in Tables 15-17, respectively. Also, the layout of cells in the workshop and the layout of machines inside each cell for the three metaheuristic algorithms are shown in Figures 10-12, respectively. It is worth noting that the dimensions of problems 26 to 30 are presented in Tables 18 and 19.

To demonstrate a more accurate estimate of the criteria for meta-heuristic algorithms, the mean relative percentage difference ( $\overline{\mathrm{RPD}}$ ) of layout cost and computational time for the 30 random problems created in Section 4.3 are shown in Table 20. Because each random problem was accomplished 5 times using meta-heuristic algorithms, the relative percentage difference (RPD) is calculated for the cost and computational time criteria. Then, the average values or ( $\overline{\mathrm{RPD}}$ ) of the performances were computed and applied for comparison among the three proposed algorithms. The results are presented in Table 20. The RPD index was acquired using the following equation:

$$
\begin{equation*}
\mathrm{RPD}_{\mathrm{ij}}=\frac{\text { Best }_{\mathrm{ij}}-\min _{j} \text { Best }_{\mathrm{ij}}}{\min _{j} \text { Best }_{\mathrm{ij}}} \times 100, \tag{27}
\end{equation*}
$$

where $i$ is the random problem number, and $j$ represents the algorithm used ( $j=1$ is ICA, $j=2$ is PSO, and $j=3$ is GA). Besides, Best $_{\mathrm{ij}}$ is the best value achieved from the implementation of algorithm number $j$ for random problem $i$, and $\min _{j}$ Best $_{i j}$ is the best result obtained from implementing the algorithms on random problem $i$.

Figures 13 and 14 show the ( $\overline{\mathrm{RPD}}$ ) of implementation of three meta-heuristic algorithms in terms of layout cost and computational time criteria, respectively. Figure 13 shows the relative difference of the layout cost of ICA, PSO, and GA with the symbols COICA, COPSO, and COGA, respectively. Figure 14 denotes the RPD values of ICA, PSO, and GA with the symbols TOICA, TOPSO, and TOGA, respectively. The mean symbol represents the RPD of the layout cost, and $N P$ symbol represents the number of random problems in Figures 13 and 14.
4.3.2. Normality Test of Three Meta-Heuristic Algorithms. The results of performing the normality test for the three proposed algorithms are displayed in Table 21. The results related to the significant value show that the layout cost of PSO and the computational time of PSO and GA are normal. Regarding the central limit theorem, since the number of samples is 30 , the setup cost of ICA and GA and the computational time of ICA are also normal.


Figure 7: Diagram of the main effects plot for signal-to-noise ratios for ICA.

> Main Effects Plot for Means
> Data Means
> Figure 8: Diagram of the main effects plot for means for ICA.
4.4. Analysis of Variance Test for Assuming Equality of Means of Layout Cost and Computational Time of Three MetaHeuristic Algorithms (ICA, PSO, and GA). To compare the mean layout costs of three proposed meta-heuristic
algorithms using the analysis of variance (ANOVA) test, four conditions must be met: samples from each group or community should have a normal distribution, samples from each group or community should be random, the three
Table 11: Parameter setting results for (ICA).

| Factor name | MaxIt | nPop | nEmp | Alpha | Beta | PRevolution | Mu | Zeta |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Factor description | Maximum iteration | Population size | Number of empires | Selection pressure | Similarity coefficient | Probability of revolution operator | Revolution operator rates | Average cost ratio of the colony |
| Optimal value | 500 | 100 | 10 | 1 | 2 | 0.1 | 0.05 | 0.1 |
| Optimal level | Third | Second | Third | First | Second | Third | Second | Second |

Table 12: Parameter setting results for (PSO).

| Factor name | MaxIt | nPop | $\mathrm{C}_{1}$ | C | $\mathrm{C}_{2}$ |
| :--- | :---: | :---: | :---: | :---: | :---: |
| Factor | Maximum | Number of | Acceleration coefficient of the best personal | Acceleration coefficient of the best overall |  |
| description | iteration | particles | solution | solution |  |
| Optimal value | 200 | 300 | 0.5 | 1.2 |  |
| Optimal level | First | Second | First | coefficient |  |

Table 13: Parameter setting results for (GA).

| Factor name | MaxIt | nPop | Pc | $P_{m}$ |
| :--- | :---: | :---: | :---: | :---: | :---: |
| Factor description | Maximum iteration | Number of population | Percentage of cross-over operator | Percentage of mutation operator |
| Optimal value | 400 | 200 | 0.8 | Mutation rate |
| Optimal level | Third | Second | Third | 0.3 |



Figure 9: Mean values of the objective function of meta-heuristic algorithms according to sample size.
communities should be independent of each other, and the variances of the three communities should be homogeneous. Since the first three conditions were met, we used Levene's statistic to test the fourth condition, and its results are shown in Table 22. Because of the high performance of $95 \%$ confidence level, the tests were performed at this confidence level.

According to Table 22, because the significance level is greater than 0.05 , there is no significant difference between the variances of the three communities; in other words, the variances of these communities are homogeneous. Therefore, to test the equality of the means of the three communities in terms of layout cost, the ANOVA test can be used at a $95 \%$ confidence level. The analysis of variance compares the mean of multiple populations. The null hypothesis in the analysis of variance states that $\overline{\mathrm{RPD}}$ values of the three algorithms are equal according to the layout cost criterion, and there is no significant difference between the mean layout costs of the three algorithms. Hypothesis one states that the mean $\overline{\mathrm{RPD}}$ value of the three algorithms differs in terms of the layout cost criterion.

ANOVA results for assuming equality of the mean layout cost of three meta-heuristic algorithms are provided in Table 23. As shown, because the value of the significance level is greater than 0.05 , there is no significant difference between the mean layout cost of the three communities, and the assumption of equality of means at $95 \%$ confidence level is accepted.

To suppose the equality of the mean computational time of the three communities, the above three conditions are met; to test the fourth condition, we used Levene's statistic (Table 24).

Because the significance level is less than 0.05 , the null hypothesis is rejected; so, the variances of three communities or three meta-heuristic algorithms are not equal. The results of the corresponding ANOVA are given in Table 25. As shown, since the significance level is less than 0.05 , the null hypothesis is rejected (i.e., a significant difference exists
between the mean computational times of the three communities). Therefore, the Tukey test should be executed to check the possible inter-group differences. The results of the Tukey test in Table 26 confirm that the mean computational time of all the three communities is different.

Since the variances are not homogeneous, the validity of the ANOVA test may be questioned. Therefore, Tamhane's T2 test was used and the results are displayed in Table 27. Fortunately, Tamhane's T2 test results manifested the previous results; i.e. the mean computational time of the three meta-heuristic algorithms is different significantly.

A comparison of the mean computational time of the three proposed meta-heuristic algorithms is shown in Figure 15 . Numbers 1,2 , and 3 on the $x$-axis represent ICA, PSO, and GA, respectively. The mean computational time of ICA is much less than that of the other two algorithms. Therefore, based on the numerical results achieved from the ANOVA, it is obvious that ICA has much better results in terms of computational time comparing to the other two algorithms.
4.5. Discussion. In this paper, we first solved a small-scale problem with GAMS software to evaluate the model validity. Then, we compared the results of GAMS software with the results acquired from ICA. Numerical results presented the validity of the model as well as the efficiency of the proposed algorithm. Next, parameter settings for meta-heuristic algorithms were executed using the Taguchi method. In the next step, 30 random problems were created using MATLAB R2015 and performed by three metaheuristic algorithms. After designing and implementing random problems with ICA, PSO, and GA, the center coordinates of the cells and machines were determined. To demonstrate a more accurate approximation of the criterion for meta-heuristic algorithms, we determined the ( $\overline{\mathrm{RPD}}$ ) values of layout cost and computational time. Also, the ( $\overline{\mathrm{RPD}})$ results of the three meta-heuristic algorithms in terms of layout cost and computational time criterion were
Table 14: Mean values of the objective function obtained from three meta-heuristic algorithms.

| Problem number | $N \times M$ | ICA |  | PSO |  | GA |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Objective function | Computational times | Objective function | Computational times | Objective function | Computational times |
| 1 | $3 \times 12$ | 2849.80 | 76.23 | 2768.62 | 221.14 | 2750.32 | 132.40 |
| 2 | $3 \times 12$ | 2659.08 | 74.98 | 2679.66 | 216.98 | 2632.20 | 130.13 |
| 3 | $3 \times 10$ | 2037.72 | 72.68 | 1996.7 | 205.33 | 2072.60 | 123.96 |
| 4 | $3 \times 10$ | 1917.26 | 73.56 | 1923.55 | 205.78 | 1933.93 | 124.43 |
| 5 | $3 \times 15$ | 2942.28 | 79.31 | 2971.85 | 243.38 | 3060.59 | 149.71 |
| 6 | $3 \times 15$ | 3451.31 | 79.45 | 3407.67 | 238.22 | 3388.70 | 146.38 |
| 7 | $3 \times 16$ | 3699.79 | 81.80 | 3658.51 | 257.32 | 3725.47 | 152.69 |
| 8 | $3 \times 16$ | 4325.25 | 80.89 | 4313.03 | 249.24 | 4133.24 | 155.19 |
| 9 | $3 \times 13$ | 1781.41 | 78.24 | 1795.53 | 227.47 | 1835.23 | 135.48 |
| 10 | $3 \times 13$ | 3327.71 | 77.63 | 3204.45 | 225.67 | 3284.96 | 136.20 |
| 11 | $4 \times 12$ | 1959.2 | 92.70 | 1969.3 | 257.33 | 2061.4 | 154.37 |
| 12 | $4 \times 12$ | 1991.82 | 92.64 | 2143.08 | 263.26 | 2166.94 | 154.68 |
| 13 | $4 \times 14$ | 3595.10 | 94.09 | 3618.97 | 273.61 | 4311.67 | 162.90 |
| 14 | $4 \times 14$ | 3308.36 | 94.76 | 3352.13 | 276.02 | 3386.49 | 160.54 |
| 15 | $4 \times 16$ | 3598.38 | 95.68 | 3656.24 | 279.74 | 3648.26 | 169.95 |
| 16 | $4 \times 16$ | 2778.13 | 96.37 | 2814.83 | 280.85 | 2791.70 | 170.07 |
| 17 | $4 \times 18$ | 4586.97 | 103.69 | 4631.98 | 295.27 | 4540.73 | 181.61 |
| 18 | $4 \times 18$ | 5171.15 | 104.47 | 5136.73 | 299.21 | 5169.58 | 179.99 |
| 19 | $4 \times 20$ | 5041.08 | 101.46 | 5190.46 | 306.47 | 5163.96 | 190.46 |
| 20 | $4 \times 20$ | 4877.92 | 103.95 | 4984.84 | 316.46 | 4877.04 | 195.01 |
| 21 | $5 \times 15$ | 5439.84 | 115.35 | 5398.24 | 313.87 | 5399 | 190.78 |
| 22 | $5 \times 16$ | 3920.98 | 114.36 | 3874.34 | 319.43 | 3871.86 | 192.94 |
| 23 | $5 \times 18$ | 3942.04 | 115.89 | 4139.03 | 334.21 | 3913.54 | 199.91 |
| 24 | $5 \times 18$ | 6779.99 | 116.76 | 6889.71 | 339.50 | 6581.08 | 199.85 |
| 25 | $5 \times 20$ | 4863.41 | 117.81 | 4776.85 | 343.90 | 4797.79 | 202.24 |
| 26 | $5 \times 20$ | 6449.17 | 129.546 | 6212.09 | 346.20 | 6160.17 | 206.52 |
| 27 | $3 \times 12$ | 2849.80 | 76.23 | 2768.62 | 221.14 | 2750.32 | 132.40 |
| 28 | $3 \times 12$ | 2659.08 | 74.98 | 2679.66 | 216.98 | 2632.20 | 130.13 |
| 29 | $3 \times 10$ | 2037.72 | 72.68 | 1996.7 | 205.33 | 2072.60 | 123.96 |
| 30 | $3 \times 10$ | 1917.26 | 73.56 | 1923.55 | 205.78 | 1933.93 | 124.43 |

Table 15: Center coordinates of cells in the workshop and center coordinates of machines inside each cell for the $30^{\text {th }}$ random problem using ICA.

| Workshop | Cells | 1 | 2 | 3 | 4 | 5 |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Center coordinates of cells along the $x$-axis | 79.30 | 114.30 | 114.32 | 146.80 | 84.32 |  |
|  | Center coordinates of cells along the $y$-axis | 132.60 | 132.60 | 100.10 | 132.60 | 102.60 |  |
|  | Orientation of cells comparing to the main direction | 0 | 1 | 0 | 0 | 0 |  |
| Cell | Machines | 1 | 2 | 3 | 4 | 5 |  |
| 1 | Center coordinates of machines along the $x$-axis | 20.45 | 11.45 | 16.45 | 8.95 | 14.45 |  |
|  | Center coordinates of machines along the $y$-axis | 8.79 | 8.79 | 8.79 | 8.79 | 8.79 |  |
|  | Orientation of machines comparing to the main direction | 0 | 1 | 0 | 1 | 0 |  |
| Cell | Machines | 6 | 7 | 8 | 9 | 10 | 11 |
| 2 | Center coordinates of machines along the $x$-axis | 10.55 | 7.49 | 3.55 | 4.49 | 6.05 | 7.55 |
|  | Center coordinates of machines along the $y$-axis | 21.95 | 28.95 | 21.95 | 29.45 | 21.95 | 21.95 |
|  | Orientation of machines comparing to the main direction | 0 | 1 | 0 | 0 | 1 | 0 |
| Cell | Machines | 12 | 13 | 14 | 15 |  |  |
| 3 | Center coordinates of machines along the $x$-axis | 10.68 | 10.68 | 6.18 | 5.18 |  |  |
|  | Center coordinates of machines along the $y$-axis | 23.33 | 17.83 | 18.33 | 23.33 |  |  |
|  | Orientation of machines comparing to the main direction | 0 | 0 | 0 | 1 |  |  |
| Cell | Machines | 16 | 17 | 18 | 19 | 20 |  |
| 4 | Center coordinates of machines along the $x$-axis | 11.48 | 11.48 | 10.48 | 14.98 | 6.48 |  |
|  | Center coordinates of machines along the $y$-axis | 11.15 | 9.65 | 11.15 | 11.15 | 11.15 |  |
|  | Orientation of machines comparing to the main direction | 0 | 1 | 1 | 0 | 0 |  |
| Cell | Machines | 21 | 22 | 23 | 24 | 25 |  |
| 5 | Center coordinates of machines along the $x$-axis | 21.19 | 21.19 | 21.19 | 26.19 | 21.19 |  |
|  | Center coordinates of machines along the $y$-axis | 18.51 | 23.01 | 21.51 | 18.51 | 14.51 |  |
|  | Orientation of machines comparing to the main direction | 1 | 0 | 0 | 1 | 0 |  |

TABLE 16: Center coordinates of cells in the workshop and center coordinates of machines inside each cell for the $30^{\text {th }}$ random problem using PSO.

| Workshop | Cells | 1 | 2 | 3 | 4 | 5 |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Center coordinates of cells along the $x$-axis | 108.24 | 110.33 | 140.33 | 80.33 | 140.74 |  |
|  | Center coordinates of cells along the $y$-axis | 117.56 | 82.56 | 82.56 | 82.56 | 115.06 |  |
|  | Orientation of cells comparing to the main direction | 0 | 0 | 0 | 0 | 0 |  |
| Cell | Machines | 1 | 2 | 3 | 4 | 5 |  |
| 1 | Center coordinates of machines along the $x$-axis | 11.08 | 17.08 | 15.08 | 15.08 | 20.08 |  |
|  | Center coordinates of machines along the $y$-axis | 12.76 | 12.76 | 12.76 | 11.26 | 12.76 |  |
|  | Orientation of machines comparing to the main direction | 0 | 1 | 0 | 0 | 0 |  |
| Cell | Machines | 6 | 7 | 8 | 9 | 10 | 11 |
| 2 | Center coordinates of machines along the $x$-axis | 18.49 | 19.04 | 18.49 | 18.49 | 13.98 | 18.49 |
|  | Center coordinates of machines along the $y$-axis | 22.46 | 18.34 | 15.32 | 9.32 | 15.32 | 12.32 |
|  | Orientation of machines comparing to the main direction | 0 | 0 | 1 | 1 | 1 | 1 |
| Cell | Machines | 12 | 13 | 14 | 15 |  |  |
| 3 | Center coordinates of machines along the $x$-axis | 10.57 | 14.07 | 15.07 | 10.07 |  |  |
|  | Center coordinates of machines along the $y$-axis | 9.24 | 9.24 | 13.74 | 16.74 |  |  |
|  | Orientation of machines comparing to the main direction | 0 | 1 | 0 | 0 |  |  |
| Cell | Machines | 16 | 17 | 18 | 19 | 20 |  |
| 4 | Center coordinates of machines along the $x$-axis | 8.94 | 7.94 | 9.94 | 13.44 | 8.94 |  |
|  | Center coordinates of machines along the $y$-axis | 12.21 | 12.21 | 13.01 | 13.01 | 7.01 |  |
|  | Orientation of machines comparing to the main direction | 0 | 0 | 1 | 0 | 0 |  |
| Cell | Machines | 21 | 22 | 23 | 24 | 25 |  |
| 5 | Center coordinates of machines along the $x$-axis | 18.84 | 15.34 | 13.84 | 22.84 | 17.81 |  |
|  | Center coordinates of machines along the $y$-axis | 10.63 | 11.19 | 11.19 | 11.19 | 15.63 |  |
|  | Orientation of machines comparing to the main direction | 0 | 1 | 1 | 1 | 0 |  |

Table 17: Center coordinates of cells in the workshop and center coordinates of machines inside each cell for the $30^{\text {th }}$ random problem using GA.

| Workshop | Cells | 1 | 2 | 3 | 4 | 5 |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Center coordinates of cells along the $x$-axis | 153.50 | 118.50 | 118.50 | 86 | 118.50 |  |
|  | Center coordinates of cells along the $y$-axis | 141.41 | 141.41 | 111.41 | 141.41 | 171.41 |  |
|  | Orientation of cells comparing to the main direction | 0 | 1 | 1 | 0 | 0 |  |
| Cell | Machines | 1 | 2 | 3 | 4 | 5 |  |
| 1 | Center coordinates of machines along the $x$-axis | 24.81 | 19.81 | 14.81 | 28.81 | 16.81 |  |
|  | Center coordinates of machines along the $y$-axis | 18.85 | 18.85 | 18.85 | 18.85 | 18.85 |  |
|  | Orientation of machines comparing to the main direction | 0 | 1 | 0 | 0 | 0 |  |
| Cell | Machines | 6 | 7 | 8 | 9 | 10 | 11 |
| 2 | Center coordinates of machines along the $x$-axis | 24.43 | 24.43 | 24.43 | 18.33 | 24.33 | 24.33 |
|  | Center coordinates of machines along the $y$-axis | 9.37 | 13.37 | 17.38 | 17.37 | 14.87 | 20.38 |
|  | Orientation of machines comparing to the main direction | 0 | 0 | 1 | 0 | 0 | 1 |
| Cell | Machines | 12 | 13 | 14 | 15 |  |  |
| 3 | Center coordinates of machines along the $x$-axis | 9.48 | 9.48 | 9.48 | 15.48 |  |  |
|  | Center coordinates of machines along the $y$-axis | 22.78 | 26.28 | 18.28 | 18.28 |  |  |
|  | Orientation of machines comparing to the main direction | 1 | 0 | 0 | 1 |  |  |
| Cell | Machines | 16 | 17 | 18 | 19 | 20 |  |
| 4 | Center coordinates of machines along the $x$-axis | 10.86 | 10.86 | 9.86 | 6.36 | 14.86 |  |
|  | Center coordinates of machines along the $y$-axis | 16.20 | 17.70 | 16.20 | 16.20 | 16.20 |  |
|  | Orientation of machines comparing to the main direction | 0 | 0 | 1 | 0 | 0 |  |
| Cell | Machines | 21 | 22 | 23 | 24 | 25 |  |
| 5 | Center coordinates of machines along the $x$-axis | 17.31 | 17.31 | 15.81 | 22.81 | 19.81 |  |
|  | Center coordinates of machines along the $y$-axis | 15.94 | 10.44 | 10.44 | 10.44 | 10.44 |  |
|  | Orientation of machines comparing to the main direction | 1 | 1 | 1 | 1 | 1 |  |



Figure 10: Layout of cells in the workshop and layout of machines inside each cell using ICA.
obtained. Then the ANOVA was executed for assuming the equality of means of layout cost and computational time of three meta-heuristic algorithms aiming to compare their mean layout costs. The results denoted the equality of means of layout cost of the three proposed meta-heuristic algorithms. However, the computational time results showed the inequality of the means of computational time of all the three meta-heuristic algorithms. Therefore, the


Figure 11: Layout of cells in the workshop and layout of machines inside each cell using PSO.

Tukey test was used to investigate the possible inter-group differences. According to the results, the mean computational time of all algorithms was different. Finally, the comparison of the mean computational time of the mentioned algorithms indicated that the mean computational time of ICA was much less than the other two algorithms; in other words, it demonstrated much better results in terms of computational time.


Figure 12: Layout of cells in the workshop and layout of machines inside each cell using GA.

Table 18: Length and width of cells and number of machines inside cells for problems 26 to 30 .

| Cells | Length of cell | Width of cell | Machines <br> inside each cell |
| :--- | :---: | :---: | :---: |
| P26-cell1 | 30 | 20 | $\{1,2,3,4,5\}$ |
| P26-cell2 | 25 | 30 | $\{6,7,8,9\}$ |
| P26-cell3 | 25 | 30 | $\{10,11,12\}$ |
| P26-cell4 | 30 | 40 | $\{13,14,15,16\}$ |
| P26-cell5 | 40 | 45 | $\{17,18,19,20\}$ |
| P27-cell1 | 40 | 35 | $\{1,2,3,4,5\}$ |
| P27-cell2 | 35 | 35 | $\{6,7,8,9,10\}$ |
| P27-cell3 | 25 | 30 | $\{11,12,13,14\}$ |
| P27-cell4 | 35 | 45 | $\{15,16,17,18\}$ |
| P27-cell5 | 40 | 30 | $\{19,20,21,22\}$ |
| P28-cell1 | 30 | 25 | $\{1,2,3,4\}$ |
| P28-cell2 | 35 | 40 | $\{5,6,7,8\}$ |
| P28-cell3 | 35 | 30 | $\{9,10,11,12,13\}$ |
| P28-cell4 | 20 | 35 | $\{14,15,16,17,18\}$ |
| P28-cell5 | 25 | 40 | $\{19,20,21,22\}$ |
| P29-cell1 | 35 | 40 | $\{1,2,3,4,5\}$ |
| P29-cell2 | 45 | 35 | $\{6,7,8,9,10\}$ |
| P29-cell3 | 30 | 40 | $\{1,12,13,14,15\}$ |
| P29-cell4 | 45 | 50 | $\{16,17,18,19,20\}$ |
| P29-cell5 | 45 | 30 | $\{21,22,23,24,25\}$ |
| P30-cell1 | 30 | 40 | $\{1,2,3,4,5\}$ |
| P30-cell2 | 35 | 20 | $\{6,7,8,9,10,11\}$ |
| P30-cell3 | 25 | 25 | $\{12,13,14,15\}$ |
| P30-cell4 | 25 |  | $\{2,17,18,19,20\}$ |
| P30-cell5 | 35 |  |  |

## 5. Managerial Insights and Practical Implications

Based on the research findings, a cellular layout that assumes unequal dimensions of cells and machines can be used for batch production of products. Such products have a wide variety and low to medium demand. In addition, cell layout can be used in CMSs for moving from traditional job shop layout to cellular layout. Likewise, cellular layout is used in
noncontinuous industries that have a job shop layout. In continuous layout, for example, one may consider a factory that produces four parts by machines $1,2,3$, and 4 using the same fixed procedure. In job shop layout, there is no need for the production procedure of all parts to be the same.

Other managerial insights are presented as follows:
(i) The flow of materials as an influencing factor in the links between machines in different cells must be determined suitably because the incorrect input of

Table 19: Length and width of machines inside cells for problems 26 to 30.

| Machines | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| P26-length | 9 | 1 | 8 | 1 | 3 | 9 | 3 | 3 | 1 | 7 | 1 | 6 | 4 | 3 | 9 | 3 | 8 | 3 | 4 | 3 |  |  |  |  |  |
| P26-width | 3 | 1 | 1 | 4 | 2 | 8 | 4 | 2 | 8 | 3 | 7 | 7 | 2 | 8 | 8 | 7 | 1 | 4 | 9 | 9 |  |  |  |  |  |
| P27-length | 8 | 8 | 6 | 8 | 3 | 4 | 2 | 2 | 8 | 2 | 5 | 2 | 4 | 4 | 9 | 6 | 7 | 1 | 1 | 6 | 5 | 7 |  |  |  |
| P27-width | 6 | 2 | 2 | 7 | 8 | 5 | 7 | 3 | 9 | 5 | 4 | 3 | 5 | 1 | 5 | 6 | 4 | 6 | 4 | 1 | 4 | 2 |  |  |  |
| P28-length | 5 | 3 | 8 | 4 | 6 | 9 | 7 | 3 | 8 | 5 | 3 | 1 | 8 | 4 | 1 | 1 | 2 | 4 | 2 | 4 | 6 | 1 |  |  |  |
| P28-width | 1 | 8 | 1 | 3 | 9 | 7 | 9 | 8 | 5 | 1 | 3 | 7 | 8 | 2 | 4 | 6 | 8 | 3 | 8 | 9 | 8 | 1 |  |  |  |
| P29-length | 2 | 1 | 6 | 7 | 9 | 3 | 7 | 6 | 5 | 7 | 7 | 2 | 2 | 4 | 9 | 5 | 3 | 5 | 5 | 5 | 1 | 6 | 3 | 7 | 6 |
| P29-width | 3 | 5 | 1 | 6 | 8 | 9 | 2 | 6 | 8 | 5 | 2 | 1 | 8 | 8 | 4 | 1 | 6 | 7 | 2 | 4 | 7 | 4 | 8 | 8 | 9 |
| P30-length | 7 | 7 | 1 | 1 | 3 | 4 | 6 | 4 | 4 | 6 | 2 | 4 | 4 | 5 | 5 | 1 | 1 | 6 | 6 | 7 | 5 | 5 | 6 | 9 | 6 |
| P30-width | 9 | 3 | 1 | 2 | 8 | 6 | 2 | 8 | 7 | 1 | 8 | 8 | 3 | 5 | 7 | 2 | 1 | 1 | 6 | 6 | 7 | 2 | 1 | 3 | 3 |

TAbLE 20: Mean values ( $\overline{\mathbf{R P D}}$ ) of the criteria obtained from implementation of three meta-heuristic algorithms on 30 random problems.

| Problem number | Problem size | ICA |  | PSO |  | GA |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Cost | Time | Cost | Time | Cost | Time |
| 1 | $3 \times 12$ | 7.29 | 1.38 | 4.24 | 194.08 | 3.55 | 76.07 |
| 2 | $3 \times 12$ | 4.13 | 0.90 | 4.94 | 192.01 | 3.08 | 75.12 |
| 3 | $3 \times 10$ | 3.75 | 0.57 | 1.66 | 184.11 | 5.52 | 71.52 |
| 4 | $3 \times 10$ | 1.38 | 0.44 | 1.72 | 180.97 | 2.27 | 69.89 |
| 5 | $3 \times 15$ | 4.83 | 0.06 | 5.88 | 208.53 | 9.05 | 89.79 |
| 6 | $3 \times 15$ | 21.05 | 1.24 | 7.69 | 203.54 | 7.09 | 86.52 |
| 7 | $3 \times 16$ | 8.23 | 2.74 | 7.02 | 223.17 | 8.98 | 91.76 |
| 8 | $3 \times 16$ | 8.77 | 1.27 | 8.46 | 212.03 | 3.94 | 94.29 |
| 9 | $3 \times 13$ | 4.17 | 3.07 | 4.99 | 199.66 | 7.32 | 78.15 |
| 10 | $3 \times 13$ | 8.20 | 1.36 | 4.19 | 194.64 | 6.81 | 77.83 |
| 11 | $4 \times 12$ | 4.04 | 0.75 | 4.58 | 179.69 | 9.47 | 67.78 |
| 12 | $4 \times 12$ | 3.09 | 0.57 | 10.92 | 185.76 | 12.16 | 67.91 |
| 13 | $4 \times 14$ | 4.78 | 2.006 | 5.47 | 196.62 | 25.66 | 76.60 |
| 14 | $4 \times 14$ | 3.16 | 1.43 | 4.52 | 195.50 | 5.59 | 71.87 |
| 15 | $4 \times 16$ | 4.70 | 1.35 | 6.39 | 196.31 | 6.15 | 80.02 |
| 16 | $4 \times 16$ | 3.96 | 0.90 | 5.34 | 194.05 | 4.47 | 78.06 |
| 17 | $4 \times 18$ | 4.61 | 4.89 | 5.63 | 198.68 | 3.55 | 83.71 |
| 18 | $4 \times 18$ | 5.18 | 5.24 | 4.48 | 201.41 | 5.15 | 81.31 |
| 19 | $4 \times 20$ | 2.64 | 1.73 | 5.69 | 207.26 | 5.13 | 90.95 |
| 20 | $4 \times 20$ | 3.42 | 1.23 | 3.83 | 210.43 | 1.59 | 91.29 |
| 21 | $5 \times 15$ | 5.80 | 2.74 | 4.99 | 179.57 | 5.01 | 69.93 |
| 22 | $5 \times 16$ | 5.25 | 1.25 | 4.003 | 182.81 | 3.93 | 70.83 |
| 23 | $5 \times 18$ | 3.40 | 0.35 | 8.57 | 189.39 | 2.65 | 73.11 |
| 24 | $5 \times 18$ | 7.07 | 0.70 | 8.80 | 192.81 | 3.72 | 72.37 |
| 25 | $5 \times 20$ | 5.97 | 1.76 | 4.09 | 197.05 | 4.55 | 74.69 |
| 26 | $5 \times 20$ | 9.32 | 10.60 | 5.30 | 195.59 | 4.42 | 76.34 |
| 27 | $5 \times 22$ | 3.24 | 0.68 | 1.75 | 203.29 | 11.36 | 103.01 |
| 28 | $5 \times 22$ | 3.45 | 0.58 | 5.16 | 204.43 | 4.22 | 79.71 |
| 29 | $5 \times 25$ | 3.72 | 1.94 | 5.38 | 216.79 | 2.76 | 88.68 |
| 30 | $5 \times 25$ | 4.23 | 1.44 | 5.32 | 152.66 | 4.56 | 86.64 |
| Average |  | 5.42 | 1.84 | 5.37 | 195.76 | 6.12 | 79.85 |

this parameter has a tremendous negative effect on the formation of cells and increases the layout cost.
(ii) The use of a meta-heuristic algorithm compared to exact solution methods is much better in terms of the speed of determining the layout, and managers are suggested to measure the efficiency of these algorithms in high-risk layouts while using multiple algorithms.
(iii) Cell layout technology can reduce the layout cost for many production units with continuous material flow and increase the speed of material flow.
(iv) Because CLPs that assume unequal dimensions for cells and machines are very difficult, entry and exit points of cells should be in their center to solve such problems.


FIGURE 13: RPD values of the layout cost of meta-heuristic algorithms for stochastic problems.


Figure 14: RPD values of the computational time of meta-heuristic algorithms for stochastic problems.

Table 21: Normality results of data related to the three proposed algorithms.

| Criterion type | Kolmogorov-Smirnov's test $^{\text {a }}$ |  |  | Shapiro-Wilk's test |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Statistic | Df | Sig | Statistic | Df | Sig |
| COICA | 0.220 | 30 | 0.001 | 0.679 | 30 | 0.000 |
| COPSO | 0.171 | 30 | 0.025 | 0.932 | 30 | 0.055 |
| COGA | 0.214 | 30 | 0.001 | 0.697 | 30 | 0.000 |
| TOICA | 0.267 | 30 | 0.000 | 0.649 | 30 | 0.000 |
| TOPSO | 0.124 | 30 | $0.200^{*}$ | 0.947 | 30 | 0.144 |
| TOGA | 0.142 | 30 | 0.124 | 0.937 | 30 | 0.076 |

*Lower limit significance value. ${ }^{\text {a }}$ Lilifores significance correction.

Table 22: Homogeneity results of variances of three independent communities in terms of layout cost.

| Leven statistic | Intercellular degree of <br> freedom $\left(\mathrm{Df}_{1}\right)$ | Intracellular degree of <br> freedom $\left(\mathrm{Df}_{2}\right)$ | significant level (sig.) |
| :--- | :---: | :---: | :---: | |  |  |  |  |
| :--- | :---: | :---: | :---: |
| 2.111 | 2 | 87 | 0.127 |

Table 23: ANOVA results related to the equality of means of the three communities in terms of layout cost.

| Source of <br> changes | Sum of squares | Degree of <br> freedom | Mean of <br> squares | Statistic $F$ | Significant level <br> (sig.) |
| :--- | :---: | :---: | :---: | :---: | :---: |
| Intercells | 10.610 | 2 | 5.305 |  |  |
| Intracells | 1074.984 | 87 | 12.356 | 0.429 | 0.652 |
| Total | 1085.594 | 89 |  |  |  |

Table 24: Homogeneity results of variances of three independent communities in terms of computational time.

| Leven statistic | Intercellular degree of <br> freedom $\left(\mathrm{Df}^{1}\right)$ | Intracellular degree of <br> freedom $\left(\mathrm{Df}^{2}\right)$ | Significant level (sig.) |
| :--- | :---: | :---: | :---: |

Table 25: Results of ANOVA related to the equality of means of the three communities in terms of computational time.

| Source of <br> changes | Sum of squares | Degree of <br> freedom | Mean of <br> squares | Statistic $F$ | Significant (sig.) |
| :--- | :---: | :---: | :---: | :---: | :---: |
| Intercells | 571265.895 | 2 | 285632.985 | 3212.937 | 0.000 |
| Intracells | 7734.377 | 87 | 88.901 |  |  |
| Total | 579000.273 | 89 |  |  |  |

Table 26: Tukey test results related to pairwise comparisons of computational time of three meta-heuristic algorithms.

| $F(I)$ | $F(J)$ | Mean difference | Standard deviation | Significant level | $95 \%$ confidence level |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $(I-J)$ |  |  | -199.7277 | -188.1177 |
| 1 | 2 | -193.92267 | 2.43449 | 0.000 | -83.8245 | -72.2145 |
| 2 | 3 | -78.01947 | 2.43449 | 0.000 | 188.1177 | 199.7277 |
| 2 | 1 | 193.92267 | 2.43449 | 0.000 | 110.0982 | 121.7082 |
| 3 | 3 | 115.90320 | 2.43449 | 0.000 | 72.2145 | 83.8245 |
|  | 1 | 78.01947 | 2.43449 | 0.000 | -121.7082 | -110.0982 |

(v) Consequently and in order to solve CLPs, entry and exit points of machines should be considered in their center.
(vi) The flow of materials between cells and machines can be nondeterministic; in other words, it can be probabilistic and dynamic.

Table 27: Tamhane's T2 test results related to pairwise comparisons of computational time of three meta-heuristic algorithms.

| $F(I)$ | $95 \%$ confidence <br> level | Mean difference <br> $(I-J)$ | Standard deviation | Significant level | $95 \%$ confidence level |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
| Low level |  |  |  |  |  |  |$\quad$ High level

*The values related to the mean difference are significant at 0.05 .


Figure 15: Mean computational time of three meta-heuristic algorithms.

These points can be determined in future works.

## 6. Conclusions

In this paper, a new mixed nonlinear programming model was presented for CLPs under the condition of unequal dimensions of cells and machines. Furthermore, it was assumed the cells' location in the workshop and the machines' location inside the cells are not predetermined, and the cells and machines can rotate. Based on the research findings, a cellular layout that assumes unequal dimensions of cells and machines can be used for products with batch production, and cell layout can be applied to CMSs aiming to move from traditional job shop layout to cellular layout. In the same way, cellular layout can be used in noncontinuous industries that have a job shop layout.

In brief, the following conclusions were made.
Due to nonlinearity of the developed model and failure to reach an optimal solution, the model was linearized. Then in order to assess its validity, a small-scale problem was solved by GAMS software and the results approved the model's validity.
(i) Since the problems considered in this research were continuous, (ICA), an efficient and continuous algorithm, was used to solve the small-scale problem. Comparison of the ICA and GAMS
software showed that the presented model was valid.
(ii) To evaluate the mixed nonlinear programming model and meta-heuristic algorithms, 30 random problems were designed and solved by three algorithms (ICA, PSO, and GA). Then statistical analysis was done on the results.
(iii) Similarly, the mean values of the objective function related to three meta-heuristic algorithms were determined.
(iv) The results related to the center coordinates of the cells in the workshop and the center coordinates of the machines within each cell were presented in Tables and Figures after implementation of ICA, PSO, and GA for the $30^{\text {th }}$ random problem.
(v) The ( $\overline{\mathrm{RPD}})$ values of the layout cost and computational time for all the three mentioned algorithms were determined.
(vi) Normality and variance homogeneity tests were performed before doing the ANOVA test on the results obtained from the three meta-heuristic algorithms.
(vii) Then ANOVA test results indicated no significant difference between the mean costs of the three meta-heuristic algorithms; however, there was a significant difference between the mean computational times among the three algorithms. Therefore, the Tukey test was used to test which two groups differed in terms of computational time. The Tukey test results also revealed that the mean computational times of all the three algorithms were different.
(viii) Finally, it was found that ICA had reached the optimal solution in a very short computational time compared to the other two meta-heuristic algorithms. Thus, the superiority of ICA over PSO and GA is evident.
6.1. Study Limitations. There are always limitations in any research, and the current study is no exception. The limitations of the current research are as follows:
(1) Considering rectangular shapes for the machines to solve cell layout problems.
(2) Considering the entry and exit points of machines in their center.
(3) Considering the entry and exit points of cells in their center.
(4) Not considering stochastic condition for cells and machines.
6.2. Future Works. For future investigations, other researchers can further develop this research in the following directions:
(1) The problems of cellular layout can be investigated in dynamic and probabilistic modes.
(2) ICA provides encouraging results for CLPs when the material flow is considered at the center of the cells and machines. In the future, ICA can be applied for CLPs while considering entry and exit points for cells and machines.
(3) ICA is an optimization method that can reach a globally optimal solution in less computational time. Some parts of this algorithm can be modified to reduce the total cost value.
(4) ICA can cope with different types of optimization problems. In the future, new constraints and multiobjective cases can be considered.
(5) The cells and machines in this research had a rectangular shape. In the future, irregular shapes can be considered for them.

## Data Availability

The data used to support the findings of this study are available in the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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