OPTIMIZATION OF SINGLE-ROW FACILITY LAYOUT DESIGN USING THE LP-METRIC METHODOLOGY

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ABSTRACT*: Material handling costs in manufacturing, constituting 15% to 70% of total manufacturing costs, can be reduced by 10% to 30% through efficient facility layout. This problem involves arranging spaces for multiple departments within a given area. Traditionally, it relied on human intuition and artistic skills, but computers excel when quantitative factors are considered. With technological advancements and increased industrial competition, facility layout's importance has grown since the mid-1990s, aiding company growth and cost reduction. We focus on the NP-hard single facility layout problem, aiming to create a mathematical model that optimally arranges departments along a single row, minimizing material handling distance while maximizing adjacency. This model supports practical problem-solving for manufacturing companies, enhancing cost efficiency. In summary, facility layout design is pivotal for manufacturing systems, with significant cost-saving potential, solvable through computerized approaches, and our work targets an optimal single plant layout solution to benefit manufacturing cost and efficiency.*

KEYWORDS*: Facility layout, Placement rating, mathematical model, distance, Lp-metric.*

1 INTRODUCTION

In recent years, the Single Row Facility Layout Problem (SRFLP) has received considerable attention, particularly as a result of the increased competition in the industry and the emergence of new technologies. Managers must find the best layout that will contribute the most to business growth and cost reduction. Researchers have aimed to achieve two objectives: firstly, to minimize the total material handling cost by multiplying the rectilinear distance by the flow matrix by the cost matrix, resulting in the final layout that generates the minimum transportation cost. Secondly, researchers have worked on maximizing adjacency, which is defined by a proximity relationship matrix that determines the strength of the relationship between each pair of installations. This need can be defined according to an international scale with the abbreviation AEIOUX, where the letter A expresses the strongest desirability of placing two facilities next to each other, up to the letter x, which expresses the undesirability. This second objective can be crucial because international standards must be followed when building a specific department or facility (Guohua & al, 2022). The SRFLP is a problem that involves finding an optimum arrangement of rectangular equipment placed along a row in order to minimize the total cost of handling and the total distance traveled. This problem is an NP-hard optimization problem (Keller & al, 2015) also known as a one-dimensional space allocation problem (Hungerländer et al, 2013). It has numerous practical applications, including in hospitals and shopping mall design plays a significant role in the industrial manufacturing sector (Meskar, 2020) (Chraibi, 2019). Several layout models have been proposed to deal with this problem (Hammad, 2016). For example, a mixed-integer nonlinear mathematical programming model is proposed to determine the optimal layout of machines in a two-dimensional area, followed by an algorithm based on the Branch and Bound approach to obtain the optimal solution of this model. However, this approach is inefficient for large problems and requires the use of meta-heuristics (Solimanpur, 2007). Semi-defined programming models and cutting plans were used to compare the global optimum solutions for the SRFLP with up to 30 installations (Anjos & al, 2008). Two implementations of taboo search have been presented, involving a 2-opt exhaustive neighborhood search and an insertion exhaustive neighbourhood search, which have improved the best solutions for 23 of the 43 instances of these references (Kothari, 2008). New mixed-integer programming models and an improved fireworks algorithm have been formulated to solve SRFLP in such a way as to minimize the handling cost, considering different kinds of constraints imposed on the placement of facilities (Liu & al, 2021) The genetic algorithm (NSGA-II) has been applied to identify the optimal layout. Taking into account the cost of handling and the proximity rate for a large number of departments, in the resolution of layout problems with uneven surfaces of an air conditioner production workshop (Wei Guo & al, 2022). The Variable neighborhood search was hybridized with ant colony algorithm optimization to solve the SRFLP, and an inverse criterion based on the modification distance measure was applied to help the ants converge to the best solution and reduce the solution space. The ant colony algorithm has been proposed to solve the single-row layout problem in flexible manufacturing systems (Solimanpur & al, 2005). In (Hungerlaender & al, 2014) ,A comparison has been made between the problem of arranging equidistant plants in a single row and linear arrangement, which are special cases of SREFLP, using the most competitive exact and heuristic approaches on multiple instances. SRFLP is an NP-complete problem (Kulkarni et al ,2015), similar to the QAP used to formulate the layout problem in (André R. S et al, 2006). To understand this notion, we need to understand the time complexity functions (TCF) of algorithms (Meskar et al, 2020). Optimal algorithms can only generate solutions for small problems, i.e., problems with 20 departments or fewer. Since finding an exact solution to the SRFLP problem is difficult, researchers have developed various heuristic techniques to obtain high-quality solutions (Zvi Drezner, 1987) (Sunderesh,1992) (Ravi Kumar,1995). More recently, other techniques have also been proposed, such as linear mixed-integer programming (LMIP) (Andres, 2006),(Andres,2009)(Robert Love,1979) semidefinite programming (Miguel F & al, 2005),(Miguel F & al, 2009)- Miguel F. Anjos and Ginger Yen, 2009) (Philipp Hungerländer,2013), branch-cut (André R. S. Amaral,2009) , (André R. S. Amaral, 2013), nonlinear programming (Sunderesh S. Heragu and Andrew,1991), and dynamic programming, (Jean-Claude,1981)]. The first attempt to solve SRFLP optimally was the branch-and-bound algorithm which provided an interesting lower bound.

The motivation of this work is to address the Facility Layout Problem (FLP) in manufacturing industries. The FLP involves the efficient arrangement of physical spaces for multiple departments within a given space, which can significantly reduce material handling costs. Traditionally, FLP has been solved using intuition and artistic skills, but this approach is limited when quantitative considerations are involved. The motivation behind this work is, therefore, to use computerized procedures to solve the FLP and to develop a mathematical model to find the optimum layout of the facilities in order to minimize the travel distance for handling and maximize contiguity.

In particular, the focus is on the Single-Row Facility Layout Problem (SFLP), which involves assigning a set of departments with equal or unequal areas to a single row. The development of a mathematical model for SFLP can help manufacturing companies improve their facility layouts, reduce costs, and increase efficiency. The use of computerized procedures over traditional methods can provide more accurate and efficient solutions to the FLP, which can help companies, grow and remain competitive in an increasingly technological and competitive industry. Adding visualization with a macro developed in Excel can provide an additional layer of value to the developed mathematical model. By visualizing the layout design on a 2D or 3D platform, manufacturing companies can get a better understanding of the optimal arrangement of facilities and can make informed decisions regarding their facility layout design. Excel is a widely used software that is accessible and user-friendly, making it an ideal platform for visualization. Thus, the addition of visualization with an Excel macro can enhance the usability and practicality of the developed mathematical model, making it more accessible and effective for manufacturing companies to implement in their facility layout design processes.

2 PROBLEM FORMULATION

In this study, we aim to tackle the challenging problem of single-row plant layout with departments of equal and unequal areas as shown in figure 1.

To achieve this goal, we will develop a mixed integer linear programming (MILP) model that will enable us to efficiently and effectively optimize the placement of departments in a single-row layout. The MILP model will take into account several important factors, such as the dimensions of each department, their inter-relationships, and the distance between them, among other things.

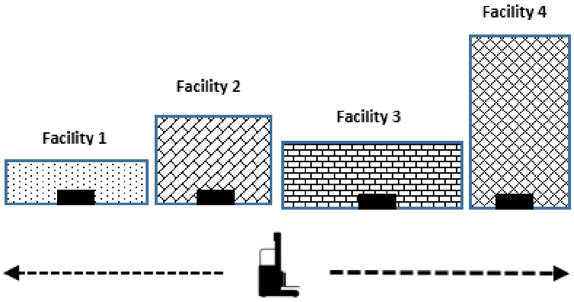

Fig. 1 SFLP Representation

Our model aims to minimize the distance travelled between departments as the first objective (OFV1) and maximize the adjacency relationship as the second objective (OFV2). To assess the impact of combining these two objective functions into a single model, we will first study each of them independently. In Part 1, we will focus on the first objective, named "min OFV1", which involves minimizing the product of the distance and flow between departments. In Part 2, we will study the second objective, named "OFV2", which involves maximizing the total closeness rating. Using the LP-metric method, we were able to convert the two-objective problem into the "min OF" single-objective optimization problem, which will be covered in Part 3.

2.1 Assumption

The main assumptions taken into account in this study are as follows:

- Departments can have equal or unequal areas.
- The orientation of the installations is considered, whether they are placed vertically or horizontally.
- The cost of transporting products between each pair of departments is proportional to the distance.
- The flow matrix is symmetric, meaning that the flow between departments i and j is the same as between departments j and i (fij = fji).
- The pick-up and drop-off points are considered from the centre of the installation.
- Distance between facilities is calculated using the Manhattan distance metric.
- The space required for machine operation is factored into the dimensions of the installation.
- The products produced in each department (machine) are assumed identical in both type and size.

2.2 Model parameters

- N = {i = 1, 2, 3,..., n}: set of all installations.
- li: length of installation i.
- wj: width of installation j.
- fij: flow between installation i and j.
- Xmax: maximum length of the row.
- Ymax: maximum width of the row.
- Rij: adjacency matrix representing the relationship between installations i and j.
- M: a large positive number used in the linear programming formulation.

2.3 Decision variables

$$v_i = \begin{cases} 1 \text{ if the length of the facility "i" is parallel} \\ \text{to the x} - \text{axis (horizontal orientation)} \\ 0 \text{ otherwise} \end{cases} \quad (1)$$

$$Zx_{ij} = \begin{cases} 1 \text{ if facility "i" is placed to the right} \\ \text{of installation j.} \\ 0 \text{ otherwise} \end{cases} \quad (2)$$

- xi: the distance on the x-axis between the center of the installation i and the vertical reference line (VRL).
- yi: the distance on the y-axis between the center of the installation i and the horizontal reference line (HRL).
- Dij: the distance between the installations i and j.
- Li: the length of the installation i on the x-axis.
- Wi: the width of the installation i on the y-axis

2.4 Constraints

This constraint specifies the dimensions of the installation along the x and y-axis. The possible orientations of the installation are illustrated in Figure 2.

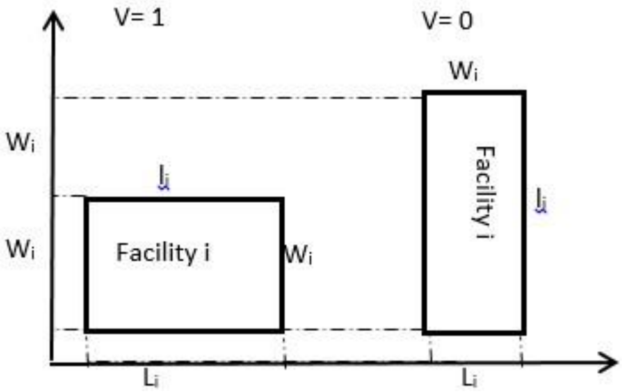

Fig. 2 Li and Wi according to installation orientation

$$L_i = l_i\ v_i + w_i\ (1 - v_i\ )\quad \forall\ i \in \mathbb{N} \tag{3}$$

$$W_i = l_i(1 - v_i\ ) + w_i\ v_i \quad \forall\ i \in \mathbb{N} \tag{4}$$

$$x_i + x_j + M(1 - Zx_{ij}) \geq \frac{L_i + L_j}{2} \quad \forall i, j \neq i \in \mathbb{N} \tag{5}$$

$$x_j + x_i + M(1 - Zx_{ji}) \geq \frac{L_i + L_j}{2} \quad \forall i, j \neq i \in \mathbb{N} \tag{6}$$

$$Zx_{ij} + Zx_{ji} = 1 \quad \forall i, j \neq i \in \mathbb{N} \tag{7}$$

Constraints 5 and 6 ensure that the distance between the two installations on the X-axis is at least half the sum of their lengths, thus avoiding any overlap. Since all installations are allocated to the same row, these constraints are necessary to ensure proper spacing. Constraint 7 stipulates that each installation must be positioned either to the right or to the left of the other installation.

$$x_i \geq \frac{L_i}{2} \quad \forall i \in \mathbb{N} \tag{8}$$

$$x_i + \frac{L_i}{2} \leq Xmax \quad \forall i \in \mathbb{N} \tag{9}$$

$$y_i \geq \frac{W_i}{2} \quad \forall i \in \mathbb{N} \tag{10}$$

$$y_i + \frac{W_i}{2} \leq Ymax \quad \forall i \in \mathbb{N} \tag{11}$$

These constraints ensure that the placements of installations do not exceed the boundaries of the row defined by the maximum length (Xmax) and the maximum width (Ymax). This means that the X and Y coordinates of each installation must not exceed their respective limits. It is important to respect these constraints to ensure that the layout is feasible and practical for implementation.

To ensure that the calculated distances are positive and meaningful, we considered four cases. Firstly, if the installation i is located to the right of the installation j, the distance between them is computed using the horizontal distance formula. Secondly, if the installation i is on the left of the installation j, the same formula is used with negative values. Thirdly, if the vertical distance between facility 'i' and the reference line is less than that of installation j, we calculate the distance using the vertical distance formula. Lastly, if the vertical distance between facility 'i' and the reference line is greater than that of installation j, we use the same formula with negative values. By considering these cases, we can accurately calculate the distance between the installations, in order to use it in our optimization model.

$$D_{ij} \geq (x_i - x_j) + (y_i - y_j) \tag{12}$$

$$D_{ij} \geq (x_j - x_i) + (y_i - y_j) \tag{13}$$

$$D_{ij} \geq (x_i - x_j) + (y_j - y_i) \tag{14}$$

$$D_{ij} \geq (x_j - x_i) + (y_j - y_i) \tag{15}$$

2.5 Objective function

As previously mentioned the model comprises two distinct objective functions, which we will analyze individually. The first objective function (OFV1) aims to minimize the distance between departments and can be expressed as follows:

$$\mathrm{OFV1} = \min \sum_{i=1}^{n} \sum_{j \neq i}^{n} f_{ij}\ D_{ij} \tag{16}$$

The second objective function, OFV2, has a qualitative aspect. Its goal is to maximize the overall proximity of the departments. Proximity is measured by the Total Placing Rating (PR), which can be calculated after the layout is selected by introducing a proximity relationship matrix (SLP) [1]. The SLP expresses the desirability of locating the facilities next to each other using an international scale, abbreviated as "AEIOUX". This scale represents the following levels of desirability: Necessary (A) represented with a score of 16, Very Important (E) represented with a score of 8, Important (I) represented with a score of 4, Ordinary Importance (O) represented with the score 2, Unimportant (U) represented with the score 0, and Undesirable (X) represented with the score -2.

OFV2 is given as follows:

$$\mathrm{OFV2} = \max \sum_{i=1}^{n} \sum_{j \neq i}^{n} b_{ij}\ R_{ij} \tag{17}$$

Where:

bij: is the ratio of the distance between facility i and facility j to the maximum distance between facilities (in our case Xmax),bij ϵ[0,1].

The variable bij represents the normalized distance between facility i and facility j, where the maximum distance between facilities (in our case Xmax) is used as the reference. The value of bij ranges between 0 and 1, with 0 indicating that the two facilities are located at the same spot and 1 indicating that they are located at the maximum distance from each other.

Table 1. Quantitative standards of bij

Distance range	b_{ij}	Distance range	b_{ij}
$0<D_{ij}\leq\frac{Xmax}{6}$	1	$\frac{Xmax}{2}<D_{ij}\leq\frac{2*Xmax}{3}$	0.4
$\frac{Xmax}{6}<D_{ij}\leq\frac{Xmax}{3}$	0.8	$\frac{2*Xmax}{3}<D_{ij}\leq\frac{5*Xmax}{6}$	0.2
$\frac{Xmax}{3}<D_{ij}\leq\frac{Xmax}{2}$	0.6	$\frac{5*Xmax}{6}<D_{ij}\leq X_{max}$	0

Table 1 provides the necessary quantitative standards for establishing the adjacency relationship. It specifies the desirability values associated with each level of proximity rating. These values are graded on a scale ranging from "A" to "X," where "A" indicates the highest desirability and "X" represents the lowest. By utilizing these desirability values, the Total Placing Rating (PR) can be calculated, which effectively reflects the overall proximity of facilities within layout.

In this study, we considered two objectives: minimizing the total distance covered by material handling and maximizing the total closeness rating. While considering the same constraints mentioned earlier, the LP-metric method combines the previous two objectives into a single objective function, as shown below in equation (18).

$$\min OF = \alpha*\frac{OFV1-OFV_{Optimal}}{OFV1_{optimal}} - \beta*\frac{OFV2-OFVoptimal}{OFV2_{optimal}} \quad (18)$$

Where: α+β=1

3 RESOLUTION APPROACH

Our mathematical model (MILP) for the single-row facility layout problem was utilized to solve a small problem instance using the library docplex in Python version 3.10 on a Windows 10 Professional platform with the following specifications: Intel(R) Core(TM) i7-3537U CPU @ 2.00GHz, 2.50 GHz, and 6.00 GB of RAM. The instance (instance 1) consists of 5 departments to be placed in an area of 10 × 4 non-square units, with the sizes of the departments given in Table 2. In this instance, the length and the width of facility 4 are 4 and 3 distance units, respectively. Additionally, there are 40 units of materials flowing from facility 2 to facility 5. To prepare fij for the MILP model, we obtained new fij = fij + fji, as mentioned earlier. The objective was to find the best possible locations (xi,yi) for the departments, in order to minimize the total material flow distance. The optimal solution was found to be 594, indicating that the total distance materials travel is minimized.

Table 2. Data of OFV1 for 5 departments

	Flow matrix fij					Length	Width
	1	2	3	4	5		
1		10	20	15	7	4	2
2	10		5	4	40	3	1
3	20	5		6	2	5	3
4	15	4	6		9	4	3
5	7	40	2	9		2	1
Dimension of departments (Xmax, Ymax) = (20,4)							

Table 3 presents the optimal solution. For example, the centre of facility 3 is located at the point (2.5, 2) distance units. It is noted that facility 3 is vertically oriented since v = 1 and its length is greater than the width (Ymax). Being vertically oriented means that the longer side of the facility is parallel to the y-axis. On the other hand, all other facilities are horizontally oriented. The optimal solution was obtained within a reasonable time of 0.30 s with an optimal sequence of 3-1-2-5-4.

Table 3 Solution of OFV1

Departments	1	2	3	4	5
Xi	6	7,5	2,5	10,5	8,5
Yj	2	2	2	2	2
Vi (orientation)	0	0	01	0	0

The results obtained from the previous calculations are utilized as an input for an Excel macro as shown in Figure 3, which generates the layout of the facility configuration by simply clicking the "draw" button. The Microsoft Excel 2010 version is used to run the macro. This macro efficiently and accurately creates a visual representation of the facility layout, allowing for a more intuitive and comprehensive understanding of the layout. Furthermore, the macro can be customized and modified to meet the specific needs and preferences of the user, which offers a high degree of flexibility and versatility.

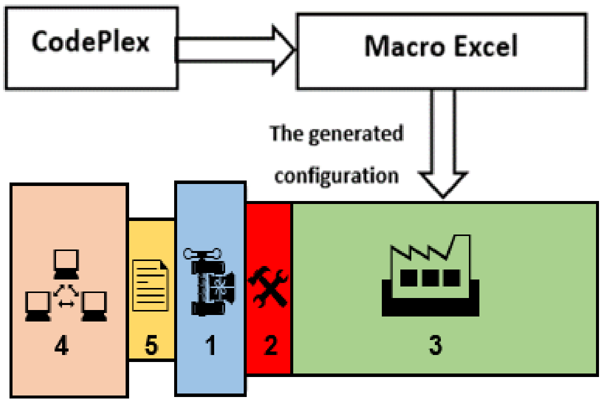

Fig. 3 Layout solution

Generally, in facility layout design, two facilities are considered adjacent if they share a common wall or divider with some minimal tolerance length between them. In this study, we consider rectangular departments, where the adjacencies can occur only along the X-axis (single-row layout). Our objective is to determine the center point coordinates of each department and assign them to appropriate positions, in order to maximize horizontal adjacencies. In a single-row layout, each department can be adjacent to other departments in two directions, either left or right.

As mentioned previously, the proposed model's objective function is to maximize the number of useful adjacencies. It can be expressed as follows:

$$\text{OFV2} = \max \sum_{i=1}^{n} \sum_{j \neq i}^{n} b_{ij} \, R_{ij}$$

This second objective function in our study is designed to maximize the number of useful adjacencies between departments. The data required to compute this objective function is presented in Table 4. The department dimensions, i.e., length and width, are the same as those used in the previous example solved using OFV1. To represent the adjacency relationships, we use Rij, where each value denotes the type of adjacency between department i and department j. For instance, the adjacency relationship between Department 1 and Department 2 is represented by the value A, which indicates that they are adjacent to each other. The value of each adjacency relationship is replaced by a specific numerical value.

Table 4. Data of OFV2

Departments	Rij					Length
	1	2	3	4	5	
1		16	2	4	-2	4
2			8	4	0	3
3				4	0	5
4					2	4
5						2
Dimension of departments (Xmax, Ymax) = (20,4)						

Table 5 displays the optimal solution for this instance, which was obtained using the proposed MILP model. For instance, the centre of facility 3 is located at points (2.5, 4) on the plant floor, with a length of 4 and a width of 3 distance units. Notably, facility 1 is vertically oriented, indicating that the longer side of the facility is parallel to the y-axis and its length is greater than the total length. All the other facilities are horizontally oriented. The actual layout of the plant floor is presented in Figure 4, where the total adjacency between departments is 34. The optimal solution is obtained in 0.30 s, with the optimal sequence of 3-2-1-4-5. The results show that the proposed MILP model is effective in maximizing the number of useful adjacencies and it can be used to solve similar facility layout problems.

Table 5. Results of OFV2

Departments	1	2	3	4	5
Xi	7	5,5	2,5	9,5	11,5
Yj	2	2	2	2	2
Vi(orientation)	0	0	1	0	0

We note that arranging the departments in the order 3-2-1-4-5, as shown in Figure 4, gave rise to the maximum value of the Total Closeness Rating (TCR), which is equal to the sum of the adjacency values between each pair of adjacent departments. Specifically, for this arrangement, TCR is calculated as 8+16+8+2=34. It indicates that the departments are placed in such a way as to maximize the number of useful adjacencies, thus improving the overall layout of the establishment.

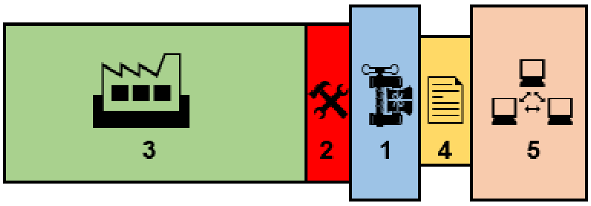

Fig. 4 Layout given by OFV2

We observed that the solution obtained from the first function objective, which is (3-1-2-5-4) as shown in Figure 3, results in a minimum distance value of 594 with a maximum PR of 18. On the other hand, the solution obtained from the second function objective, which is (3-2-1-4-5) as shown in Figure 5, gave us the maximum PR value of 34 with a minimum distance value of 681. It is worth noting that the first layout minimizes both the distance travelled and the adjacency score, whereas the second layout maximizes them. However, our goal is to minimize the distance and maximize the adjacency score. To achieve this, we will employ the LP-metric concept to solve this problem.

4 LP-METRIC RESULT SIMULATION

$$Min\ OF = \alpha^{*}\frac{OFV1-OFV_{Optimal}}{OFV1_{optimal}} - \beta * \frac{OFV2-OFVoptimal}{OFV2_{optimal}}$$

To observe the effect of the weight coefficients (α, β) on the behavior of the LP metric while solving the research problem and to determine the optimal pair of weights for the two research objectives, we conducted an experiment where we varied the values of the weight coefficients. We used three different weight coefficient pairs: [0.4 - 0.6], [0.5 - 0.5] and [0.6 - 0.4]. The obtained results for the sequence of facilities are as follows:

- Case 1 [0.4 - 0.6]: the optimal sequence is 4-5-1-2-3.
- Case 2 [0.5 - 0.5]: the optimal sequence is 3-1-2-5-4.
- Case 3 [0.6 - 0.4]: the optimal sequence is 4-5-2-1-3.

We noticed that each pair of weights affects the order of facilities in the optimal sequence, which indicates the importance of choosing appropriate weight coefficients for each research objective. The LP- metric proved to be useful in finding the optimal solution that minimizes the distance and maximizes the adjacency of facilities.

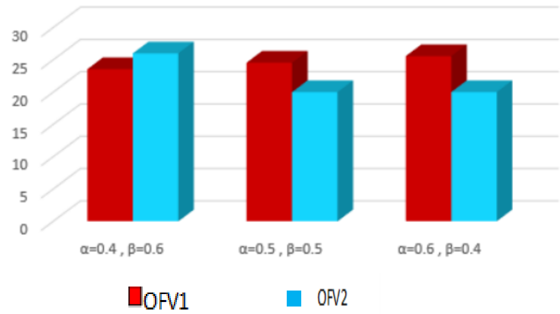

Fig. 5 The impact of the variation of weighting coefficient pair

After analyzing the results obtained from varying the coefficients (α, β), we determined that the choice of these coefficients had a significant impact on the behavior of the LP-metric when solving the research problem. Specifically, when α was greater than or equal to 0.5, the algorithm provided a solution that minimized the total distance and generated a layout that reduced the overall distance travelled. This conclusion was supported by observing the layouts generated in case 2 and case 3.

Conversely, when α was set to 0.4 and β to 0.6, we obtained a solution that considered both objective functions equally without giving preference to one over the other. In this case, the solution minimized the total distance travelled while also maximizing the value of PR. This approach provided a well-rounded solution that considered both distance and adjacency objectives, resulting in a balanced layout.

To better understand the influence of the choice of α and β on the total distance and the total PR, we plotted a diagram in Figure 5. The chart clearly showed that as α increased, the total distance decreased while the total PR increased. This observation provided a helpful insight for decision-makers who were seeking to balance the competing objectives of minimizing distance and maximizing adjacency when designing facility layouts.

5 CONCLUSIONS

In this paper, we have presented a linear mathematical model to solve the SRFLP problem, considering both equal and unequal areas of departments. Our first objective function aimed to minimize the product of flux and distance, which is a crucial factor in reducing material transport costs. The second objective function aimed to maximize the total adjacency between departments, promoting the desirability of placing departments close to each other. By combining both objective functions, we obtained an optimal arrangement that balances quantitative and qualitative aspects.

In the future, several avenues can be explored to further improve the solution to the SRFLP problem. One possible approach is to incorporate machine-learning techniques, such reinforcement learning, to find optimal solutions. Reinforcement learning is a type of machine learning that allows an agent to learn through interactions with an environment by taking actions and receiving rewards or penalties. In the context of SRFLP, the environment could be the plant layout and the agent could be a decision-making algorithm that learns from past actions to optimize the layout for future production.

Another area for improvement is the consideration of more complex constraints in the SRFLP problem, such traffic flow, safety and environmental impact. These constraints can have a significant impact on the performance of the plant and must be taken into account when designing the layout. Additionally, the use of advanced optimization algorithms, such genetic algorithms and simulated annealing, could lead to improved solutions by exploring a wider range of possible layouts.

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