A Genetic Algorithm for Multi-Floor Multi-Row Facility Layout Problem

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In today's competitive business environment, companies need to manage their limited resources. The Multi-Floor Facility Layout Problem (MFLP) is an approach to managing limited space and budgets. The goal of MFLP is to determine the placement of facilities in a multi-floor building without any overlapping with the aim of minimizing costs. In this study, a Multi-floor Multi-row Facility Layout Problem (MFMRFLP) model is proposed. The proposed model presented an MFLP with a multi-row layout on each floor. Besides the layout of the facilities, the model also determines the elevator location based on both horizontal and vertical movements. Since the problem is NP-hard, a genetic algorithm (GA) was also employed to solve the problem. The proposed GA is compared against an exact method to evaluate their performances. The results demonstrate the GA's efficiency in solving the MFMRFLP within a reasonable timeframe, outperforming the exact method, particularly in large-scale instances. Specifically, the GA achieved optimal or near-optimal solutions, showing its superior performance in solving complex, real-world facility layout optimization problems.

Keywords: *Facility layout, Multi-Row Facility Layout Problem, Multi-Floor Facility Layout Problem, Genetic algorithm, nonlinear programming, material flow.*

1. INTRODUCTION

The Facility Layout Problem (FLP) is a critical issue in manufacturing management intended to find an optimal configuration for a set of facilities to minimize the overall cost associated with predicted interactions between facilities [1]. A multi-level or multi-floor layout problem (MFLP) is a type of FLP that seeks to locate the position of each facility on each factory floor without overlapping between facilities to optimize a specific objective function, usually the sum of material flow costs [2].

MFLP is a central problem in facility design, which can be a solution to issues like limited available space, high material handling costs, limited capacity of transportation means, air conditioning problems, traffic problems, and accessibility to facilities [3]. Environmental considerations and other pertinent criteria are occasionally considered when planning multi-floor structures. For example, in tropical regions, the efficiency of air-conditioning systems is expected to be higher in multi-floor buildings compared to those with a single floor. [4]. According to experts' estimations, applying improper layout is likely to result in the loss of more than 65% of the system's efficiency. Moreover, facility design and material handling account for a significant portion, ranging from 20% to 50%, of the total operating expenses in the manufacturing sector. [5]. Nowadays, due to the generally expensive land supply, the utilization of multi-floor buildings in facility layout is deemed more favorable compared to single-floor structures [6]. In many situations, the land is limited in supply or very expensive; hence, it is more efficient to construct the facility in a multi-floor building [6].

This research presents an MFLP model with a multi-row layout on each floor. In other words, each floor is used to arrange in a multi-row layout structure. The multi-row facility layout problem (MRFLP) determines the arrangement of facilities in a fixed number of rows to minimize materials transportation costs [7]. MRFLP can be applied in a variety of real-world situations. It is a common form of layout problem which may be used with most layouts and material-handling equipment [8]. The layout problem literature is rather extensive; however, more research is needed in the field. Surprisingly, the existing literature does not encompass research on MFLP with a multi-row configuration on each floor. To fill this research gap, the present work has proposed a new model.

The combination of MFLP and MRFLP to arrange the facilities in several rows on each floor of the factory is the underestimated issue of this case to achieve the optimal solution of minimum material handling costs. The main purpose of this study is to provide a Multi-Floor Multi-Row Facility Layout Problem (MFMRFLP) with unequal area facilities that intend to minimize the material flow cost between facilities and elevators or among the facilities themselves. The combination of MFLP and MRFLP has not been considered before, furthermore, the location of the elevator is another decision variable which has not been worked on before. Given the NP-Hard nature of the problem and the limited computational feasibility of exact methods in achieving timely solutions, this research introduces a Genetic Algorithm (GA) approach to address the model. In the proposed model, the location of the elevator is also a decision variable. Since the problem is NP-Hard and the exact methods are incapable of solving the model in a reasonable time, a GA approach is proposed to solve the model.. In this context, our research seeks to address the following research questions:

1. How does the incorporation of multi-row layouts within multi-floor structures contribute to improved space utilization and material flow efficiency?
2. What factors influence the optimal placement of elevators to facilitate efficient horizontal and vertical material movements in the MFMRFLP?
3. How does the proposed GA solution approach compare to traditional exact methods in terms of computational efficiency and solution quality when applied to the MFMRFLP?

Here the aim is to provide practical solutions that address the real-world complexities faced by industries operating in multi-floor environments. Through a combination of theoretical modeling and numerical examples based on real-world cases, we demonstrate the effectiveness of our approach in optimizing facility layouts and improving operational efficiency.

The rest of the paper is organized as follows. Section 2 is devoted to a literature review. Next, the proposed model and the solution approach are presented. Computational results are shown in the next section, and managerial implications are then provided. Finally, conclusions and future research directions are provided.

2. LITERATURE REVIEW

This section provides a literature review on MRFLP and MFFLP separately, including the background research conducted on FLP in the past decade. Finally, the findings and key insights from the literature review are summarized (Table 1).

2.1 Multi-Row Facility Layout Problem

There are three different types of facility layouts based on the space allocated to the facilities: one-dimensional, two-dimensional, and three-dimensional layout problems. Single Row Layout Problem (SRLP) is a one-dimensional layout problem and seeks to locate the facilities given along a single row to minimize the material handling cost [9]. Initially, the MFLP is solved using a hybrid version of the Dantzig-Wolfe decomposition algorithm [10] An inquiry into the dynamic extended row facility layout problem is conducted, considering the dynamic nature of the manufacturing process [11].

MRLP is an extension of SRLP. In the MRLP, a set of rectangular facilities, a fixed number of rows, and weights assigned to each pair of departments are considered. The objective is to determine an assignment of departments to rows and their positions within each row to minimize the total weighted sum of the center-to-center distances between all pairs of departments. This problem seeks an optimal layout solution that minimizes the overall interaction costs among departments. The MRLP addresses the complex task of efficiently organizing departments in a multi-row facility layout while considering the spatial relationships and interdependencies between them [12]. Aims to provide improved solutions to an MRLP model of prefabricated factories in the construction industry, Chen, Huy, Tiong, et al. proposed a simulation-based non-dominated sorting GA[13]. MRFLP is the primary layout problem that determines how to design facilities in order to cut down the materials transportation cost. Koosha and Safarzadeh presented a mixed-integer programming model with fuzzy constraints, and then solved it with the genetic algorithm [7]. Dickey and Hopkins used TOPAZ to provide a solution to the arrangement of buildings on a university campus [14].

Hungerländer and Anjos developed a semidefinite relaxation technique to address the discrete optimization formulation. They also demonstrated the applicability of their recent approach for the Space-Free Multi-Row Facility Layout Problem to a more general MRFLP. By constructing a semidefinite relaxation, they provided a method to efficiently tackle the optimization problem and extend the solution framework to accommodate the complexities of Multi-Row Facility Layout. This research contribution highlights the advancement in addressing layout optimization challenges by introducing a flexible approach that can handle various layout configurations and facilitate improved decision-making processes [12]. Uribe, Herran, Colmenar, et al. focused on the Multiple Row Equal Facility Layout Problem (MREFLP) and proposed a Greedy Randomized Adaptive Search Procedure (GRASP) to select the solution [15]. Miao and Xu improved A hybrid algorithm which is the superposition of GA and Tabu Search [4] is proposed to solve the MRFLP [16]. Wan, Zuo, Li, et al. proposed an MRFLP with Extra Clearances. To address this problem, they proposed an approach that combines an enhanced multi-objective greedy randomized adaptive search procedure (mGRASP) with linear programming (LP) [17].

2.2 Multi-Floor Facility Layout Problem

Recently, the significance of expanding applied models for MFLP has a wide appeal among researchers. For the first time, Moseley was a pioneering researcher, concentrating his attention on MFLP [18]. He proposed a model in which facilities were permitted to be in predetermined locations on multiple floors [19].

Meller and Bozer presented a two-step approach in which the assignment of facilities to the floors is followed by layout determination of facilities on each floor [20]. Notably, some experimenters in designing multi-floor structures assumed that all departments have different shapes in three-dimensional space for chemical plants [21],[22],[23]. Kia and colleagues presented a mixed-integer programming model for addressing the dynamic multi-floor layout design of cellular manufacturing systems (CMSs). [24]. Ahmadi and Akbari Jokar presented a multi-stage mathematical programming method for multi-floor problems, which can also be applied to single-floor problems [2]. They used five nonlinear programming models and a mixed-integer programming model in the stages. Izadinia, Eshghi, and Salmani recommended a discrete MFLP that all departments were placed without any overlapping in predetermined locations with an elevator set [25]. Prior to this research, the focus was primarily on avoiding overlaps solely in continuous space layouts. The authors addressed this limitation by proposing a model that effectively handles overlapping restrictions in predetermined locations. Additionally, the authors introduced a robust approach for incorporating interval uncertainty in material demand, which had not been previously explored in the context of multi-floor layout problems [26].

Some articles used a GA metaheuristic approach to solve MFLP. For instance, Kochhar and Heragu presented a GA-based metaheuristic method to optimize MFLP by generating block layouts [18]. Krishnan and Jaafari designed a Memetic Algorithm (MA). A comparative analysis was conducted between the proposed approach and a GA approach for large-scale test problems, as well as a LP solver solution for small-scale test problems [27]. Matsuzaki, Irohara, and Yoshimoto proposed a GA method for MFLP, considering the capacity constraint of the elevator [28]. Lee, Roh, and Jeong introduced an extension for GA to obtain solutions to MFLP featuring elevator characteristics. The proposed GA adopts a gene structure comprising a chromosome divided into five segments [29].

Insert Table 1 here.

As maintained by our investigation of the MFLP literature, and a summary is provided in Table 1, this problem has attracted a lot of interest over the past few years. However, The absence of studies on MFLP, focusing on multi-floor layouts and the arrangement of facilities across rows and floors, highlights a significant research gap warranting further investigation. MFMRFLP is an approach that can be adopted to fill the gap in the extant literature. To the best of our knowledge, there is no known published study investigating the MFMRFLP.

3. MATHEMATICAL MODELING

Here, a mathematical programming model for MFMRFLP is provided. In the proposed model, the placement of facilities in a factory is determined by minimizing the cost of material flow between facilities. The model also determined the optimal location of the elevator. Meanwhile, manufacturing the process can be performed on multiple floors, and the number of floors is also known. In this section, after expressing the assumptions, a nonlinear mathematical model is presented. Finally, the nonlinear model is converted to a linear one.

3.1 Assumptions

In this section, the mathematical model is formulated based on the following set of assumptions:

1) The travel distances between facilities are calculated using rectilinear distance.
2) The center of each facility is considered as the coordinates of located facilities in the proposed layout.
3) The origin is defined as the southwest corner of each floor.
4) All facilities have rectangular shapes and overlapping is not allowed with another and the elevator set (none of the facilities are allowed to be located in an elevator area).
5) It is assumed that the costs and time associated with material loading and unloading is disregarded.
6) A minimum travel distance or clearance between the facilities and elevators has been considered.

3.2. Notations

The related notations are illustrated below: (Measurements are in meters for distance and square meters for area)

Indices	Description
$i.j \in \{1,2,\ldots,I\}$	Facility index
$e \in \{1,2,\ldots,E\}$	Elevator index
I	Total number of facilities
E	Total number of elevators
Z	Total number of floors
Parameter	**Description**
f_{ij}	The flow between facilities i and j
d_{ij}	Minimum distance between facility i and j
Ce	Cost per unit of vertical flow among the floors
C_H	Cost per unit of horizontal flow on the floor
l_i, b_i	The dimensions of facility i, length and width, respectively
l_e, b_e	The dimensions of the elevator set, respectively, length and width
l, b	Length and width of each floor, respectively
(a_e, b_e)	Coordinates of location e for elevator set
Decision variable	**Description**
$(\mathrm{x_i}, \mathrm{y_i}, \mathrm{z_i})$	Coordinates of facility i
$(\mathrm{x_e}, \mathrm{y_e})$	Coordinates of elevator set
Z_i	Floor index that indicates the number of each floor
w_e	0 or 1 depending on the location of the elevator

3.3. Objective function

In this mathematical model, the main objective is to minimize material flow costs among facilities and between facilities and elevators. In this study, it is assumed that the total material flow costs can be determined by the summation of f_1 and f_2. When the flow between facilities is on the same floor, the condition f_1 is established. However, if it is on two different floors, the condition f_2 is set. According to the explanation above, both cost functions are formulated as follows:

$$f_1 = \sum_{i=1}^{I}\sum_{j=1}^{J} C_H f_{ij}(|x_i - x_j| + |y_i - y_j|) \tag{1}$$

$$f_2 = \sum_{i=1}^{I}\sum_{j=1}^{J} C_H f_{ij}(|x_i - \sum_{e=1}^{E} a_e w_e| + |y_i - \sum_{e=1}^{E} b_e w_e|) + C_e f_{ij}(|z_i - z_j|) + \\ C_H f_{ij}(|\sum_{e=1}^{E} a_e w_e - x_j| + |\sum_{e=1}^{E} b_e w_e - y_j|) \tag{2}$$

Therefore, for each pair of facilities, only one of the abovementioned formulations (f_1 or f_2) will be active. For better simplification and based on equations (1) and (2), the objective function is considered in the following form:

$$min \sum_{i=1}^{I}\sum_{j=1}^{J}(\delta_{1ij} f_1(x_i.x_j.y_i.y_j) + \delta_{2ij} f_2(x_i.x_j.y_i.y_j.w_e)) \tag{3}$$

3.4. Mathematical constraints

Constraints (4) and (5) are used to establish only one of the cost functions.

$$1 - \delta_{1ij} \le \left| z_i - z_j \right| \le M\delta_{2ij} \qquad \forall i, j \tag{4}$$

$$\delta_{1ij} + \delta_{2ij} = 1 \qquad \forall i, j \tag{5}$$

Constraint (6) is employed to assign the elevator to a single location.

$$\sum_{e=1}^{E} w_e = 1 \qquad \forall e \tag{6}$$

Constraints (7)-(10) are utilized to prevent any overlap of facilities and elevator sets. These constraints represent an extension of the ABSMODEL [30].

$$M\left|z_i - z_j\right| + \left|x_i - x_j\right| + M\mu_{ij} \geq \frac{1}{2}(l_i + l_j) + d_{ij} \qquad \forall i, j \qquad (7)$$

$$M\left|z_i - z_j\right| + \left|y_i - y_j\right| + M\left(1 - \mu_{ij}\right) \geq \frac{1}{2}(b_i + b_j) + d_{ij} \qquad \forall i, j \qquad (8)$$

$$\left|\sum_{e=1}^{E} a_e w_e - x_i\right| + M\mu_{ei} \geq \frac{1}{2}(l_i + l_e) + d_{ei} \qquad \forall i, e \qquad (9)$$

$$\left|\sum_{e=1}^{E} b_e w_e - y_i\right| + M\left(1 - \mu_{ei}\right) \geq \frac{1}{2}(b_i + b_e) + d_{ei} \qquad \forall i, e \qquad (10)$$

Considering the binary variables μ_{ij} and μ_{ei}, either constraint (7) or (8) is enforced. To do this, a large positive value *M* is used in equations (9) and (10).

Constraints (11)-(14) are imposed to ensure that the layout is entirely contained within the building area as shown in Figure 1. The visual depiction of constraints (13) and (14) under specific scenarios can be observed.

$$x_i \geq \frac{1}{2} l_i \qquad \forall i \qquad (11)$$

$$y_i \geq \frac{1}{2} b_i \qquad \forall i \qquad (12)$$

$$x_i \leq l - \frac{1}{2} l_i \qquad \forall i \qquad (13)$$

$$y_i \leq b - \frac{1}{2} b_i \qquad \forall i \qquad (14)$$

Insert Figure 1 here

3.5. The Proposed Linear Model

To apply an exact integer programming for solving the model, The nonlinearity of the model is first addressed, by substitution of the nonlinear parts with linear counterparts is employed. To simplify the model's complexity, we redefine the objective function as depicted in equation (15):

$$min\sum_{i=1}^{I}\sum_{j=1}^{J}(C_H f_{ij}\delta_{1ij}(p_{ij}+u_{ij})+C_H f_{ij}\delta_{2ij}(r_{ie}+s_{ie})+C_e f_{ij}\delta_{2ij}(t_{ij})+C_H f_{ij}\delta_{2ij}(v_{ej}+m_{ej}) \qquad (15)$$

Where:

$$|x_i-x_j|=p_{ij} \qquad (16) \qquad\qquad |y_i-y_j|=u_{ij} \qquad (17)$$

$$|z_i-z_j|=t_{ij} \qquad (18)$$

$$\sum_{e=1}^{E}a_e w_e = x_e \qquad (19) \qquad\qquad \sum_{e=1}^{E}b_e w_e = y_e \qquad (20)$$

$$|x_i-x_e|=r_{ie} \qquad (21) \qquad\qquad |y_i-y_e|=s_{ie} \qquad (22)$$

$$|x_e-x_j|=v_{ej} \qquad (23) \qquad\qquad |y_e-y_j|=m_{ej} \qquad (24)$$

Some new variables are defined as follows in (25) to (31):

$$\delta_{1ij}p_{ij}=pp_{ij} \qquad (25) \qquad \delta_{1ij}u_{ij}=uu_{ij} \qquad (26) \qquad \delta_{2ij}r_{ie}=rr_{ije} \qquad (27)$$

$$\delta_{2ij}s_{ie}=ss_{ije} \qquad (28) \qquad \delta_{2ij}t_{ij}=tt_{ij} \qquad (29) \qquad \delta_{2ij}v_{ej}=vv_{ije} \qquad (30)$$

$$\delta_{2ij}m_{ej}=mm_{ije} \qquad (31)$$

By incorporating equations (25)-(31) into the model, A linear objective function is able to be derived, which is represented by equation (32). By applying linearization techniques to (25)-(31) and using these new variables, the linear model will be obtained as (33) to (67).

$$min\sum_{i=1}^{I}\sum_{j=1}^{J}(f_{ij}\left(C_H(pp_{ij}+uu_{ij})+C_H(rr_{ije}+ss_{ije})+C_e(tt_{ij})+C_H(vv_{ije}+mm_{ije})\right)) \qquad (32)$$

S.t:

$$x_i-x_j\le p_{ij} \qquad \forall i,j \qquad (33)$$

$$x_i - x_j \geq \left(-p_{ij}\right) \qquad \forall i, j \qquad (34)$$

$$y_i - y_j \leq u_{ij} \qquad \forall i, j \qquad (35)$$

$$y_i - y_j \geq \left(-u_{ij}\right) \qquad \forall i, j \qquad (36)$$

$$z_i - z_j \leq t_{ij} \qquad \forall i, j \qquad (37)$$

$$z_i - z_j \geq \left(-t_{ij}\right) \qquad \forall i, j \qquad (38)$$

$$x_i - x_e \leq r_{ie} \qquad \forall i, e \qquad (39)$$

$$x_i - x_e \geq \left(-r_{ie}\right) \qquad \forall i, e \qquad (40)$$

$$y_i - y_e \leq s_{ie} \qquad \forall i, e \qquad (41)$$

$$y_i - y_e \geq \left(-s_{ie}\right) \qquad \forall i, e \qquad (42)$$

$$x_e - x_j \leq v_{ej} \qquad \forall e, j \qquad (43)$$

$$x_e - x_j \geq \left(-v_{ej}\right) \qquad \forall e, j \qquad (44)$$

$$y_e - y_j \leq m_{ej} \qquad \forall e, j \qquad (45)$$

$$y_e - y_j \geq \left(-m_{ej}\right) \qquad \forall e, j \qquad (46)$$

$$pp_{ij} \leq M\delta_{1ij} \qquad \forall i, j \qquad (47)$$

$$pp_{ij} \leq p_{ij} \qquad \forall i, j \qquad (48)$$

$$pp_{ij} \geq p_{ij} + \left(\delta_{1ij} - 1\right)M \qquad \forall i, j \qquad (49)$$

$$uu_{ij} \leq M\delta_{1ij} \qquad \forall i, j \qquad (50)$$

$$uu_{ij} \leq u_{ij} \qquad \forall i, j \qquad (51)$$

$$uu_{ij} \geq u_{ij} + \left(\delta_{1ij} - 1\right)M \qquad \forall i, j \qquad (52)$$

$$rr_{ije} \leq M\delta_{2ij} \qquad \forall i, j, e \qquad (53)$$

$$rr_{ije} \leq r_{ie} \qquad \forall i, j, e \qquad (54)$$

$$rr_{ije} \geq r_{ie} + \left(\delta_{2ij} - 1\right)M \qquad \forall i, j, e \qquad (55)$$

$$ss_{ije} \leq M\delta_{2ij} \qquad \forall i, j, e \qquad (56)$$

$$ss_{ije} \leq s_{ie} \qquad \forall i, j, e \qquad (57)$$

$$ss_{ije} \geq s_{ie} + \left(\delta_{2ij} - 1\right)M \qquad \forall i, j, e \qquad (58)$$

$$tt_{ij} \leq M\delta_{2ij} \qquad \forall i, j \qquad (59)$$

$$tt_{ij} \leq t_{ij} \qquad \forall i, j \qquad (60)$$

$$tt_{ij} \geq t_{ij} + \left(\delta_{2ij} - 1\right)M \qquad \forall i, j \qquad (61)$$

$$vv_{ije} \leq M\delta_{2ij} \qquad \forall i, j, e \qquad (62)$$

$$vv_{ije} \leq v_{ej} \qquad \forall i, j, e \qquad (63)$$

$$vv_{ije} \geq v_{ej} + \left(\delta_{2ij} - 1\right)M \qquad \forall i, j, e \qquad (64)$$

$$mm_{ije} \leq M\delta_{2ij} \qquad \forall i, j, e \qquad (65)$$

$$mm_{ije} \leq m_{ej} \qquad \forall i, j, e \qquad (66)$$

$$mm_{ije} \geq m_{ej} + \left(\delta_{2ij} - 1\right)M \qquad \forall i, j, e \qquad (67)$$

Now, to linearize constraints, we rewrite them as (68) to (73).

$$M\left(uu_{ij}\right)+\left(pp_{ij}\right)+M\mu_{ij}\geq\frac{1}{2}(l_i+l_j)+d_{ij}\qquad\forall i,j\qquad(68)$$

$$M\left(uu_{ij}\right)+\left(qq_{ij}\right)+M\left(1-\mu_{ij}\right)\geq\frac{1}{2}(b_i+b_j)+d_{ij}\qquad\forall i,j\qquad(69)$$

$$oo_{ei}+M\mu_{ei}\geq\frac{1}{2}(l_i+l_e)+d_{ei}\qquad\forall i,e\qquad(70)$$

$$kk_{ei}+M\left(1-\mu_{ei}\right)\geq\frac{1}{2}(b_i+b_e)+d_{ei}\qquad\forall i,e\qquad(71)$$

$$1-\delta_{1ij}\leq uu_{ij}\qquad\forall i,j\qquad(72)$$

$$M\delta_{2ij}\geq 2uu_{ij}-\left(z_i-z_j\right)\qquad\forall i,j\qquad(73)$$

Where:

$$\left|x_i-x_j\right|=pp_{ij}\qquad(74)\qquad\qquad\left|y_i-y_j\right|=qq_{ij}\qquad(75)$$

$$\left|z_i-z_j\right|=uu_{ij}\qquad(76)\qquad\qquad\left|x_e-x_i\right|=oo_{ie}\qquad(77)$$

$$\left|y_e-y_i\right|=kk_{ie}\qquad(78)$$

Where the model needs to include the following additional constraints:

S.t:

$$uuu_{ij}\geq z_i-z_j\qquad\forall i,j\qquad(79)$$

$$uuu_{ij}\leq\left(z_i-z_j\right)+\left(1-a_{ij}\right)M\qquad\forall i,j\qquad(80)$$

$$uuu_{ij}\leq-\left(z_i-z_j\right)+a_{ij}M\qquad\forall i,j\qquad(81)$$

$$ppp_{ij} \le \left(x_i - x_j\right) + \left(1 - \beta_{ij}\right)M \qquad \forall i, j \qquad (82)$$

$$ppp_{ij} \le -\left(x_i - x_j\right) + \beta_{ij}M \qquad \forall i, j \qquad (83)$$

$$qqq_{ij} \le \left(y_i - y_j\right) + \left(1 - \gamma_{ij}\right)M \qquad \forall i, j \qquad (84)$$

$$qqq_{ij} \le -\left(y_i - y_j\right) + \gamma_{ij}M \qquad \forall i, j \qquad (85)$$

$$ooo_{ie} \le \left(x_e - x_i\right) + \left(1 - \tau_{ei}\right)M \qquad \forall i, e \qquad (86)$$

$$ooo_{ie} \le -\left(x_e - x_i\right) + \tau_{ei}M \qquad \forall i, e \qquad (87)$$

$$kkk_{ie} \le \left(y_e - y_i\right) + \left(1 - \sigma_{ei}\right)M \qquad \forall i, e \qquad (88)$$

$$kkk_{ie} \le -\left(y_e - y_i\right) + \sigma_{ei}M \qquad \forall i, e \qquad (89)$$

$$\alpha_{ij}, \beta_{ij}, \gamma_{ij}, \tau_{ei}, \sigma_{ei} \in \left(0,1\right) \qquad (90)$$

4. NUMERICAL RESULTS AND ANALYSIS

In this section, we present the results of applying our proposed model to a simulated real-world scenario inspired by a job shop company located in Mashhad, Iran. While the test problems are designed to reflect the challenges faced by such companies in multi-floor facility layout planning, the data are generated randomly to create representative test cases for evaluating the performance of our approach. In the generation of the six test problems (small-scale, medium-scale, and large-scale problems), we establish specific conditions and constraints that reflect the characteristics of the problem under investigation. These conditions include parameters such as the dimensions of the facility layout, material flow rates, minimum distance requirements between facilities, and costs associated with vertical and horizontal material flow. With these defined conditions, we then employ a randomization method to generate problem instances that adhere to the specified constraints. The model and analyses are conducted on six defined test problems, with their respective characteristics presented in Table 2.

Insert Table 2 here

Here, a three-floor factory building with the following measurements is considered. Six test problems are defined to study the presented model. In the first example, the length and width of each floor are 20×20m^2, and for the second problem are 8×8m^2. To ensure safe and efficient material flow within the facility, a minimum clearance of 1m is maintained between all facilities. Additionally, material flow costs are incorporated into the model, with the vertical material flow cost between floors set at 40 units and the horizontal material flow cost on each floor set at 60 units for both examples. (Table 3).

Insert Table 3 here

Here, we present a GA-based solution method and compare it with the exact method. Finally, the analysis of results, including sensitivity analysis is presented.

4.1 The proposed GA

GA which was first introduced by Holland has increasingly gained in popularity in optimization during the last decade than other evolutionary computation algorithms [31]. This algorithm uses historical data about algorithm inheritance to use in the search process. Pearce, Markandya, and Barbier created the fundamental principles of the genetic algorithm [32]. The most significant characteristics of GA are efficiency, ease of programming, and exceptional robustness with regard to input data. In contrast to GA generates a group of solutions, then assesses and improves them rather than a single solution. Due to its benefit, this parallel procedure is a qualified option even for NP-hard problems [33],[34]. The approach relies on the encoding of each set of solutions into a genetic code known as a chromosome. Each chromosome represents a potential layout that includes the arrangement of facilities on multiple floors. The chromosome can be represented as a sequence of genes, where each gene corresponds to a facility and its location in the layout. The proposed chromosome structure can be represented as a sequence of genes, where each gene represents a facility location and includes information about its coordinates and its floor assignment. Each gene i.e. facility is represented by the following values: (x,y,z). x and y show the coordinates on the location map and z shows the floor. This representation allows the GA to explore layout configurations considering both the facility locations within each floor and the assignment of facilities to different floors.

To deploy GA, the following steps are followed: First, the initial population is created by generating random solutions and then evaluated by the proposed fitness function. Then, the fittest individuals are selected for producing the next generation by using cross-over and mutation operators. Finally, if the stop conditions are not met, we return to the previous step. Otherwise, the algorithm is terminated [35].

To select the chromosomes for cross-over or mutation, the fitness function is used to identify the best chromosomes and then the population is sorted based on the fitness function values, with the best solutions placed at the beginning of the population. There exist various methods for determining the probability of selecting chromosomes. In this study, we use the Boltzmann method based on equations (91) and (92) which are as follows. This method is one of the most popular methods [36].

$$p_i = e^{-\beta c_i} \qquad \beta \geq 0 \tag{91}$$

$$p_i = \frac{e^{-\beta c_i}}{\sum_{k=1}^{n_{pop}} e^{-\beta c_k}} \qquad \beta \geq 0 \tag{92}$$

Where n_{pop} is the population of the major chromosomes, p_i represents the probability associated with the selection of chromosome i as the parent, the parameter β shows the impact of the fitness function value on the probability of selecting a chromosome to make the next generation, and c_i represents the value of the fitness objective function determined for per chromosome i.

The crossover should be carried out once the chromosomes have been selected. Among the existing approaches, the uniform crossover usually demonstrates superior performance. It exhibits faster convergence towards the optimal solution compared to alternative methods such as single-point and double-point crossover, which tend to exacerbate exploration.

In comparison to traditional methods that utilize an array of bits, the proposed method employs a single-bit function. However, it is worth noting that excessive exploration can potentially result in convergence to a suboptimal local solution. This limitation is inherent to the uniform crossover method. To address this issue, a hybrid approach combining both single-point and two-point crossovers was employed. By leveraging the benefits of each method, this hybrid approach aims to overcome the shortcomings of the uniform crossover and improve the overall performance of the genetic algorithm [35]. Figure 2 shows the flowchart of the proposed GA.

To perform the crossover operation, we exchange the genes of the parents from the crossover point onwards. This step involves swapping the facility location genes between the parents' chromosomes while keeping the floor assignments intact.

As illustrated in Figure 3, crossover operators demonstrate this process effectively. Some individuals from the population are randomly selected (based on mutation rate p_m) and mutated by applying the mutation operator. The operator randomly changes the value of the gene at the mutation point. For example, if the gene represents the floor assignment, it can be mutated to a different valid floor. After performing crossover and mutation operations, the resulting individuals are added to the existing population. This merged population contains a mixture of parent individuals, offspring individuals, and mutant individuals. Finally, for each population, the best solution and its fitness value are recorded.

Insert Figure 2 here

Insert Figure 3 here

4.2 Parameter tuning of the algorithm

Parameter tuning in meta-heuristic algorithms plays a crucial role in optimizing their performance by selecting the most suitable values for their parameters. The effectiveness and efficiency of the proposed algorithm heavily rely on the appropriate selection of parameter values. The process of accurately determining these values significantly impacts the overall algorithm performance. To attain this objective, the Taguchi method, renowned for its robustness and efficiency in parameter optimization, was employed. Through systematic experimentation and analysis, the Taguchi method was utilized to fine-tune the algorithm's parameters and identify the optimal values for each parameter. This approach ensures that the algorithm operates at its peak performance, enhancing its effectiveness in solving the problem at hand [37], [38].

The performance of an algorithm is greatly impacted by the selection of its parameters, emphasizing the importance of parameter tuning in meta-heuristic algorithms. The objective of parameter tuning is to identify the optimal values for each parameter, maximizing the efficiency and effectiveness of the algorithm. This method enables systematic experimentation and analysis to efficiently adjust the parameters and identify the most favorable values. By employing the Taguchi method, the algorithm can be fine-tuned to operate at its highest level of performance, mitigating the extensive experimentation typically required to find the optimal value for each parameter [37],[38].

In the present research, the proposed GA involved the tuning of eight parameters to enhance its performance. These parameters included the maximum iteration (*Max-it*), population size (n_{pop}), crossover rate (P_c), mutation rate (P_m), and the percentage of mutation bits (M_u). The tuning process aimed to identify the optimal values for these parameters, enabling the GA to operate with improved efficiency and effectiveness. By adjusting these parameters, the algorithm's behavior and convergence properties were fine-tuned, leading to enhanced exploration and exploitation capabilities within the search space. The selection of suitable parameter values was crucial to achieve the desired balance between exploration and exploitation and to optimize the GA's ability to converge towards high-quality solutions (Table 4).

Insert Table 4 here

The objective function values were converted into non-scale data using the Relative Percentage Deviation (RPD). The RPD was computed as follows:

$$RPD = \frac{|Answer\ GA - Best\ answer\ GA|}{|Best\ answer\ GA|} \times 100$$

Initially, three levels were proposed for each parameter of the algorithm based on the structure of the Taguchi method. The adjustment of these parameters was performed using the L27 design. Each experiment was conducted 10 times, and the average values obtained from these repetitions were recorded as the final results. The MINITAB 21 software was utilized for this purpose, employing the three predefined levels in accordance with the standard

Taguchi table. The mean response graph and the Signal-to-Noise (SN) ratio graph, as presented in Figures 4 and 5, respectively, provide visual representations of the data. Table 6 illustrates the solution values (SN ratios) corresponding to different levels of each parameter, while the solution stability index indicates the extent of fluctuations observed in each parameter. Based on the SN ratio charts, the highest value in the SN ratios chart for each parameter is considered the optimal choice. Therefore, the predefined values listed in Table 5 are regarded as optimal in relation to the genetic algorithm.

Insert Table 5 here

Insert Figure 4 here

Insert Figure 5 here

4.3. Computational results and analysis

Due to the MRFLP and the MFFLP being an NP-hard problem [7], [39] and the MFMRFLP is the combination of the MRFLP and MFLP, it has been proven that the proposed model is an NP-hard problem. Therefore, exact methods may not be efficient in large-scale problems. In this research, The exact method and GA were compared, and two problems solved with each technique. Exact techniques were originally developed to facilitate the resolution of the large, and complex non-linear models whereas it takes considerable time to solve models which are performed with related software. GA helps to find optimal or near-optimal solutions to a problem. Thus, an algorithm is developed based on GA to solve large-scale instances of the problem, which is performed better in comparison with exact methods. The results are shown in Tables 6 and 7, which are solved with 0% relative error by GA. As can be seen, by increasing the number of facilities, the running time of the exact method increases significantly. For example, in the first medium-scale problem with 6 facilities and 4 candidate places for the elevator, the running time will be approximately 7200 seconds. Moreover, in the first large-scale problem with 8 facilities, the running time will be more than 18000 seconds. Consequently, it appears it is more beneficial to use GA for instances with more than 6 facilities because it has a good performance compared to the exact method.

Insert Table 6 here

Insert Table 7 here

In this section, the determination of the number of variables and constraints is performed based on the proposed linear mathematical model. Clearly, the application of exact optimization methods to solve the proposed FLP on large-scale problems is infeasible. Therefore, the utilization of meta-heuristic optimization methods is strongly advised in such cases. Since the binary variables are the most troublesome in the model, some of them were considered as parameters in the original model in GAMS to facilitate the process. Obviously, more variables make the model more difficult and time-consuming to solve. Therefore, applying fewer variables makes it possible to solve the model on large-scale problems in GAMS. The algorithm's parameters were set by the Taguchi method. The proposed GA was performed with MATLAB on a computer with a 2.40 GHz processor and 8G RAM. To solve the proposed model, two software tools, MATLAB2016a and GAMS24.1.3, were employed. The nonlinear BARON software solver in GAMS24.1.3 was utilized for solving the model.

4.4. Sensitivity Analysis

In this section, we conduct a comprehensive analysis of the sensitivity of the objective function to changes in the main parameters. The key parameters under investigation include the cost per unit of vertical material flow between floors, the cost per unit of horizontal material flow on each floor, the material flow rate, and the minimum distance between facilities. By carefully examining the impacts of varying these parameters, we aim to gain insights into their influence on the overall performance of the system.

4.4.1 Sensitivity analysis of the vertical cost

First, the sensitivity of the objective function to the vertical cost is analyzed. When the horizontal cost is considered fixed at 40 and the vertical cost increases from 5 to 20, the facilities are located on different floors. As a result, the value of the objective function reaches its maximum at 384000. However, with an increase in the vertical cost of more than 30, the value of the objective function remained the same, due to the fact that the vertical cost between floors is higher than the horizontal cost. Therefore, all facilities repeatedly are set on one floor in the optimal solution. The results are shown in Figure 6. The sensitivity analysis of the objective function to changes in the vertical cost reveals important insights into the impact of vertical material flow expenses on facility layout optimization. The results indicate that as the vertical cost increases, there is a corresponding shift in the optimal layout configuration, with facilities being strategically positioned across different floors to minimize total material flow costs. However, beyond a certain threshold, further increases in vertical cost do not significantly affect the objective function, suggesting that other factors may become dominant in determining the optimal layout.

Insert Figure 6 here

4.4.2 Sensitivity analysis of the horizontal cost

In the second sensitivity analysis, the effect of the horizontal cost on the value of the objective function is examined. The behavior of the objective function toward the increase in the horizontal cost and considering the fixed vertical cost is nonlinear. Furthermore, as this cost increases, the value of the objective function increases with a non-uniform slope. Figure 7 demonstrates the results of the sensitivity analysis. The varying slope of the objective function in response to changes in horizontal cost highlights the need for careful consideration of both horizontal and vertical material flow costs when designing efficient facility layouts.

Insert Figure 7 here

4.4.3 Sensitivity analysis of the material flow

In this analysis, the impact of the material flow on the objective function was investigated. As shown in Figure 8, increasing the material flow would cause the objective function value to increase with a constant slope. The constant slope observed in the objective function demonstrates that increasing material flow rates leads to proportional increases in total material flow costs. This finding underscores the importance of accurately estimating material flow requirements and optimizing layout configurations to minimize material handling expenses.

Insert Figure 8 here

4.4.4 Sensitivity analysis of the minimum distance between facilities

In this analysis, the effect of the minimum distance between facilities on the objective function was examined. With the increase in the minimum distance between facilities, the value of the objective function increased with a non-uniform slope. Afterward, it significantly dropped from 1267200 to zero, while the minimum distance rose from 5 to 6. As the minimum distance increased more, due to the lack of space to locate the facilities, the value of the objective function was stable at zero repeatedly (Figure 9). Analyzing the sensitivity of the objective function to changes in the minimum distance between facilities highlights the impact of spatial constraints on layout optimization. The non-uniform slope observed in the objective function reflects the varying degrees of sensitivity to changes in minimum distance, with layout configurations becoming increasingly constrained as minimum distance requirements are tightened. The abrupt drop in the objective function value at certain thresholds indicates critical points where layout feasibility is compromised due to space limitations.

Insert Figure 9 here

5. Conclusion and Future Research

In this paper, a novel multi-floor multi-row facility layout model aimed at minimizing material flow costs through optimized facility layout and elevator placement is developed. The proposed model seeks to minimize material flow costs by finding the optimal layout of facilities and the related elevator for flowing among floors. To the best of our knowledge, this is the first modeling for the MFMRFLP in the literature. Since the problem is NP-hard, exact methods are applicable to small-size problems. Here, a GA approach is proposed to solve large-scale instances. Since the computation times with the exact method are so much larger than with the GA, and GA provides optimal or near-optimal solutions, the GA shows its superiority in terms of efficiency.

In terms of contributions, this study offers a valuable methodological approach to addressing the MFMRFLP, filling a significant gap in the literature. The application of GA is promising for efficiently tackling large-scale instances of the problem, showcasing its superiority over exact methods in terms of computational efficiency.

While the proposed approach has shown efficiency in solving large-scale instances of the problem, it is crucial to acknowledge the limitations inherent in this study. Real-world scenarios may involve additional constraints and uncertainties not fully captured in the proposed model. Additionally, while the GA offers computational efficiency, it may not always guarantee the absolute optimal solution due to the complexity of the problem.

Looking ahead, future research should aim to address these limitations and further enhance the applicability of our findings. Firstly, exploring alternative metaheuristic algorithms could provide additional insights into solving the MFMRFLP efficiently while considering different constraints and objectives. Additionally, incorporating more realistic assumptions and objective functions, such as minimizing hazardous material handling or optimizing facility accessibility, would contribute to the practical relevance of our research.

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Table 1

Research	Solution Method	Formulation		layout	
		Method or model	Objective function(s)	Multi row	Multi floor
[9]	fireworks algorithm	SRLP	Min		
[10]	Dantzig-Wolfe decomposition algorithm	MFLP	Min		*
[11]	a hybrid evolutionary algorithm	RFLP	Min	*	
[12]	Global optimization	MRFLP	Min	*	
[13]	non-dominated sorting genetic algorithm	MRLP	Min	*	
[7]	genetic algorithm	MRFLP	Min	*	
[14]	TOPAZ	Campus Building Arrangement	Min	*	
[40]	Variable Neighborhood Search (VNS) algorithm	SF-MRFLP	Min	*	
[15]	GRASP	MREFLP	Min	*	
[16]	GA, tabu search[4]	MRFLP	Min	*	
[17]	mGRASP	MRLP-EC	Min , Max	*	
[19]	Spacecraft	MFLP	Min		*
[20]	Alternative approaches	MFLP	Min		*
[24]	efficient genetic algorithm	CMSs	Min		*
[3]	robust approach	MFDLP	Min		*
[26]	Robust discrete Optimization	MFLP	Min		*
[18]	genetic algorithm	MFLP	Min		*
[28]	memetic algorithm (MA)	MFLP	Min , Max		*
[27]	memetic algorithm	MFLP	Min , Max		*
[22]	MINLP	MFPLP	Min		*
[23]	TNT equivalency	MFPLP	Min		*
[21]	Exact	MILP	Min		*

Notes: SF—Space Free, MREFLP— Multiple Row Equal FLP, GRASP — Greedy Randomized Adaptive Search Procedure, MRLP-EC — Multi-Row Facility Layout Problem with Extra Clearances, mGRASP — multi-objective greedy randomized adaptive search procedure, MFLP— Multi-Floor layout planning, CMSs — Cellular Manufacturing Systems, MFDFLP — Multi-Floor Discrete FLP, MILP — Mixed Integer Linear Programming, MINLP__ Mixed Integer Non-Linear Programming, MFPLP__ Multi-floor Plant Layout Problem, GA__ genetic algorithm, MRFLP__ multi-row facility layout problem, SRLP__Single Row Layout Problem.

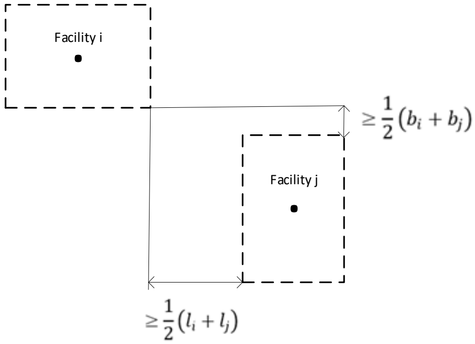

Figure 1

Table 2

Test problem number	size	Number of departments	Number of candidates for elevator	Number of possible floors
1	Small	4	4	3
2	Small	4	4	3
3	Medium	6	4	3
4	Medium	6	4	3
5	Large	6	4	3
6	Large	6	4	3

Table 3

Coordinates for elevator set	$(a_1 \times b_1)$	$(a_2 \times b_2)$	$(a_3 \times b_3)$	$(a_4 \times b_4)$
	(1×1)	(5×5)	(1×5)	(5×1)

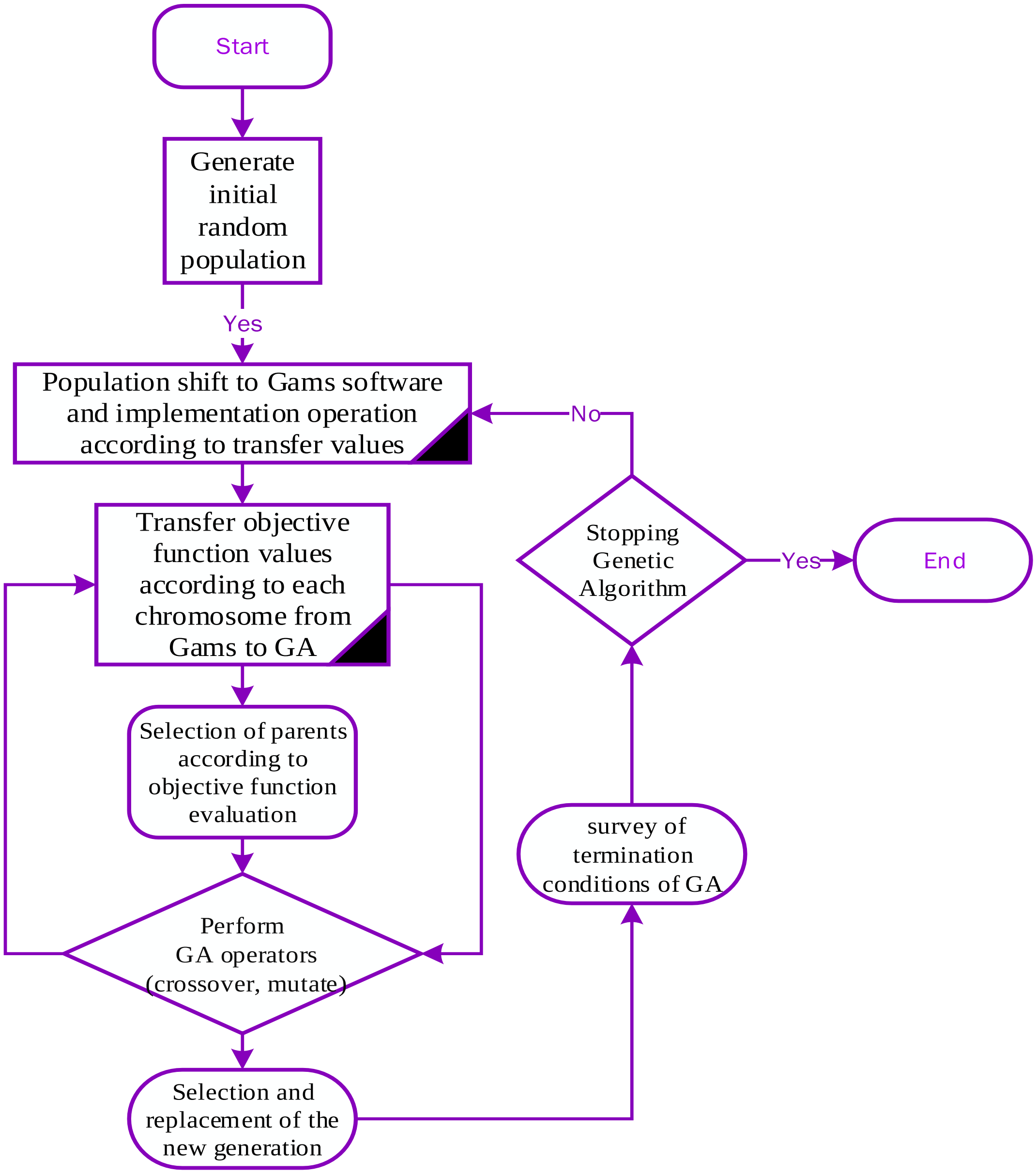
Start
Generate initial random population
Yes
Population shift to Gams software and implementation operation according to transfer values
No
Transfer objective function values according to each chromosome from Gams to GA
Stopping Genetic Algorithm
Yes
End
Selection of parents according to objective function evaluation
survey of termination conditions of GA
Perform GA operators (crossover, mutate)
Selection and replacement of the new generation

Figure 2

Facility Sequence

Sol A:

x_1A	y_1A	z_1A	x_2A	y_2A	z_2A	x_3A	y_3A	z_3A

Sol B:

x_1B	y_1B	z_1B	x_2B	y_2B	z_2B	x_3B	y_3B	z_3B

New Sol 1:

x_1A	y_1A	z_1A	x_2A	y_2A	z_2A	x_3B	y_3B	z_3B

New Sol 2:

x_1B	y_1B	z_1B	x_2B	y_2B	z_2B	x_3A	y_3A	z_3A

Figure 3

Table 4

Parameter	Levels		
	L1	L2	L3
Max-It	40	50	70
n_{pop}	25	30	35
P_c	0.6	0.8	0.9
P_m	0.1	0.2	0.3
M_u	0.02	0.05	0.1

Table 5

Parameters	optimal level
Max-It	50
n_{pop}	35
P_c	0.9
P_m	0.3
M_u	0.02

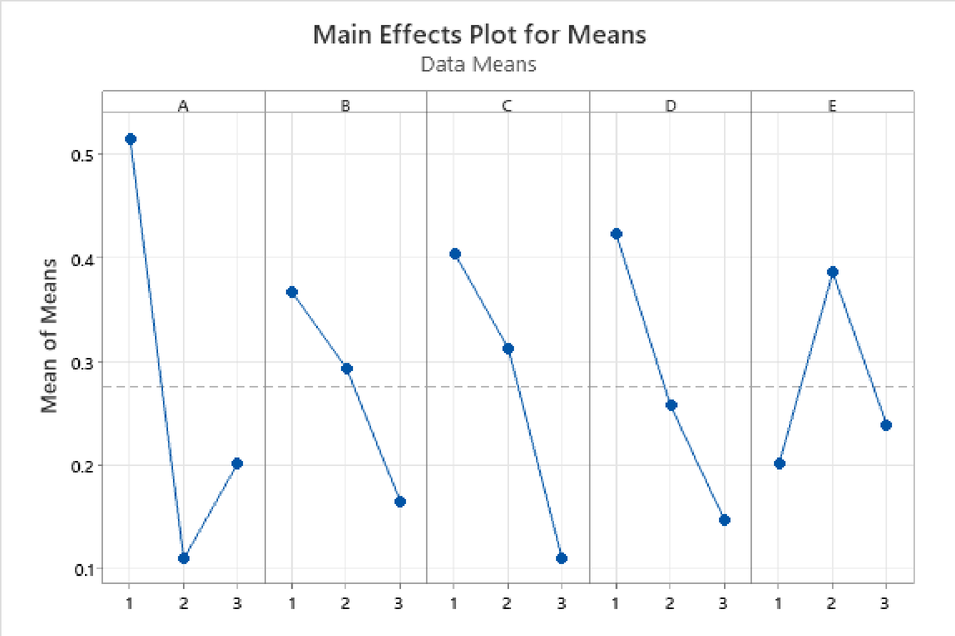

Figure 4

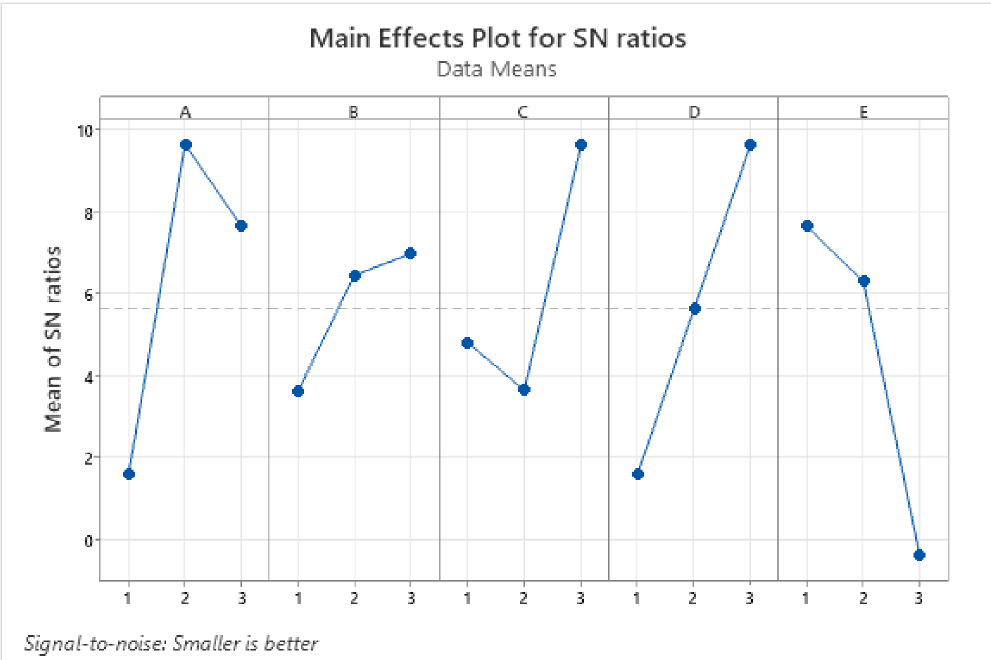

Figure 5

Table 6

			Exact Method				GA				
	Size	n	OFV	Time	x_e	y_e	OFV	Time	x_e	y_e	Gap
1	small	4	384000.000	5639.59	1	1	384000	1130	1	1	0
2	small	4	384000.000	5639.59	1	1	384000	1130	1	1	0
3	medium	6	672000.000	6652.4	1	1	672000.000	1740	1	1	0
4	medium	6	3787194.000	7258.000	1	5	3787194.000	1780	1	5	0
5	large	8	-	-	-	-	4100005.000	2532	5	5	0
6	large	8	-	-	-	-	5760000.000	2655	5	5	0

*Notes: OFV— Objective Function Value, GA—Genetic Algorithm

Table 7

		Coordinates of facility i								
	Facility	Large size			Average size			Small size		
		x_i	y_i	z_i	x_i	y_i	z_i	x_i	y_i	z_i
Exact Method	1		It		1	5	1	3	1	1
	2		did not		5	3	1	5	5	1
	3		work out		3	3	1	7	3	1
	4		In a		3	1	1	1	7	1
	5		reasonable		1	3	1			
	6		time		7	5	1			
	7									
	8									
	1		It		1	3	1	3	1	1
	2		did not		4.5	4.5	2	5	5	1
	3		work out		2.5	1	1	7	3	1
	4		In a		4.5	4.5	1	1	7	1
	5		reasonable		4.5	2.5	2			
	6		time		2.5	2.5	2			
	7									
	8									
GA	1	1	2	1	1	5	1	3	1	1
	2	3	2	1	5	3	1	5	5	1
	3	1	4	1	3	3	1	7	3	1
	4	7	4	1	3	1	1	1	7	1
	5	11	11	1	1	3	1			
	6	3	5	1	7	5	1			
	7	9	9	1						
	8	3	7	1						
	1	1	2	1	1	3	1	3	1	1
	2	3	2	1	4.5	4.5	2	5	5	1
	3	1	4	1	2.5	1	1	7	3	1
	4	3	6	2	4.5	4.5	1	1	7	1
	5	7	7	2	4.5	2.5	2			
	6	3	2	2	2.5	2.5	2			
	7	2	6	1						
	8	6	1	1						

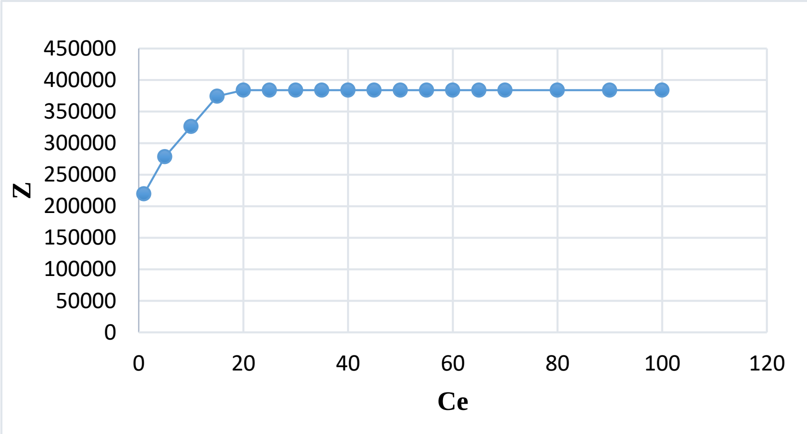

Figure 6

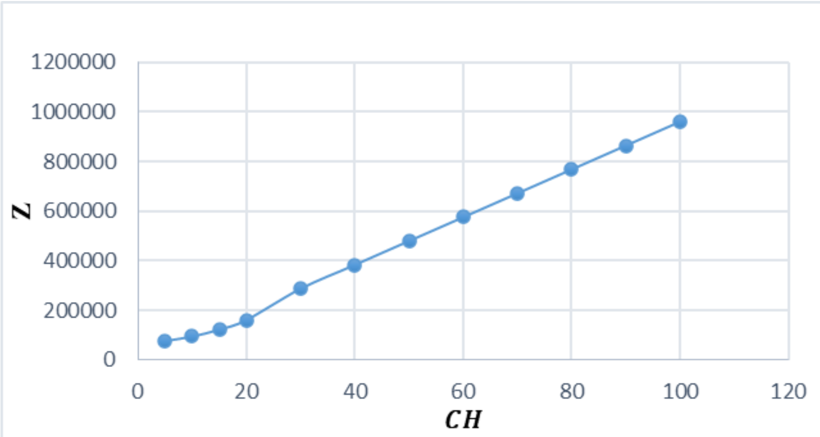

Figure 7

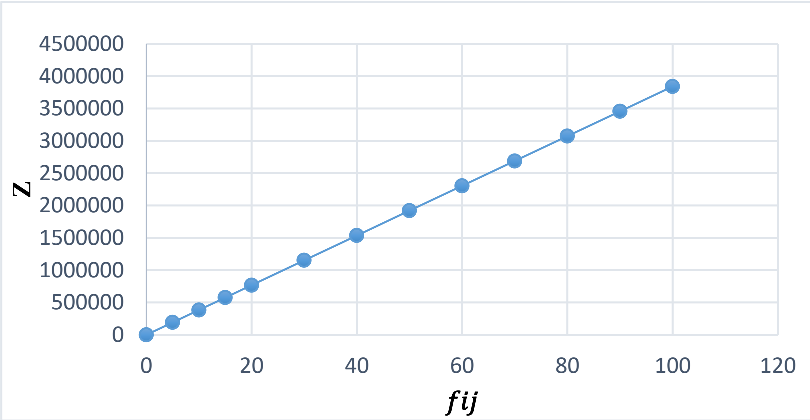

Figure 8

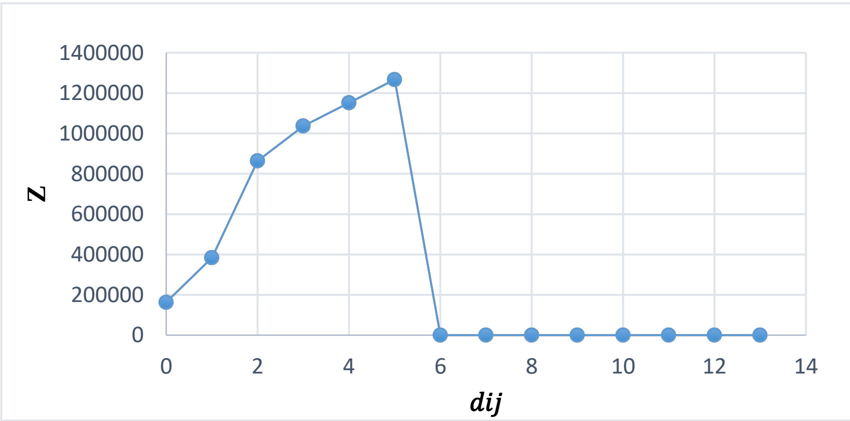

Figure 9

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