Population-based improvement heuristic with local search for single-row facility layout problem

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Abstract. The Single-Row Facility Layout Problem (SRFLP) is a well-known combinatorial optimization problem. The objective of SRFLP is to find out the arrangement of facilities with given lengths on a line so that the weighted sum of the distances between all pairs of facilities is minimized. This problem is known to be NP-hard. Hence, a population-based improvement heuristic algorithm with local search is presented in this article to solve SRFLP. The proposed algorithm works well also for the Single-Row Equidistant Facility Layout Problem (SREFLP), where the length of each facility is equal. The computational efficiency of the proposed algorithm is checked with the instances of sizes ranging from 5 to 300 available in the literature for SRFLP and SREFLP. The obtained results are compared to those from different state-of-the-art algorithms. The proposed algorithm achieves best known solutions to date for every instance considered in this article in reasonable computational time.

Keywords. Single-row facility layout problem (SRFLP); single-row equidistant facility layout problem (SREFLP); population-based heuristic; improvement heuristic; local search.

1. Introduction

The *Single-Row Facility Layout Problem (SRFLP)* was first introduced by Simmons [1]. Given a set of facilities with different lengths, SRFLP is the problem of finding an arrangement of facilities in a single row such that the weighted sum of the distances between all pairs of facilities is minimized [1–13]. SRFLP is a well-studied combinatorial optimization problem and it is a special case of the *Weighted Betweenness Problem*, which is again a special case of the *Quadratic Ordering Problem* [14]. When each facility has unit length, SRFLP is known as the *Minimum Linear Arrangement Problem (MinLA)* [6]. Another special case of SRFLP is the *Single-Row Equidistant Facility Layout Problem (SREFLP)* [14, 15], where the length of each facility is equal. SREFLP is sometimes called as the *one-dimensional machine location problem* [16] or the *linear machine-cell location problem* [17].

Many applications of SRFLP can be found in [1, 2, 4]. The arrangement of rooms in hospitals and supermarkets [1],

arrangement of machines in flexible manufacturing systems [4], assignment of computer disk cylinders to files [2], warehouse layouts [2], arranging books on a shelf in a library [2], the assignment of planes at an airport terminal [5], etc. can be modelled as SRFLP. A comprehensive review on SRFLP can be found in [9]. Surveys on different computational modelling approaches used to solve SRFLP can be found in [18, 19]. Recent developments on SRFLP over the last one and half decades can be found in the survey articles [20, 21].

In this article, a population-based improvement heuristic with local search is proposed. The proposed algorithm maintains a set of candidate solutions, known as *population*, and tries to improve each candidate solution using different local search techniques. The proposed algorithm can solve both SRFLP and SREFLP instances, and the performance of the proposed algorithm is compared to those of different exact algorithms based on mathematical programming [14, 22, 23] and meta-heuristic algorithms [8, 10, 13, 24–26] for small-scale instances to the large-scale instances of sizes ranging from 5 to 300. There are many real-world problems such as the *maximal covering location problem* [27], the *uncapacitated facility location problem* [28–31], the *tool indexing problem* [32], etc. related to SRFLP, which are NP-hard in general, and heuristic/meta-heuristic algorithms are developed for these problems. Hence, it is very obvious to use a population-

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based improvement heuristic algorithm to solve SRFLP that also falls under the class of NP-hard problems [3].

The organization of the article is as follows. A concise literature review on SRFLP is given in section 2. Different notations, terminologies used in this article and the problem definition are mentioned in section 3. In section 4, the proposed algorithm is described in detail. The results obtained using the proposed algorithm for different instances of both SRFLP and SREFLP and comparisons to the existing algorithms are discussed in section 5. Finally, section 6 concludes the article.

2. Literature review

A concise literature review is given in this section. Due to the enormous applications of SRFLP, it has gained considerable attention by the researchers of different fields since its inception by Simmons [1]. Moreover, SRFLP is known to be NP-hard [3]. Hence, different approaches have been used to solve SRFLP by many researchers. We can broadly categorize the different approaches used to solve SRFLP in two ways: exact methods and approximate methods. The different exact methods for solving SRFLP include branch-and-bound method [1, 23], integer programming [33–36], cutting plane method [37], dynamic programming [2], branch-and-cut [11], semidefinite programming [7, 19, 38, 39] and many more. The polyhedral studies of SRFLP can be found in [11, 40]. The different approximate methods include greedy like algorithm [4], iterative construction heuristics [4, 41, 42], tabu search [12, 43, 44], local search algorithms [10, 26], simulated annealing [15, 43, 45, 46], ant colony optimization [47], scatter search method [25, 48], particle swarm optimization [49], genetic algorithm [8, 13, 24, 50], Greedy Randomized Adaptive Search Procedure (GRASP) with Path Relinking (PR) [51], etc. A hybrid algorithm was developed combining ant colony optimization (ACO) and particle swarm optimization (PSO) in [52]. An imperialist competitive evolutionary algorithm was proposed in [53]. These different methods are summarized in figure 1.

3. Notations, terminologies and problem definition

The notations and terminologies used in this article are described in this section.

- The *weight matrix* $\mathcal{W} = (w_{ij})_{n \times n}$ denotes the weight w_{ij} of each pair (i, j) of facilities, where n is the total number of facilities available.
- The *length matrix* $\mathcal{L} = \{\ell_1, \ell_2, \dots, \ell_n\}$ denotes the length ℓ_i of the facility i .
- The set of valid layouts, $\Pi = \{\pi^1, \pi^2, \dots, \pi^p\}$, where $\pi^i = \{\pi_1^i, \pi_2^i, \dots, \pi_n^i\}$ is the permutation of n facilities.

Figure 1. Solution approaches to solve SRFLP.

Here, the term valid implies that $\pi_m^i \neq \pi_n^i, \forall m \neq n$ in each π^i . For example, with $n = 5$, one of the valid layouts may be $\{3, 2, 5, 1, 4\}$. We call each π^i as a valid layout.

- Cost for each layout in Π is denoted as $C_\Pi = \{C_{\pi^1}, C_{\pi^2}, \dots, C_{\pi^n}\}$, where C_{π^i} denotes the cost of the layout π^i . The cost of a layout π is calculated as

$$C_\pi = \sum_{1 \leq i < j \leq n} w_{ij} d_{\pi_i \pi_j},$$

$$\text{where } d_{\pi_i \pi_j} = \frac{1}{2}(\ell_{\pi_i} + \ell_{\pi_j}) + \sum_{i < k < j} \ell_{\pi_k} \quad [11, 9].$$

Using the afore-mentioned terminologies, the SRFLP can be now defined as follows: given a set $\{1, 2, \dots, n\}$ of n facilities with the weight matrix $\mathcal{W}$ and the length matrix $\mathcal{L}$, the objective of SRFLP is to find out a layout π with the minimum cost C_π among all the possible layouts [9, 11].

The following example illustrates SRFLP. Consider the following specifications of the weight matrix ($\mathcal{W}$) and the length matrix ($\mathcal{L}$) as shown in figure 2 with $n = 5$:

Note that in figure 2, $\mathcal{W}$ is shown as an upper triangular matrix because $\mathcal{W}$ is a symmetric matrix, i.e., $w_{ij} = w_{ji}$,

$$\mathcal{W} = \begin{bmatrix} 0 & 2 & 10 & 10 & 14 \\ 0 & 0 & 16 & 6 & 8 \\ 0 & 0 & 0 & 2 & 10 \\ 0 & 0 & 0 & 0 & 14 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$\mathcal{L} = [1 \quad 1 \quad 1 \quad 1 \quad 1].$$

Figure 2. Weight matrix ($\mathcal{W}$) and length matrix ($\mathcal{L}$).

$$\begin{aligned}
d_{23} &= \frac{1}{2}(1+1) = 1 \\
d_{25} &= \frac{1}{2}(1+1) + 1 = 2 \\
d_{21} &= \frac{1}{2}(1+1) + (1+1) = 3 \\
d_{24} &= \frac{1}{2}(1+1) + (1+1+1) = 4 \\
d_{51} &= \frac{1}{2}(1+1) = 1 \\
d_{54} &= \frac{1}{2}(1+1) + 1 = 2 \\
d_{35} &= \frac{1}{2}(1+1) = 1 \\
d_{31} &= \frac{1}{2}(1+1) + 1 = 2 \\
d_{34} &= \frac{1}{2}(1+1) + (1+1) = 3 \\
d_{14} &= \frac{1}{2}(1+1) = 1 \\
C_\pi &= w_{23}d_{23} + w_{25}d_{25} + w_{21}d_{21} + w_{24}d_{24} + w_{35}d_{35} + w_{31}d_{31} + w_{34}d_{34} + w_{51}d_{51} + w_{54}d_{54} + w_{14}d_{14} \\
&= 150.
\end{aligned}$$

Figure 3. Scheme of calculation to compute C_π .

$\forall i, j$. The objective of SRFLP is to find a valid layout π so that the cost of π (C_π) is minimized. Now, let us consider a valid layout $\pi = \{2, 3, 5, 1, 4\}$. A detailed calculation to compute C_π is shown in figure 3.

Note that in this article, the assignment operation $\{i_1, i_2, \dots, i_n\} \leftarrow \{j_1, j_2, \dots, j_n\}$ implies that $i_1 \leftarrow j_1$, $i_2 \leftarrow j_2$ and so on. This kind of assignment operation is used in the proposed algorithm.

4. Proposed heuristic

In this section, a population-based improvement heuristic with local search is proposed. In this article, five different heuristic methods are developed to construct the proposed heuristic algorithm for SRFLP. One of the five heuristic methods is used to construct the initial population and they are all used to improve the solution obtained in any particular generation. The proposed algorithm tries to improve the solution over several generations and in each generation, different heuristic methods are used to improve the current available set of solutions. We will discuss the five proposed methods at first independently and after this we will discuss the main proposed algorithm for SRFLP. We will explain each of these five methods using the weight matrix $\mathcal{W}$ and the length matrix ($\mathcal{L}$) as shown in figure 2.

4.1 Weighted pair

In this section, a heuristic method is described and we call this method as the *Weighted Pair*. The description of this heuristic method is given in Algorithm 1. It takes weight matrix $\mathcal{W} = (w_{ij})_{n \times n}$, length matrix $\mathcal{L} = \{\ell_1, \ell_2, \dots, \ell_n\}$ and a partial layout $\pi^* = \{\pi_1^*, \pi_2^*, \dots, \pi_k^*\}$ where $0 \leq k \leq n$ and produces as its outputs a valid layout $\pi^\circ = \{\pi_1^\circ, \pi_2^\circ, \dots, \pi_n^\circ\}$ and cost of the layout π° , i.e., C_{π° . Step 1 of Algorithm 1 computes the *rank* $\mathcal{R}_{ij}$ ($\forall i, j$ and $i < j$) for each pair (i, j) by evaluating $w_{ij}(\ell_i + \ell_j)$ and then by sorting in descending order. Note that $\mathcal{R}_{ij} = \mathcal{R}_{ji}$, $\forall i, j$ and $i \neq j$. Hence, we compute $\mathcal{R}_{ij}$ only for $i < j$. For example, consider the weight matrix ($\mathcal{W}$) and the length matrix ($\mathcal{L}$) as

mentioned in figure 2. For these specifications, the rank $\mathcal{R}_{ij}$ is computed according to Step 1 and we show this as a triplet $(i, j, \mathcal{R}_{ij})$ as follows:

$$\begin{aligned}
&\{(i, j, \mathcal{R}_{ij}) \mid \mathcal{R}_{ij} = w_{ij}(\ell_i + \ell_j), \forall i, j \text{ and } i < j, \\
&\quad \text{and } \mathcal{R}_{ij} \text{ is sorted in descending order}\} \\
&= \{(2, 3, 32), (1, 5, 28), (4, 5, 28), (1, 3, 20), \\
&\quad (1, 4, 20), (3, 5, 16), (2, 4, 12), (1, 2, 4), (3, 4, 4)\}.
\end{aligned}$$

Now, we consider the case where partial layout π^* is empty. Then $\pi_1^\circ = 2$ and $\pi_1^\circ = 3$, since $\mathcal{R}_{2,3}$ is the maximum. In this case, the final valid layout will be $\pi^\circ = \{2, 3, 5, 4, 1\}$ and the corresponding cost C_{π° is 150. Again, we consider a case where the partial layout π^* is non-empty and say $\pi^* = \{4, 5\}$. In this case, the *for loop* in line 6 will iteratively generate the final valid layout π° . The next facility 1 will be added next since $\mathcal{R}_{5,1}$ ($= \mathcal{R}_{1,5}$) is the next maximum. Note that if $\mathcal{R}_{mn} = \mathcal{R}_{pq}$, then we consider $\mathcal{R}_{mn}$ for our evaluation if $m \leq p$ and $n \leq q$; otherwise we consider $\mathcal{R}_{pq}$ for our evaluation. Here, the final valid layout will be $\pi^\circ = \{4, 5, 1, 3, 2\}$ and the corresponding cost C_{π° is 152.

Algorithm 1: Weighted Pair

Input: Weight matrix $\mathcal{W} = (w_{ij})_{n \times n}$, Length matrix $\mathcal{L} = \{\ell_1, \ell_2, \dots, \ell_n\}$, A partial layout $\pi^* = \{\pi_1^*, \pi_2^*, \dots, \pi_k^*\}$ where $0 \leq k \leq n$.
Output: A layout $\pi^\circ = \{\pi_1^\circ, \pi_2^\circ, \dots, \pi_n^\circ\}$, cost of layout π° , i.e., C_{π° .
1 Find $\mathcal{R}_{ij}$ ($\forall i, j$ and $i < j$) for each pair (i, j) by evaluating $w_{ij} * (\ell_i + \ell_j)$ and by sorting in descending order;
2 **if** π^* is empty **then**
3 $\{\pi_1^\circ, \pi_1^\circ\} \leftarrow \{i, j\}$ for which $\mathcal{R}_{ij}$ is the maximum;
4 **end**
5 $k \leftarrow \text{size of } \pi^*$;
6 **for** $i = k + 1$ to n **do**
7 Find j ($\neq i$) for which $\text{Rank}_{\pi_{1..i-1}^*}^*$ is maximum, provided
7 $j \notin \{\pi_1^*, \dots, \pi_{i-1}^*\}$;
8 $\pi_i^\circ \leftarrow j$;
9 **end**
10 $C_{\pi^\circ} \leftarrow \text{cost of } \pi^\circ$;

4.2 Partial ordered replacement

This heuristic method takes two valid layouts π^{i_1} and π^{i_2} as its inputs and produces two valid layouts π^{O_1} and π^{O_2} as its outputs. The description of this method is given in Algorithm 2. Let us now consider two valid layouts

$$\pi^{i1} = \{6, 5, 2, 9, 7, 10, 4, 3, 1, 8\}$$

and

$$\pi^{i2} = \{9, 10, 1, 3, 4, 8, 5, 2, 6, 7\}.$$

In this example, the number of facilities (n) is 10. If we assume that line 1 of Algorithm 2 generates r_1 and r_2 as 3 and 6, respectively, then lines 2 and 3 will create

$$\pi^{O1} = \{-, -, 1, 3, 4, 8, -, -, -, -\}$$

and

$$\pi^{O2} = \{-, -, 2, 9, 7, 10, -, -, -, -\}$$

respectively. The symbol ‘-’ indicates that the facility at that position is yet to be determined. Thus, partial replacements of two layouts are done. In lines 4 and 5, the positions marked with ‘-’ in π^{O1} and π^{O2} are filled with the facilities located at the same position in π^{i1} and π^{i2} , respectively, if the corresponding facilities have not been included in earlier steps. They create $\pi^{O1} = \{6, 5, 1, 3, 4, 8, -, -, -, -\}$ and $\pi^{O2} = \{-, -, 2, 9, 7, 10, 5, 2, -, -\}$. In the next step, the remaining positions marked with ‘-’ of both π^{O1} and π^{O2} are filled up with the remaining elements of π^{i1} and π^{i2} , respectively, with the same order in which they appear in π^{i1} and π^{i2} . These creates $\pi^{O1} = \{6, 5, 1, 3, 4, 8, 2, 9, 7, 10\}$ and $\pi^{O2} = \{1, 3, 2, 9, 7, 10, 5, 4, 6, 8\}$.

Algorithm 2: Partial Ordered Replacement.

Input: Two layouts $\pi^{i1} = \{\pi_1^{i1}, \pi_2^{i1}, \dots, \pi_n^{i1}\}$ and $\pi^{i2} = \{\pi_1^{i2}, \pi_2^{i2}, \dots, \pi_n^{i2}\}$.

Output: Two layouts $\pi^{O1} = \{\pi_1^{O1}, \pi_2^{O1}, \dots, \pi_n^{O1}\}$ and

$$\pi^{O2} = \{\pi_1^{O2}, \pi_2^{O2}, \dots, \pi_n^{O2}\}, \text{ cost of layouts } \pi^{O2} \text{ and } \pi^{O2}.$$

- 1 Generate two distinct integer random numbers r_1 and r_2 ($> r_1$) in $[1, n]$;
 - 2 $\{\pi_{r_1}^{O1}, \dots, \pi_{r_2}^{O1}\} \leftarrow \{\pi_{r_1}^{i1}, \dots, \pi_{r_2}^{i1}\}$;
 - 3 $\{\pi_{r_1}^{O2}, \dots, \pi_{r_2}^{O2}\} \leftarrow \{\pi_{r_1}^{i2}, \dots, \pi_{r_2}^{i2}\}$;
 - 4 If $\pi_j^{i1} \notin \{\pi_{r_1}^{O1}, \dots, \pi_{r_2}^{O1}\}$, $\pi_j^{O1} \leftarrow \pi_j^{i1}$, $\forall j \in [1, r_1] \cup (r_2, n]$;
 - 5 If $\pi_j^{i2} \notin \{\pi_{r_1}^{O2}, \dots, \pi_{r_2}^{O2}\}$, $\pi_j^{O2} \leftarrow \pi_j^{i2}$, $\forall j \in [1, r_1] \cup (r_2, n]$;
 - 6 Fill the remaining positions of π^{O1} and π^{O2} with the remaining elements of π^{i1} and π^{i2} with the same order as they have appeared in π^{i1} and π^{i2} respectively.
-

4.3 Adjacent neighbour

This local search method takes weight matrix $\mathcal{W}$, length matrix $\mathcal{L}$, an old set of layouts Π_{old} and neighbourhood size (α) as its inputs and generates a new set of layouts Π_{new} and its corresponding cost $\mathcal{C}_{\Pi_{new}}$. Algorithm 3 gives a description of this local search method. We will show the mechanism of this method for only one layout $\pi^i \in \Pi_{old}$ using an example. The computations for all the other layouts in Π_{old} will be similar. Let us consider $\mathcal{W}$ and $\mathcal{L}$ as shown in figure 2, $\pi^i = \{3, 2, 4, 1, 5\}$ and $\alpha = 2$. Since α is 2, we consider π_1^i, π_2^i at first, then compute all possible permutations of π_1^i, π_2^i , replace π_1^i, π_2^i by each of the permutations and compare cost of π^i with that of the modified

π^i . We keep that modified π^i for which cost is minimum. Then we again repeat the same procedure for π_2^i, π_3^i up to π_4^i, π_5^i . Then we compare the cost of the current π^i with that of the old π^i . If improvement occurs in terms of cost, then we change the old π^i with the current one. For this example, at the end of this method we get π^o as $\{2, 3, 1, 5, 4\}$. This method is so named because in each step we always consider the facilities within a predefined *neighbourhood size*, α . The complexity of this method greatly depends on the value of α . Hence, in our experiment, we will keep this value within the range 2–3.

Algorithm 3: Adjacent neighbour

Input: Weight matrix $\mathcal{W} = (w_{ij})_{n \times n}$, Length matrix $\mathcal{L} = \{\ell_1, \ell_2, \dots, \ell_n\}$, Old set of layouts $\Pi_{old} = \{\pi^1, \pi^2, \dots, \pi^p\}$, where $\pi^i = \{\pi_1^i, \pi_2^i, \dots, \pi_n^i\}$, neighbourhood size (α).

Output: New set of layouts $\Pi_{new} = \{\pi^1, \pi^2, \dots, \pi^p\}$, Cost for each layout in Π_{new} , i.e., $\mathcal{C}_{\Pi_{new}} = \{C_{\pi^1}, C_{\pi^2}, \dots, C_{\pi^p}\}$.

```

1   $p \leftarrow$  no. of layouts in  $\Pi_{old}$ ;
2  for  $i = 1$  to  $p$  do
3       $old\_best\_cost \leftarrow$  cost of  $\pi^i$ ;
4       $\pi^{old} \leftarrow \pi^i$ ;
5       $k \leftarrow 2$ ;
6      while  $k \leq \alpha$  do
7          for  $j = 1$  to  $n - (k - 1)$  do
8               $\pi^{temp} \leftarrow \pi^i$ ;
9               $old\_cost \leftarrow$  cost of  $\pi^{temp}$ ;
10              $f \leftarrow \{\pi_j^{temp}, \dots, \pi_{j+(k-1)}^{temp}\}$ ;
11              $\pi \leftarrow \{\}$ ;
12              $\pi \leftarrow$  all possible permutations of the elements of  $f$ ;
13              $ns \leftarrow$  size of  $\pi$ ;
14              $index \leftarrow \{\}$ ;
15             for  $m = 1$  to  $ns$  do
16                  $\{\pi_j^{temp}, \dots, \pi_{j+(k-1)}^{temp}\} \leftarrow \{\pi_m^1, \dots, \pi_k^m\}$ ;
17                  $new\_cost \leftarrow$  cost of  $\pi^{temp}$ ;
18                 if  $new\_cost < old\_cost$  then
19                      $index \leftarrow m$ ;
20                      $old\_cost \leftarrow new\_cost$ ;
21             end
22         end
23         if  $index \neq \{\}$  then
24              $\{\pi_j^i, \dots, \pi_{j+(k-1)}^i\} \leftarrow \{\pi_1^{index}, \dots, \pi_k^{index}\}$ ;
25         end
26     end
27      $k = k + 1$ ;
28 end
29  $new\_best\_cost \leftarrow$  cost of  $\pi^i$ ;
30 if  $new\_best\_cost \geq old\_best\_cost$  then
31      $\pi^i \leftarrow \pi^{old}$ ;
32      $C_{\pi^i} \leftarrow old\_best\_cost$ ;
33 else
34      $C_{\pi^i} \leftarrow new\_best\_cost$ ;
35 end
36 end
```

4.4 Best permutation

This improvement method takes weight matrix $\mathcal{W}$, length matrix $\mathcal{L}$ and a layout π^* as its inputs and generates a new layout π^o and its corresponding cost C_{π^o} . The method is described in Algorithm 4. In this method, given a layout π^* , we will generate a few other permutations generated from π^* and select that permutation for which the corresponding cost is minimum. This is the reason why we call this method as the *best permutation*, though we do not explore all the permutations of π^* as this is time consuming if n is large. Let us consider $\pi^* = \{1, 2, 3, 4, 5\}$. From this, we generate the permutations as shown in figure 4.

2, 1, 3, 4, 5	1, 3, 2, 4, 5
2, 3, 1, 4, 5	1, 3, 4, 2, 5
2, 3, 4, 1, 5	1, 3, 4, 5, 2
2, 3, 4, 5, 1	
1, 2, 4, 3, 5	1, 2, 3, 5, 4
1, 2, 4, 5, 3	

Figure 4. Generated permutations.

There is a relation between π^* and π° . Observe the first four permutations in the first column of figure 4. In these four permutations, only the first element of π^* , i.e. 1, is shifted to its right one place at a time. Then observe the permutations as shown in the second column of figure 4, where the second element of π^* , i.e. 2, is shifted to its right one place at a time and so on up to the second last element. The pattern of generating these permutations can be easily understood from figure 4.

Algorithm 4: Best permute

Input: Weight matrix $W = (w_{ij})_{n \times n}$, Length matrix $\mathcal{L} = \{\ell_1, \ell_2, \dots, \ell_n\}$, A layout $\pi^* = \{\pi_1^*, \pi_2^*, \dots, \pi_n^*\}$.

Output: A layout $\pi^\circ = \{\pi_1^\circ, \pi_2^\circ, \dots, \pi_n^\circ\}$, cost of layout π° , i.e., C_{π° .

```

1  $k \leftarrow 1$ ;
2 for  $i = 1$  to  $n - 1$  do
3    $\pi^{temp} \leftarrow \pi^*$ ;
4   Remove  $\pi_i^{temp}$  from  $\pi^{temp}$ ;
5   for  $j = i + 1$  to  $n$  do
6      $\pi^k \leftarrow []$ ;
7      $\pi^k \leftarrow \{\pi_1^{temp}, \dots, \pi_{j-1}^{temp}, \pi_i^*, \pi_j^{temp}, \dots, \pi_{n-1}^{temp}\}$ ;
8      $k \leftarrow k + 1$ ;
9      $C_{\pi^k} \leftarrow \text{cost of } \pi^k$ ;
10  end
11 end
12 Find index for which  $C_{\pi^k}$  is minimum;
13 if  $C_{\pi^{index}} \leq \text{old\_cost}$  then
14    $\pi^\circ \leftarrow \pi^{index}$ ;
15 else
16    $\pi^\circ \leftarrow \pi^*$ ;
17 end
```

Note that this method of generating permutations from a given valid layout will explore $\frac{n(n-1)}{2}$ number of different permutations. Among all the generated permutations as shown in figure 4, $\{2, 3, 4, 5, 1\}$ will be selected as π° because for this layout the corresponding cost is minimum and here the cost is 160.

4.5 Random replacement

Random replacement is a heuristic method that is used to get diversity in the current population of solutions. This method helps in overcoming the difficulty of getting stuck into a local optimum. This method takes the weight matrix W , the length matrix $\mathcal{L}$ and an old set of layouts Π_{old} and produces a new modified set of layout Π_{new} and the corresponding $C_{\Pi_{new}}$. This heuristic method is described in Algorithm 5. For a layout $\pi^i \in \Pi_{old}$, we generate two distinct numbers $r_1, r_2 \in [1, n]$ and we swap $\pi_{r_1}^i$ and $\pi_{r_2}^i$ if improvement occurs in terms of cost. This step is repeated n times for each layout.

Algorithm 5: Random replacement.

Input: Weight matrix $W = (w_{ij})_{n \times n}$, Length matrix $\mathcal{L} = \{\ell_1, \ell_2, \dots, \ell_n\}$, Old set of layouts $\Pi_{old} = \{\pi^1, \pi^2, \dots, \pi^p\}$, where $\pi^i = \{\pi_1^i, \pi_2^i, \dots, \pi_n^i\}$.

Output: New set of layouts $\Pi_{new} = \{\pi^1, \pi^2, \dots, \pi^p\}$, Cost for each layout in Π_{new} , $C_{\Pi_{new}} = \{C_{\pi^1}, C_{\pi^2}, \dots, C_{\pi^p}\}$.

```

1  $p \leftarrow \text{no. of layouts in } \Pi_{old}$ ;
2 for  $i = 1$  to  $p$  do
3   for  $j = 1$  to  $n$  do
4      $\text{old\_cost} \leftarrow \text{cost of } \pi^i$ ;
5      $\pi^{temp} \leftarrow \pi^i$ ;
6     Generate two distinct integer random numbers  $r_1$  and  $r_2$  in  $[1, n]$ ;
7     Swap( $\pi_{r_1}^{temp}, \pi_{r_2}^{temp}$ );
8      $\text{new\_cost} \leftarrow \text{cost of } \pi^{temp}$ ;
9     if  $\text{new\_cost} \leq \text{old\_cost}$  then
10       $\pi^i \leftarrow \pi^{temp}$ ;
11       $C_{\pi^i} \leftarrow \text{new\_cost}$ ;
12    else
13       $C_{\pi^i} \leftarrow \text{old\_cost}$ ;
14    end
15  end
16 end
```

4.6 Proposed heuristic algorithm for SRFLP**Algorithm 6:** Population-based improvement heuristic with local search for SRFLP.

Input: Weight matrix $W = (w_{ij})_{n \times n}$, Length matrix $\mathcal{L} = \{\ell_1, \ell_2, \dots, \ell_n\}$, Population size $\mathcal{PS}$, Number of generation $\mathcal{G}$.

Output: A valid layout π^* with minimum cost C_{π^*} .

/ Generation of initial population (line 1--9) */*

```

1  $\pi^1 \leftarrow$  randomly generated permutation of numbers in  $[1, n]$ ;
2 Calculate  $C_{\pi^1}$ ;
3 for  $i = 2$  to  $\mathcal{PS}$  do
4   Randomly generate a number  $r$  in  $[1, n]$ ;
5    $\pi \leftarrow []$ ; //  $\pi$  will denote partial layout.
6    $\{\pi_1, \dots, \pi_r\} \leftarrow \{\pi_1^1, \dots, \pi_r^1\}$ ;
7    $\{\pi', C_{\pi'}\} \leftarrow \text{Weighted Pair}(W, \mathcal{L}, \pi)$ ;
8 end
9  $\Pi \leftarrow \{\pi^1, \dots, \pi^{\mathcal{PS}}\}$ ; // initial population
10  $C_\Pi \leftarrow \{C_{\pi^1}, \dots, C_{\pi^{\mathcal{PS}}}\}$ ; // cost of initial population
11  $g \leftarrow 1$ ;
12 /* Generation starts (line 12--50) */
13 while  $g \leq \mathcal{G}$  or no improvement occurs for consecutive five generations do
14   change(1, ...,  $\mathcal{PS}$ )  $\leftarrow 0$ ;
15   /* Improvement using Partial Ordered Replacement (line 14--29) */
16   for  $i = 1$  to  $\mathcal{PS}$  do
17     Randomly select  $\pi^{r1}, \pi^{r2} \in \Pi$ , where  $r_1 \neq r_2$ ;
18      $\pi^{r1} \leftarrow \pi^{r1}$ ;
19      $\pi^{r2} \leftarrow \pi^{r2}$ ;
20      $[\pi^{r1}, \pi^{r2}, C_{\pi^{r1}}, C_{\pi^{r2}}] \leftarrow \text{Partial Ordered Replacement}(\pi^{r1}, \pi^{r2})$ ;
21     if  $C_{\pi^{r1}} < C_{\pi^{r2}}$  then
22        $\pi^{r1} \leftarrow \pi^{r1}$ ;
23        $C_{\pi^{r1}} \leftarrow C_{\pi^{r1}}$ ;
24       change( $r_1$ )  $\leftarrow 1$ ;
25     end
26     if  $C_{\pi^{r2}} < C_{\pi^{r1}}$  then
27        $\pi^{r2} \leftarrow \pi^{r2}$ ;
28        $C_{\pi^{r2}} \leftarrow C_{\pi^{r2}}$ ;
29       change( $r_2$ )  $\leftarrow 1$ ;
30     end
31   end
32   /* Improvement using Weighted Pair (line 30--40) */
33   for  $i = 1$  to  $\mathcal{PS}$  do
34     Randomly generate a number  $r$  in  $[1, n]$ ;
35      $\pi \leftarrow []$ ; //  $\pi$  will denote partial layout.
36      $\{\pi_1, \dots, \pi_r\} \leftarrow \{\pi_1^i, \dots, \pi_r^i\}$ ;
37      $[\pi^\circ, C_{\pi^\circ}] \leftarrow \text{Weighted Pair}(W, \mathcal{L}, \pi)$ ;
38     if  $C_{\pi^\circ} < C_{\pi^i}$  then
39        $\pi^i \leftarrow \pi^\circ$ ;
40        $C_{\pi^i} \leftarrow C_{\pi^\circ}$ ;
41       change( $i$ )  $\leftarrow 1$ ;
42     end
43   end
44   /* Improvement using adjacent neighbour and best permute (line 41--46) */
45   for  $i = 1$  to  $\mathcal{PS}$  do
46     if change( $i$ ) = 1 then
47        $[\pi', C_{\pi'}] \leftarrow \text{adjacent neighbour}(W, \mathcal{L}, \pi^i, \alpha)$ ;
48        $[\pi', C_{\pi'}] \leftarrow \text{best permute}(W, \mathcal{L}, \pi^i)$ ;
49     end
50   end
51   /* Improvement using Random Replacement (line 47) */
52    $[\Pi, C_\Pi] \leftarrow \text{Random Replacement}(W, \mathcal{L}, \Pi)$ ;
53    $\pi^* \leftarrow$  a layout of  $\Pi$  with minimum cost;
54    $g \leftarrow g + 1$ ;
55 end
```

The population-based improvement heuristic algorithm with local search for SRFLP is proposed in this section. This algorithm takes the weight matrix $\mathcal{W}$, the length matrix $\mathcal{L}$, population size $\mathcal{PS}$, number of generation $\mathcal{G}$ and neighbourhood size (α) as its inputs and produces a valid layout π^* with minimum cost C_{π^*} . The proposed heuristic algorithm for SRFLP is described in Algorithm 6. All the heuristic methods discussed previously are used for constructing this algorithm. Line 1 of Algorithm 6 generates a random solution and the cost of this solution is computed in line 2. The rest of the population is created by the *Weighted Pair* method using the random solution generated earlier. Generation starts in line 12 and it stops when either the maximum generation $\mathcal{G}$ is reached or no improvement occurs for any five consecutive generations in terms of cost of layout. A flag array *change*[1, ..., $\mathcal{PS}$] is used to identify the layout that is modified in any particular generation. At the start of every generation, each element of *change* is initialized to 0. Whenever an improvement of a solution occurs, then the corresponding element of *change* is set to 1. This flag array has an effect on the performance of the algorithm. Each solution in the population is improved using the *Partial Ordered Replacement* method first, followed by the *Weighted Pair* method. Note that these two

methods modify a solution only if improvement occurs in terms of cost. Otherwise, the old solution is kept unchanged. If improvement occurs, then the corresponding

Table 3. Results for O, S, Y and N types of SREFLP instances ($5 \leq n \leq 35$).

Instance	n	Cost ^a	Time ^b	Time ^c	Proposed heuristic	
					Cost	Time
O-5	5	150	1	1	150	0.03
O-6	6	292	1	1	292	0.04
O-7	7	472	1	1	472	0.05
O-8	8	784	1	1	784	0.09
O-9	9	1032	1	1	1032	0.12
O-10	10	1402	1	1	1402	0.18
O-15	15	5134	2	4	5134	0.44
O-20	20	12924	37	37	12924	0.73
S-12	12	4431	1	4	4431	0.24
S-13	12	5897	1	4	5897	0.40
S-14	14	7316	1	15	7316	0.89
S-15	15	8942	2	19	8942	1.02
S-16	16	11019	3	27	11019	1.21
S-17	17	13172	5	50	13172	1.26
S-18	18	15699	8	48	15699	1.66
S-19	19	18700	22	01:43:00	18700	2.15
S-20	20	21825	55	02:09:00	21825	2.07
S-21	21	24891	01:41:00	03:20:00	24891	7.01
S-22	22	28607	03:48:00	03:57:00	28607	8.10
S-23	23	33046	08:12:00	03:15:00	33046	9.86
S-24	24	37498	13:41:00	03:31:00	37498	11.13
S-25	25	42349	36:21:00	07:07:00	42349	11.29
Y-6	6	1372	1	1	1372	0.04
Y-7	7	1801	1	1	1801	0.07
Y-8	8	2302	1	1	2302	0.09
Y-9	9	2808	1	1	2808	0.13
Y-10	10	3508	1	2	3508	0.20
Y-11	11	4022	1	4	4022	0.51
Y-12	12	4793	1	10	4793	0.58
Y-13	13	5471	1	9	5471	0.63
Y-14	14	6445	1	34	6445	0.87
Y-15	15	7359	2	26	7359	1.04
Y-20	20	12185	23	01:14:00	12185	3.09
Y-25	25	20357	22:38:00	05:14:00	20357	5.27
Y-30	30	27673	16:17:07	17:46:00	27673	18.03
Y-35	35	38194	459:08:51	25:50:00	38194	27.23
N-15	15	2186	2	17	2186	0.90
N-16a	16	3050	—	8	3050	0.98
N-16b	16	2400	—	6	2400	1.01
N-17	17	3388	—	13	3388	1.03
N-18	18	3986	—	16	3986	1.17
N-20	20	5642	41	01:11:00	5642	4.07
N-21	21	5084	—	01:16:00	5084	4.84
N-22	22	6184	—	01:20:00	6184	4.59
N-24	24	8270	—	02:12:00	8270	5.19

^aRefers to the results reported in [14]

^bRefers to the results reported in [23]

^cRefers to the results reported in [22]

'Time' indicates the computational time in s, min:s or h:min:s

Table 1. Results for N type instances of SRFLP ($n = 40$).

Instance	n	Cost ^a	Time ^a	Proposed heuristic	
				Cost	Time
N40_1	40	107348.5	01:01:36	107348.5	00:00:37
N40_2	40	97693	00:52:52	97693	00:00:39
N40_3	40	78589.5	01:21:40	78589.5	00:00:42
N40_4	40	76669	01:15:58	76669	00:00:35
N40_5	40	103009	02:20:09	103009	00:00:38

^aRefers to the results reported in [22]

'Time' indicates the computational time in min:s or in h:min:s

Table 2. Best layouts obtained for N type instances of SRFLP.

Instance	Best layout
N40_1	34 12 20 10 27 19 9 28 17 37 5 8 21 15 35 24 38 2 36 40 18 33 7 11 25 32 22 26 6 30 3 31 29 4 23 14 1 39 16 13
N40_2	14 8 15 3 6 31 26 40 1 4 33 35 25 11 27 16 9 32 28 19 5 39 13 20 34 21 2 22 29 10 18 17 23 30 36 12 7 38 37 24
N40_3	14 11 17 39 13 4 25 12 9 1 15 31 28 29 18 38 5 2 10 3 33 6 26 37 16 20 8 23 40 36 32 34 21 30 27 24 22 7 35 19
N40_4	29 19 17 11 38 20 28 37 8 14 23 7 25 35 39 2 3 9 15 26 32 31 33 30 16 34 5 36 27 22 1 21 13 10 24 40 18 12 4 6
N40_5	12 21 29 23 9 2 24 5 32 27 1 36 33 26 20 6 19 14 28 18 39 38 30 37 35 10 4 34 15 13 16 40 25 7 31 22 8 11 3 17

Table 4. Best layouts obtained for O, S, Y and N type instances of SREFLP.

Instance	Best layout	Instance	Best layout
O-5	2 3 5 1 4 and 4 1 5 3 2	Y-6	6 2 3 4 1 5 and 5 1 4 6 2 3
O-6	1 6 5 4 3 2 and 3 4 5 1 6 2 and 2 6 1 5 4 3	Y-7	4 5 6 2 3 7 1
O-7	2 3 7 5 6 1 4 and 4 1 6 5 7 3 2 and 1 5 6 3 7 2 4	Y-8	1 5 8 6 7 2 3 4 and 6 7 2 3 4 8 5 1
O-8	3 7 5 8 4 1 6 2 and 2 6 4 8 7 5 1 3 and, 3 1 5 8 4 7 6 2 and 7 3 5 1 8 4 6 2 and 2 6 1 4 8 5 3 7 and 7 3 5 8 4 1 6 2	Y-9	1 4 9 3 2 8 7 6 5
O-9	9 2 5 4 7 8 3 6 1	Y-10	9 6 3 8 4 7 10 2 5 1
O-10	9 7 8 2 10 3 4 5 6 1	Y-11	3 1 11 10 5 7 9 8 2 4 6
O-15	3 15 10 2 13 12 11 9 14 8 7 6 4 1 5	Y-11	3 1 11 10 5 7 9 8 2 4 6
O-20	10 2 7 3 8 17 14 9 13 19 20 6 15 18 5 11 16 12 1 4	Y-12	12 4 1 11 3 9 5 8 6 10 2 7
S-12	8 11 7 10 6 4 12 5 3 1 9 2	Y-13	1 13 11 6 10 2 12 8 5 4 9 7 3
S-13	11 7 6 10 5 4 13 2 9 12 3 1 8	Y-14	12 14 6 2 1 13 7 3 9 5 10 11 4 8
S-14	11 7 6 14 12 4 10 5 13 2 9 3 1 8	Y-15	13 9 7 15 1 14 2 3 5 12 11 10 8 6 4
S-15	8 1 3 15 2 9 13 5 4 12 10 14 6 7 11	Y-20	4 7 12 18 11 2 20 19 17 15 8 3 14 5 13 10 9 1 6 16
S-16	11 7 14 6 10 12 16 4 5 13 2 9 15 3 1 8	Y-25	20 22 18 17 19 16 8 1 23 2 12 24 7 21 14 5 11 3 9 6 15 13 4 25 10
S-17	11 14 7 6 17 10 4 12 16 5 13 9 2 15 3 1 8	Y-30	29 11 21 4 24 17 13 23 8 9 14 6 30 20 27 16 12 3 25 26 22 1 19 10 2 7 5 18 15 28
S-18	8 1 3 15 18 9 2 12 16 5 13 4 10 14 6 7 17 11	Y-35	21 24 16 31 13 34 19 4 30 12 25 14 27 23 15 17 18 9 2 6 26 22 32 20 3 11 10 33 8 35 28 29 5 7 1
S-19	11 14 6 7 17 10 5 13 4 16 12 2 9 18 15 3 19 1 8	N-15	1 2 4 13 14 3 9 11 8 7 12 5 6 15 10
S-20	8 1 3 19 15 2 9 18 12 20 16 10 13 4 17 5 6 7 14 11	N-16a	16 4 11 8 15 2 14 12 7 1 5 10 3 6 13 9
S-21	8 21 2 15 3 1 19 9 18 20 12 16 5 13 4 10 17 6 14 7 11	N-16b	14 15 16 4 2 12 13 9 7 10 6 1 3 8 11 5
S-22	8 21 2 15 3 1 19 9 18 20 16 12 5 4 13 10 17 22 7 6 14 11	N-17	17 4 16 11 8 15 2 14 12 7 1 5 10 3 6 13 9
S-23	8 21 2 15 20 18 9 1 19 3 16 12 23 5 13 4 14 10 6 22 17 7 11	N-18	17 18 4 16 11 8 15 2 14 12 7 1 5 10 3 6 13 9
S-24	8 21 15 2 20 18 9 1 3 19 5 16 10 13 4 23 12 14 6 24 22 7 17 11	N-20	9 16 3 18 14 10 2 19 4 11 15 12 8 20 7 1 5 6 13 17
S-25	11 17 7 22 24 25 6 12 23 14 4 13 10 5 16 19 3 1 9 18 20 2 15 21 8	N-21	5 2 21 13 6 12 9 10 16 7 11 3 1 18 19 8 20 14 4 17 15 and 15 17 20 14 4 8 19 18 1 3 11 7 16 10 9 12 6 13 21 2 5
N-22	20 14 4 15 17 8 19 18 1 22 3 11 7 16 10 9 12 6 13 21 2 5	N-24	5 2 21 13 6 12 24 9 10 16 7 1 3 22 18 19 8 11 23 17 15 4 14 20

Table 5. Performance comparison for Anjos instances ($60 \leq n \leq 80$).

Instance	n	Cost ^a	Time ^a	Cost ^b	Time ^b	Cost ^c	Time ^c	Cost ^d	Time ^d	Cost ^e	Time ^e	Proposed heuristic	
												Cost	Time
Anjos_60_1	60	1477834	19.54	1477834	3.702	1477834	106.4	1477834	46.73	1477834	10.31	1477834	40.04
Anjos_60_2	60	841792	22.34	841776	4.031	841776	123.6	841776	41.54	841776	10.45	841776	40.93
Anjos_60_3	60	648337.5	68.81	648337.5	7.28	648337.5	101.6	648337.5	50.4	648337.5	10.89	648337.5	41.20
Anjos_60_4	60	398468	20.71	398406	6.391	398406	115.2	398406	53.52	398406	10.64	398406	39.97
Anjos_60_5	60	318805	26.41	318805	4.03	318805	102	318805	52.35	318805	10.43	318805	40.27
Anjos_70_1	70	1528621	64.83	1528537	9.031	1528537	274.62	1528537	82.61	1528537	18.15	1528537	44.54
Anjos_70_2	70	1441028	77.49	1441028	8.156	1441028	277.84	1441028	88.16	1441028	17.55	1441028	44.08
Anjos_70_3	70	1518993.5	68.26	1518993.5	7.499	1518993.5	327.98	1518993.5	83.17	1518993.5	18.17	1518993.5	43.93
Anjos_70_4	70	968796	100.59	968796	16.311	968796	340.4	968796	102.26	968796	18.73	968796	42.29
Anjos_70_5	70	4218017.5	60.48	4218002.5	8.375	4218002.5	247.94	4218002.5	81.59	4218002.5	17.74	4218002.5	44.06
Anjos_75_1	75	2393456.5	125.26	2393456.5	18.281	2393456.5	616.5	2393456.5	127.66	2393456.5	25.18	2393456.5	47.57
Anjos_75_2	75	4321190	128.95	4321190	9.796	4321190	588	4321190	118.01	4321190	25.14	4321190	47.32
Anjos_75_3	75	1248537	157.95	1248423	24.562	1248423	595.5	1248423	143.69	1248423	25.13	1248423	46.90
Anjos_75_4	75	3941891.5	119.92	3941816.5	11.359	3941816.5	601.5	3941816.5	125.37	3941816.5	25.03	3941816.5	47.01
Anjos_75_5	75	1791408	101.67	1791408	18.14	1791408	655.5	1791408	138.71	1791408	25.72	1791408	47.33
Anjos_80_1	80	2069097.5	75.41	2069097.5	33.578	2069097.5	974.67	2069097.5	162.59	2069097.5	32.6	2069097.5	49.93
Anjos_80_2	80	1921177	68.75	1921136	19.03	1921136	1010.18	1921136	174.8	1921136	32.15	1921136	49.08
Anjos_80_3	80	3251368	85.9	3251368	43.578	3251368	895.17	3251368	181.84	3251368	32.42	3251368	48.60
Anjos_80_4	80	3746515	77.81	3746515	44.077	3746515	902.59	3746515	148.41	3746515	31.71	3746515	48.89
Anjos_80_5	80	1588901	196.51	1588885	41.188	1588885	1119.36	1588885	199.79	1588885	33.12	1588885	49.01

^aRefers to the results reported in [8]^bRefers to the results reported in [24]^cRefers to the results reported in [10]^dRefers to the results reported in [25]^eRefers to the results reported in [13]

‘Time’ indicates the computational time in seconds

element of *change* is set to 1. Now two local search methods, viz. *adjacent neighbour* and *best permutation*, are used to improve a solution only if the corresponding element of *change* is 1. This strategy is useful to minimize the computation time of the algorithm. We employ this strategy because for the same input layout, these two local search improvement methods create the same output layout. The *Random Replacement* method is used at the end to introduce diversity in the solutions if any solution gets stuck to local optima. Again, the next generation is started with the modified population of layouts if termination condition is not met.

5. Results and discussion

The effectiveness of the proposed heuristic algorithm is tested with the instances of sizes ranging from 5 to 300. Note that the size of an instance is defined by the number of facilities. In this article, the instances of SRFLP and SREFLP are taken from FLPLIB: Facility Layout Database (<http://www.miguelanjos.com/flplib>) and [54]. The proposed heuristic algorithm is programmed using

MATLAB and run on an Intel Core i5 with 3.10 GHz processor and 8 GB RAM having Ubuntu 16.04 LTS operating system. In the experiment, when the instance size is less than 10, between 10 and 50, and more than 50, the population size (PS) is considered as 4, 12 and 24, respectively. The neighbourhood size (α) is considered as 2 when the instance size is less than or equal to 50 and it is considered as 3 when the instance size is more than 50. We have set these parameter values experimentally. In this article, the results reported are the best results obtained by running the proposed algorithm 10 times on each problem instance.

For comparatively smaller instances of sizes up to 40 facilities, we have compared the performance of the proposed algorithm with different exact algorithms based on mathematical programming [14, 22, 23]. For larger instances of sizes up to 300 facilities, we have used different meta-heuristic algorithms [8, 10, 13, 24–26] for comparison.

The N type instances [22] of SRFLP with 40 facilities are first considered in this article. The result obtained for each of the instances using the proposed algorithm is shown in table 1 and the corresponding best layout is mentioned in

Table 6. Best layouts obtained for Anjos type instances of SRFLP.

Instance	Best layout
Anjos_60_1	1 34 18 39 20 55 60 58 30 19 59 52 10 53 50 37 43 31 45 23 5 38 29 41 49 22 42 14 17 2 26 8 33 32 4 35 13 16 44 36 9 47 12 57 7 54 46 51 6 25 40 3 21 15 24 28 56 48 11 27
Anjos_60_2*	53 10 13 41 29 50 30 9 15 42 8 14 34 32 40 33 28 21 56 37 25 5 24 1 54 39 17 46 45 18 36 52 27 6 43 59 51 26 55 58 16 60 38 47 7 49 31 3 12 48 23 2 4 19 22 57 35 44 11 20
Anjos_60_3*	5 19 3 42 38 29 16 24 48 20 11 41 44 21 2 14 52 55 37 57 12 18 15 9 35 40 33 50 8 43 46 30 26 39 17 60 45 25 56 28 23 58 51 7 10 31 34 32 1 13 54 22 27 47 36 49 53 59 6 4
Anjos_60_4	13 20 31 19 55 57 10 39 7 44 24 22 36 33 56 11 21 6 23 17 46 40 59 53 5 3 45 2 50 35 14 27 15 18 58 8 16 60 29 26 42 37 54 47 30 51 32 48 52 9 49 38 28 1 4 41 34 25 43 12
Anjos_60_5	39 53 37 7 16 47 59 4 19 41 54 9 13 2 55 46 17 35 20 30 36 60 40 28 8 25 48 6 50 10 27 21 42 56 24 45 31 58 15 51 5 18 22 23 57 14 32 29 43 26 1 11 3 38 34 52 44 49 33 12
Anjos_70_1	53 47 65 40 2 28 62 22 15 8 32 9 63 31 69 51 68 1 4 16 64 61 41 38 56 67 70 44 10 26 14 19 33 42 49 5 30 36 23 55 60 13 18 21 24 27 54 11 12 58 6 59 52 7 20 66 3 34 45 46 25 43 48 17 29 57 39 35 37 50
Anjos_70_2	28 39 50 53 52 10 47 21 36 26 1 7 3 19 13 69 58 9 67 33 23 45 29 62 18 30 63 11 14 68 6 49 44 43 24 42 16 8 40 2 4 20 54 46 22 5 27 15 37 34 31 32 55 35 12 65 17 38 60 70 66 48 41 59 51 61 64 57 25 56
Anjos_70_3	8 30 63 51 54 27 29 43 21 32 23 24 20 1 41 67 6 47 9 26 11 65 22 4 61 7 70 19 2 42 37 68 50 10 14 49 53 5 18 56 25 28 66 39 36 40 3 35 62 60 45 13 55 48 12 59 58 38 33 46 15 64 69 34 17 31 57 52 44 16
Anjos_70_4	16 25 7 15 30 51 47 52 9 63 54 6 64 22 11 29 61 42 33 12 14 23 58 60 68 53 24 26 5 46 2 34 18 36 50 1 28 44 27 37 49 56 57 69 59 19 70 17 21 67 55 62 40 20 48 43 3 13 32 10 45 65 31 39 38 4 8 35 66 41
Anjos_70_5	19 38 9 1 68 23 62 31 51 2 40 58 37 50 22 39 10 6 54 16 65 63 27 49 8 26 61 41 43 56 24 14 35 20 70 5 30 36 12 4 21 53 11 7 29 34 60 46 3 66 42 59 15 55 45 48 57 25 47 52 13 18 33 69 32 64 44 17 28 67
Anjos_75_1	38 47 46 16 29 9 63 72 54 28 51 5 13 33 21 8 45 17 22 25 11 75 39 62 53 43 3 68 70 4 1 66 10 31 34 12 19 74 20 42 32 24 2 37 40 55 71 44 41 7 35 6 65 50 23 30 49 15 61 56 18 26 59 27 52 36 57 73 67 69 48 60 14 64 58
Anjos_75_2*	25 26 43 56 37 72 47 70 66 30 39 45 35 24 69 54 33 10 41 4 19 31 9 74 17 48 36 46 55 13 68 16 38 27 15 62 8 12 23 22 11 67 34 3 71 65 75 20 53 5 52 58 73 29 1 57 59 7 18 50 60 42 40 63 14 6 44 28 2 21 61 32 64 51 49
Anjos_75_3	22 50 54 1 14 63 53 55 25 8 72 18 70 66 38 2 37 44 30 31 62 16 3 34 59 52 49 6 32 7 40 73 58 75 9 24 35 28 21 45 67 5 57 65 11 71 48 13 27 12 36 20 56 61 64 74 39 4 60 26 68 23 29 46 41 51 43 17 15 33 19 10 42 69 47
Anjos_75_4*	21 17 9 49 72 38 69 68 27 25 6 51 61 74 11 31 4 71 43 54 59 58 23 26 66 63 56 48 55 19 2 67 1 32 13 45 24 18 34 73 44 53 28 52 16 65 35 64 3 12 46 39 33 40 29 41 20 57 22 47 30 70 8 37 62 42 10 75 7 50 15 14 5 60 36
Anjos_75_5*	24 20 37 72 52 51 50 60 35 43 58 1 68 71 44 47 74 32 7 65 73 66 23 31 22 38 49 8 42 3 28 17 10 5 30 70 12 55 29 25 46 45 34 36 59 11 57 54 48 15 67 4 56 21 69 75 39 61 18 41 16 53 14 40 64 62 2 6 13 19 63 9 26 33 27
Anjos_80_1*	55 70 2 60 80 67 44 27 65 40 21 16 29 43 19 46 14 63 61 39 53 52 12 68 47 45 75 49 51 34 62 56 66 54 48 41 32 20 10 50 58 15 42 76 9 31 36 6 22 23 74 33 13 17 24 37 18 7 69 26 72 73 30 5 59 35 3 8 77 38 64 28 1 4 71 79 11 57 25 78
Anjos_80_2*	11 66 61 45 48 43 49 63 69 51 80 60 78 64 52 31 71 37 79 7 70 30 73 76 59 19 68 26 13 75 42 62 44 50 2 65 8 34 40 9 36 39 38 4 20 53 3 67 6 21 35 25 23 28 27 72 1 77 33 16 29 41 54 12 47 74 32 56 15 46 14 58 5 55 17 10 24 18 57 22
Anjos_80_3*	57 63 54 53 37 62 61 26 29 32 64 35 48 72 30 22 25 76 67 77 10 50 52 51 8 3 39 78 27 17 80 44 21 14 11 59 23 7 41 19 73 75 15 1 18 2 71 55 60 66 9 38 31 6 12 28 79 65 56 4 42 24 5 45 47 46 43 13 70 69 49 34 36 68 20 33 16 58 40 74
Anjos_80_4	69 60 64 75 71 38 35 78 54 30 46 28 32 42 66 80 12 43 74 76 14 29 9 62 27 17 6 4 18 67 15 3 7 16 2 20 72 31 19 79 52 26 1 33 48 37 53 77 13 49 8 51 65 70 5 59 11 39 45 68 23 25 73 63 34 24 55 10 44 36 21 58 57 22 56 61 40 50 41 47
Anjos_80_5*	25 17 48 41 58 60 69 78 13 49 42 72 12 29 16 51 14 64 26 28 24 15 56 5 57 50 46 23 63 40 45 20 80 4 18 77 39 32 3 59 65 55 66 71 35 53 43 6 44 54 75 79 34 30 62 36 33 76 9 19 31 8 70 1 22 11 74 37 10 68 67 21 73 61 27 38 52 47 7 2

*Indicates that the best layout is same as mentioned in [54]

table 2. The proposed algorithm finds the optimal cost for each of the instances. It is evident from table 1 that the proposed algorithm significantly improves the computational time.

The O [55], S [56], Y [17] and N [57] type instances of SREFLP are considered with up to 35 facilities in table 3. All the facilities have the same length for these instances. Columns 4 and 5 of table 3 give the computational times required using specialized LP-based branch and bound approach [23] and general SDP-based approach [22], respectively. It is clear from table 3 that the optimal cost as mentioned in [14] is achieved for

each instance using the proposed algorithm and the computational time is improved significantly. The corresponding best layout for each of the O, N, S and Y type instances is given in table 4. Note that there exists more than one layout for O-6, O-7, O-8 and N-21 instances with the same cost. It is also to be noted that the reverse of a particular layout gives the same cost and in this article, we have considered a layout and its reverse as the same solution.

The *Anjos* benchmark instances [38] are considered next in this article. This benchmark data set consists of 20 instances of sizes ranging from 60 to 80. We have

Table 7. Performance comparison for sko instances ($64 \leq n \leq 100$).

Instance	n	Cost ^b	Time ^b	Cost ^c	Time ^c	Cost ^d	Time ^d	Cost ^e	Time ^e	Proposed heuristic	
										Cost	Time
sko-64-01	64	—	—	96933	196.98	96883	82.8	96881	15.37	96881	41.23
sko-64-02	64	—	—	634338.5	189.84	634332.5	68.31	634332.5	13.98	634332.5	40.97
sko-64-03	64	—	—	414323.5	185.22	414323.5	80.33	414323.5	14.12	414323.5	41.56
sko-64-04	64	—	—	297205	190.68	297129	91.05	297129	14.28	297129	39.97
sko-64-05	64	—	—	501922.5	182.7	501922.5	75.86	501922.5	13.92	501922.5	41.26
sko-72-01	72	—	—	139150	465.12	139150	115.21	139150	25.55	139150	45.57
sko-72-02	72	—	—	712005	419.04	711998	192.12	711998	22.99	711998	45.02
sko-72-03	72	—	—	1054110.5	412.8	1054110.5	114.16	1054110.5	22.48	1054110.5	45.97
sko-72-04	72	—	—	919635.5	418.56	919586.5	135.46	919586.5	22.3	919586.5	44.92
sko-72-05	72	—	—	428879.5	433.44	428226.5	116.5	428226.5	23.28	428226.5	44.98
sko-81-01	81	—	—	205166	1298.16	205106	311.63	205108.5	40.74	205106	48.01
sko-81-02	81	—	—	521391.5	1402.38	521391.5	226.91	521391.5	36.33	521391.5	47.89
sko-81-03	81	—	—	970862	1276.56	970796	241.5	970796	35.88	970796	47.56
sko-81-04	81	—	—	2031979	1425.06	2031803	193.98	2031803	37.49	2031803	48.07
sko-81-05	81	—	—	1303805	1301.4	1302711	287.22	1302711	35.94	1302711	48.11
sko-100-01	100	378234	1220.76	378614	7279.14	378234	877.12	378234	99.34	378234	57.93
sko-100-02	100	2076008.5	91.98	2076048.5	7632.9	2076008.5	526.09	2076008.5	86.1	2076008.5	57.27
sko-100-03	100	16145614.5	505.92	16148818	7510.8	16145614	599.92	16145598	82.37	16145614.5	57.89
sko-100-04	100	3232522	405	3232740	7395.96	3232531	592	3232522	80.61	3232522	58.92
sko-100-05	100	1033080.5	518.28	1033345.5	7087.08	1033080.5	591.75	1033080.5	84.63	1033080.5	57.98

^bRefers to the results reported in [24]^cRefers to the results reported in [10]^dRefers to the results reported in [25]^eRefers to the results reported in [13]

‘Time’ indicates the computational time in seconds

Missing entry (‘—’) indicates that the corresponding method has not been applied to the instance

compared the performance of the proposed algorithm for these 20 large size instances to those of the recently developed five meta-heuristic algorithms, and the performance comparison is given in table 5. The first column of table 5 gives the name of the instance. The second column gives the number of facilities (n). The performance of the proposed algorithm has been compared to that of a permutation-based genetic algorithm (GA) [8], a hybrid GA with local search [24], insertion-based Lin–Kernighan heuristic proposed in [10], scatter search algorithm [25] and a GA incorporated with local search [13]. The proposed algorithm achieves the best known cost for every instance as compared with the literature, and the computation time is comparable to those of other existing methods. The best layouts found by the proposed algorithm are given in table 6.

Next, we considered *sko* [58] benchmark instances, which were originally used for *Quadratic Assignment Problem* (QAP) [59] and later these instances were adapted for SRFLP in [7]. Here, 20 large size sko instances have been used. The size of these instances ranges from 64 to 100. The performance comparisons of the proposed algorithm for these 20 instances to the four heuristic methods

are given in table 7. Here, we have compared the performance of the proposed algorithm to those of two customized genetic algorithms [13, 24], insertion-based Lin–Kernighan heuristic [10] and scatter search algorithm [25]. The layouts corresponding to the best cost mentioned in table 7 are given in table 8. The computational time requirements of the proposed algorithm and the methods proposed by Kothari and Ghosh [10, 13, 25] are graphically compared in figures 5 and 6.

We have also considered *Amaral* instances, each having 110 facilities [60]. The performance of the proposed algorithm is tested with two customized GAs [13, 24], insertion-based Lin–Kernighan heuristic [10] and scatter search algorithm [25]. The performance comparison for these three *Amaral* instances is given in table 9 and the corresponding best layouts are given in table 10. The computational time required by the proposed algorithm for each of the *Amaral* instances is graphically compared in figure 7 with the time required by each of the methods of Ozcelik [24] and Kothari and Ghosh [10, 13, 25].

We further investigate the performance of the proposed algorithm with larger instances of SRFLP. These benchmark instances having size ranging from 110 to 300 are

Table 8. Best layouts obtained for sko type instances of SRFLP.

Instance	Best layout
sko-64-01	15 36 12 27 61 41 34 3 46 32 54 11 28 43 30 5 40 39 51 47 6 38 48 55 62 20 19 64 4 42 53 16 10 49 13 23 52 29 9 22 24 58 8 14 21 44 33 45 1 7 59 26 17 37 50 25 56 2 63 60 18 35 57 31
sko-64-02*	8 53 19 25 42 64 62 63 57 22 26 58 10 9 31 33 13 2 44 24 4 59 49 21 17 35 56 16 50 37 1 7 45 29 23 20 60 48 55 28 6 38 15 52 61 36 46 14 11 12 39 41 34 54 43 3 51 40 5 30 27 32 18 47
sko-64-03	6 62 59 50 7 20 48 32 19 37 33 8 2 54 11 40 28 26 60 5 39 1 45 34 38 17 35 30 47 18 43 63 25 10 53 24 57 58 14 44 3 31 27 21 55 64 51 36 46 16 23 22 52 4 29 13 49 42 41 56 9 61 12 15
sko-64-04	15 59 57 53 11 54 32 41 30 8 19 10 33 56 25 17 2 38 50 26 34 37 1 7 45 47 35 44 58 13 49 21 24 4 64 39 62 5 16 23 12 29 55 22 9 28 48 14 40 61 52 18 6 3 51 46 20 63 27 43 36 42 60 31
sko-64-05	62 59 15 25 53 50 26 17 19 2 44 1 37 57 7 8 32 38 34 33 39 11 54 41 45 35 21 56 30 24 48 60 28 40 23 3 27 4 31 47 51 43 5 6 16 42 55 58 13 64 10 14 52 12 61 46 20 49 63 29 22 18 9 36
sko-72-01	12 53 31 64 60 18 35 8 56 10 70 27 30 17 67 21 2 14 22 28 26 47 65 52 23 61 29 1 7 38 59 46 49 33 50 13 37 63 32 39 16 9 6 71 44 55 57 36 51 68 42 40 48 41 15 19 58 20 66 43 4 62 72 69 25 5 11 45 54 24 34 3
sko-72-02	34 5 58 41 45 11 62 64 20 9 40 71 17 1 19 4 66 6 54 16 72 61 15 36 69 68 57 26 44 55 24 67 39 33 29 25 48 42 51 8 50 31 21 49 7 30 27 2 38 46 60 22 35 28 10 70 52 47 65 53 3 43 63 37 32 13 59 23 14 56 18 12
sko-72-03*	58 7 72 15 5 3 2 49 38 51 41 55 20 71 34 1 4 36 29 44 57 40 45 11 32 66 19 68 24 42 52 69 25 12 37 43 6 53 47 35 16 27 54 33 48 23 64 22 65 63 13 46 50 8 21 62 61 59 70 10 30 26 28 9 67 17 39 18 60 56 14 31
sko-72-04*	12 3 56 64 24 72 45 50 36 41 20 11 65 61 15 4 66 43 62 63 37 58 34 69 25 6 53 18 5 19 39 9 68 67 16 54 48 51 42 40 44 57 55 31 29 38 60 46 23 49 22 14 35 33 71 70 13 10 30 7 27 28 1 47 52 26 21 2 32 59 17 8
sko-72-05	51 29 34 40 71 9 44 23 1 7 33 38 55 16 41 58 59 46 65 6 19 15 20 14 49 66 68 61 36 4 57 45 5 69 25 11 24 26 13 43 32 47 52 42 62 63 22 50 37 21 12 2 35 72 17 31 67 64 60 39 48 30 28 54 27 70 10 18 56 3 53 8
sko-81-01	8 47 60 54 53 16 76 34 40 10 28 46 64 29 72 71 77 80 75 79 12 63 37 51 24 59 43 73 18 20 58 27 5 1 62 13 68 32 52 45 2 44 78 57 11 55 22 42 35 70 26 36 39 7 31 49 38 19 15 14 81 21 41 6 4 17 23 69 33 65 67 56 48 9 50 25 30 61 3 66 74
sko-81-02*	8 28 77 60 64 57 76 16 47 72 54 62 7 63 27 10 39 20 18 24 43 53 75 71 40 59 73 37 68 13 46 51 78 1 58 5 79 29 80 32 12 45 2 44 19 31 26 34 9 11 4 42 65 30 36 67 23 50 41 70 74 66 33 17 69 3 21 61 15 6 56 48 52 14 81 35 25 49 38 55 22
sko-81-03*	47 77 53 16 44 54 10 34 40 76 60 59 63 20 37 51 13 18 64 68 57 21 27 62 24 78 43 7 49 22 45 52 58 69 75 73 1 8 71 32 46 56 4 67 42 23 17 50 65 41 66 81 26 36 80 19 12 33 38 70 3 25 61 2 14 15 31 9 5 6 48 72 28 11 55 29 79 74 39 35 30
sko-81-04	66 74 8 25 26 65 69 23 51 3 14 81 20 50 2 30 61 21 12 28 6 44 9 11 19 17 15 70 48 33 46 39 72 40 34 32 49 60 4 67 37 56 78 42 54 10 18 35 36 55 1 45 52 27 62 58 75 64 47 63 73 31 13 68 57 76 77 24 53 38 16 43 59 7 41 5 29 22 79 71 80
sko-81-05	66 74 56 48 52 36 6 15 8 9 5 3 55 72 61 68 27 2 45 7 62 39 78 70 57 31 13 16 44 21 17 50 1 46 11 32 81 28 41 14 53 49 71 10 25 20 58 67 24 51 59 77 69 73 33 23 76 37 63 12 18 19 43 60 42 26 35 80 30 65 75 47 38 29 64 22 4 79 54 34 40
sko-100-01	3 35 44 29 17 21 7 76 53 45 12 36 50 41 48 61 23 49 2 70 82 92 38 72 81 64 90 66 47 51 46 26 100 69 20 40 14 99 43 94 67 85 73 30 24 89 8 68 93 96 4 56 98 42 19 59 9 84 87 86 62 52 22 16 31 34 75 80 54 55 13 27 10 60 28 57 32 63 5 88 77 25 58 74 95 11 6 15 33 79 39 83 37 71 91 1 97 78 18 65
sko-100-02	78 91 97 58 27 5 39 24 42 65 10 73 18 93 88 25 32 11 95 60 64 9 85 30 96 62 54 63 71 83 13 75 84 79 22 34 87 74 37 57 6 80 16 89 15 28 31 55 56 4 23 82 1 19 86 44 90 66 47 98 2 21 52 51 49 92 45 67 35 46 20 69 70 100 59 14 43 81 8 68 40 26 7 72 38 94 50 48 76 36 41 77 61 12 53 3 99 17 29 33
sko-100-03*	44 78 97 35 39 89 24 80 54 21 5 37 71 82 91 31 63 27 13 83 75 11 16 14 9 62 65 73 30 85 99 96 12 93 56 95 10 4 55 74 25 1 18 84 79 57 6 32 77 20 88 34 81 22 15 17 42 98 26 59 23 64 46 7 52 51 67 50 94 29 48 36 38 72 19 86 87 68 66 90 2 43 69 70 41 47 100 61 40 92 53 49 45 76 60 33 8 28 58 3
sko-100-04	49 42 39 79 71 25 32 93 97 18 5 94 52 68 8 98 83 9 16 88 22 33 43 21 27 75 80 24 60 67 86 28 31 74 19 89 54 15 1 56 96 65 4 91 85 55 13 11 78 63 57 62 37 77 59 81 61 50 92 48 90 100 38 46 26 82 69 53 35 72 66 70 36 51 10 40 20 30 47 73 14 41 87 34 64 95 44 29 23 12 17 99 2 76 58 45 84 6 3 7
sko-100-05*	78 90 55 63 25 13 58 6 30 84 60 4 65 96 74 28 85 54 75 10 80 24 27 31 15 95 37 71 97 11 83 39 42 89 16 9 91 18 57 79 5 88 22 43 33 77 1 32 93 56 81 34 73 64 87 14 2 20 67 99 46 41 26 53 94 68 40 36 82 66 49 70 44 8 100 35 21 7 47 98 29 61 59 51 69 19 62 23 12 17 38 92 52 72 86 45 48 50 3 768

*Indicates that the best layout is the same as mentioned in [54]

Figure 5. Performance comparison with Kothari and Ghosh [10, 13, 25] for sko SRFLP instances ($n = 64, 72$) (see the first 10 rows of table 7).

Figure 6. Performance comparison with Kothari and Ghosh [10, 13, 25] for sko SRFLP instances ($n = 81, 100$) (see the last 10 rows of table 7).

Table 9. Performance comparison for Amaral instances ($n = 110$).

Instance	n	Cost ^b	Time ^b	Cost ^c	Time ^c	Cost ^d	Time ^d	Cost ^e	Time ^e	Proposed heuristic	
										Cost	Time
Amaral-110-01	110	144296664.5	574.08	144330992	10514.19	144297440	975.11	144296768	119.02	144296664.5	88.91
Amaral-110-02	110	86050037	553.68	86060416	12810.04	86050208	680.1	86050112	189.56	86050037	89.46
Amaral-110-03	110	2234743.5	744.66	2234825.5	10052.1	2234798.5	811.08	2234743.5	119.02	2234743.5	92.37

^b Refers to the results reported in [24]

^c Refers to the results reported in [10]

^d Refers to the results reported in [25]

^e Refers to the results reported in [13]

'Time' indicates the computational time in seconds

Table 10. Best layouts obtained for Amaral type instances of SRFLP.

Instance	Best layout
Amaral-110-01*	8 80 53 83 98 6 49 17 54 100 57 48 2 44 52 29 94 106 41 23 18 34 30 107 78 13 70 32 31 12 105 89 81 61 59 38 45 66 68 85 37 27 103 101 104 72 36 82 10 58 87 63 21 60 96 95 20 51 102 47 25 35 43 42 88 99 97 46 90 26 50 91 71 28 5 64 16 74 77 15 56 84 69 1 93 39 24 22 55 79 7 14 92 108 4 33 110 86 3 109 9 11 65 76 67 75 73 62 19 40
Amaral-110-02*	64 62 1 13 33 11 104 69 74 25 54 16 5 57 86 96 47 55 34 80 14 58 3 70 101 91 75 48 51 9 46 99 56 26 15 88 39 76 77 84 107 2 30 73 7 93 28 22 42 35 92 108 23 100 71 68 4 90 85 94 52 6 72 78 83 82 60 24 49 10 97 17 19 31 63 53 43 66 45 38 61 29 41 20 27 89 44 105 95 81 79 110 50 36 106 59 109 102 98 37 65 103 18 21 67 87 32 40 12 8
Amaral-110-03	62 24 10 91 7 17 95 102 94 40 58 71 73 16 86 106 104 90 108 89 42 46 1 83 18 41 9 74 29 87 96 53 97 66 12 54 60 2 81 101 65 47 77 67 48 39 19 21 43 70 49 28 32 64 79 85 13 37 78 82 57 15 105 72 36 59 69 103 5 93 31 110 6 50 109 14 56 52 23 100 76 11 107 26 30 75 4 22 88 44 80 63 3 35 98 55 25 8 99 34 45 33 68 38 92 27 51 61 20 84

*Indicates that the best layout is the same as mentioned in [54]

Figure 7. Performance comparison with Ozcelik [24] and Kothari and Ghosh [10, 13, 25] for Amaral instances ($n = 110$) (see table 9).

taken from [54]. This set of large size SRFLP instances are used in [15, 26]. Three insertion-based local search procedures have been developed by Palubeckis [26] and these local search procedures have been incorporated into a variable neighbourhood structure (VNS) to form different algorithms for solving large size SRFLP instances. In this article, we have compared the performance of the proposed algorithm for the larger instances of SRFLP to that of the best performing algorithm VNS-LS3 developed in [26]. We have set the parameter α to 5 while performing experiments on these large data sets to get the best cost mentioned in [26]. This eventually increased the computational time for our experiment. The computational results are given in table 11. Column 3 of table 11 gives the best cost obtained by running VNS-LS3 for 5 h [26]. The proposed algorithm also achieves the same best cost within reasonable

computational time, as shown in table 11. In our experiment, we terminate the program execution for these 20 large size instances whenever it achieves the best cost obtained by VNS-LS3 as mentioned in [26]. The computational time required by the proposed algorithm for each of these large size instances is graphically compared with the time required by each of the methods proposed by Palubeckis [26] as shown in figure 8. In table 12, we present the best layouts corresponding to the best cost mentioned in table 11. It is to be noted that the best layouts for all the instances mentioned in table 12 are different from those given in [54], although the corresponding costs are the same. Further, note that we have considered two layouts as the same if they are reverse of each other. This indicates the existence of multiple layouts having the same cost and it is quite natural in any combinatorial optimization problem.

Table 11. Performance comparison for large-scale SRFLP instances ($110 \leq n \leq 300$).

Instance	n	Cost ^f	Time ^f	Proposed heuristic	
				Cost	Time
p110	110	4435868	5	4435868	3.3
p120	120	6282721	5	6282721	3.7
p130	130	7880929.5	5	7880929.5	3.8
p140	140	9257162	5	9257162	3.9
p150	150	10624389.5	5	10624389.5	4.2
p160	160	14873277	5	14873277	4.3
p170	170	16630187	5	16630187	4.3
p180	180	18746031.5	5	18746031.5	4.9
p190	190	24453272	5	24453272	4.7
p200	200	27482649.5	5	27482649.5	4.9
p210	210	29512000.5	5	29512000.5	4.4
p220	220	37351850.5	5	37351850.5	4.5
p230	230	46744886	5	46744886	4.5
p240	240	46717781	5	46717781	4.8
p250	250	54526293.5	5	54526293.5	4.8
p260	260	63300360.5	5	63300360.5	4.9
p270	270	68960438.5	5	68960438.5	5.1
p280	280	73845821	5	73845821	5.1
p290	290	86255267.5	5	86255267.5	5.4
p300	300	95937735	5	95937735	5.7

^fRefers to the results reported in [26]

‘Time’ indicates the computational time in hours

Figure 8. Performance comparison with Palubeckis [26] for large-scale SRFLP instances ($110 \leq n \leq 300$) (see table 11).

Table 12. Best layouts obtained for large-scale SRFLP instances ($110 \leq n \leq 300$).

Instance	Best layout
p110	97 20 4 30 38 63 94 103 109 50 7 96 2 59 70 83 85 34 47 11 19 100 86 3 89 98 27 1 69 45 28 44 76 81 71 107 53 46 14 22 73 101 36 79 56 48 65 37 102 12 87 62 92 26 84 99 66 25 42 90 106 32 61 80 13 15 52 35 6 21 51 104 91 58 93 10 74 39 55 41 43 72 82 16 110 33 29 88 77 9 60 17 67 57 105 78 64 75 40 108 31 5 54 68 23 24 49 95 18 8
p120	109 4 99 115 92 35 79 11 81 108 49 74 61 23 22 40 46 84 110 51 9 8 34 91 37 12 10 104 96 3 18 5 56 87 44 26 45 117 60 15 62 100 114 116 86 105 113 39 64 14 82 90 42 53 2 13 67 17 118 29 36 16 94 38 73 101 69 80 59 52 33 54 102 72 95 66 19 107 71 83 21 68 93 63 98 85 70 57 28 119 111 97 55 6 48 32 88 43 50 89 75 25 76 65 30 58 106 47 78 1 31 24 27 103 7 77 112 41 120 20
p130	113 122 3 59 97 77 123 117 39 101 114 47 129 56 6 67 9 44 19 12 124 79 2 41 29 92 26 11 116 76 99 40 66 80 90 82 83 126 57 30 46 17 20 14 121 74 8 61 86 45 112 55 106 84 125 35 65 72 95 105 102 24 64 127 28 13 31 107 38 128 93 70 68 81 25 60 52 7 49 63 87 108 130 96 109 34 119 58 16 18 23 33 91 110 103 115 15 120 85 32 111 100 89 4 54 94 48 5 104 75 21 69 42 37 22 53 73 43 51 62 27 1 98 71 88 36 118 10 50 78
p140	68 109 116 48 136 66 18 69 113 93 2 34 133 19 137 86 79 119 94 11 132 114 35 77 4 76 140 31 110 53 49 91 101 107 20 22 84 24 30 58 59 138 111 130 127 40 26 9 13 37 15 97 118 117 124 45 92 131 78 128 65 120 121 33 16 52 64 21 23 50 8 27 1 100 42 51 104 98 10 125 46 82 28 75 5 139 81 60 95 103 99 55 106 73 70 14 102 36 85 63 90 7 74 105 25 12 129 54 123 17 62 108 38 135 41 29 71 39 80 115 96 43 126 72 6 89 56 87 3 67 61 112 57 83 44 88 32 47 134 122
p150	55 54 45 78 64 5 83 85 84 60 110 103 146 20 2 15 127 42 58 126 149 49 147 134 6 79 150 67 74 96 73 144 33 24 137 120 47 97 56 59 141 28 1 75 148 52 48 38 91 65 32 139 132 81 23 29 112 82 26 16 72 11 43 130 131 140 129 86 37 111 108 40 68 61 138 70 99 17 113 9 66 135 30 128 39 35 122 7 100 44 87 71 119 92 3 107 125 95 104 102 118 98 27 10 21 89 62 93 114 53 50 63 76 77 136 116 133 115 88 46 8 117 18 121 41 4 19 94 106 12 13 34 51 25 124 36 22 142 101 69 109 90 143 31 105 123 14 145 80 57
p160	78 142 120 107 68 109 108 79 72 151 160 73 106 134 21 43 11 144 8 155 19 25 62 95 33 111 136 119 10 150 85 1 122 124 27 158 40 39 35 103 9 137 91 37 61 143 44 102 129 18 135 101 157 63 110 139 60 4 66 50 147 23 112 148 130 115 41 105 56 127 82 121 99 65 104 5 59 114 116 154 92 128 71 96 70 48 54 7 141 118 98 51 140 133 28 20 29 138 76 80 152 6 132 32 83 16 89 46 58 13 94 69 126 113 49 90 30 24 84 67 42 93 15 22 64 47 117 57 125 97 131 38 87 153 34 3 12 75 86 100 31 53 36 88 81 55 149 17 52 145 156 146 123 14 26 45 74 159 2 77
p170	151 110 131 114 61 3 68 154 29 6 88 91 94 146 54 1 77 48 90 8 87 129 7 37 59 98 134 156 108 72 20 99 148 117 136 157 24 5 137 111 169 158 23 70 92 160 170 11 18 93 153 60 12 78 145 58 42 106 74 55 25 103 32 36 64 19 162 14 122 116 102 163 79 161 27 96 133 128 46 164 124 143 130 82 30 31 71 97 80 75 62 69 109 49 120 2 127 47 9 107 101 13 86 141 140 126 21 17 50 112 152 52 132 63 73 34 147 113 150 144 119 83 41 16 51 43 104 123 76 38 65 159 100 10 66 39 139 155 22 95 35 167 168 81 166 33 118 56 44 105 26 135 165 121 28 53 115 84 89 4 138 67 45 85 149 142 15 57 40 125
p180	11 140 128 132 150 136 92 137 142 109 163 54 51 165 99 31 33 63 66 178 166 82 113 175 29 69 88 91 151 70 162 37 177 49 26 160 24 153 138 16 73 27 95 59 149 84 112 157 114 18 36 48 47 9 127 14 25 124 108 32 120 19 152 139 61 169 1 23 148 50 89 30 83 98 86 65 44 119 125 103 156 93 126 131 13 123 174 5 28 78 34 129 155 122 79 2 68 58 56 179 170 41 104 80 115 17 71 81 100 102 6 74 87 64 159 141 46 77 15 145 106 117 172 53 4 97 110 7 75 105 60 118 12 147 143 176 171 90 38 55 8 85 107 164 116 45 133 135 43 22 94 40 121 67 72 21 57 130 154 167 62 134 168 144 146 180 42 52 39 161 10 20 76 111 35 96 158 173 101 3
p190	96 47 39 14 187 53 18 24 99 183 168 62 21 86 109 180 90 156 159 30 176 146 148 41 37 102 16 165 104 9 131 45 34 150 122 52 127 110 57 22 10 115 3 74 12 163 44 48 92 166 154 83 35 87 101 67 33 157 123 179 145 133 188 153 125 134 77 89 75 81 23 189 186 172 19 91 136 58 32 55 167 13 149 137 141 46 28 135 139 73 38 17 182 88 108 15 184 144 1 5 120 78 105 151 93 65 4 68 107 71 117 70 31 60 42 85 64 63 79 190 98 171 113 8 175 66 169 7 36 152 76 103 173 43 181 80 25 51 26 40 178 69 20 185 147 116 119 158 72 6 82 174 162 132 121 142 95 118 126 106 11 124 111 2 29 100 54 97 130 128 94 112 170 114 56 160 164 61 161 177 140 129 155 27 50 84 59 138 143 49
p200	136 75 176 102 48 89 17 52 155 177 197 60 16 11 154 149 109 55 35 125 152 117 14 99 161 50 68 103 71 145 158 111 181 196 96 184 51 165 139 156 142 83 100 70 122 151 190 37 159 32 45 148 87 25 49 24 84 192 8 27 198 61 28 135 62 57 185 12 167 110 41 54 90 113 44 105 108 107 128 88 26 13 112 129 134 141 106 146 9 38 36 180 133 31 91 126 144 80 18 7 86 140 82 5 20 43 163 186 147 104 115 157 200 92 150 34 10 178 76 22 74 2 164 171 85 79 77 179 66 42 19 6 137 118 182 187 194 160 124 23 130 174 170 58 138 162 33 183 195 64 72 168 81 188 131 123 93 4 53 29 189 119 175 47 166 95 114 73 97 59 40 127 132 39 116 98 78 30 199 3 191 69 1 101 21 172 56 169 153 46 120 67 173 15 121 193 143 94 63 65
p210	140 94 101 45 83 98 187 39 51 33 90 12 35 162 104 19 123 10 95 52 207 61 170 206 20 169 166 57 26 124 3 205 196 204 71 27 73 137 143 164 152 6 109 172 208 106 102 91 185 131 136 119 60 84 54 75 66 59 63 67 110 55 31 97 81 194 171 22 103 178 13 88 188 191 92 2 93 40 23 48 165 34 11 175 132 16 87 174 180 43 82 108 158 173 139 86 111 115 193 142 105 160 125 37 138 184 116 74 153 157 179 198 24 195 144 78 64 145 141 77 202 118 114 49 4 134 155 17 70 182 177 9 201 181 1 30 72 15 120 183 53 209 44 168 146 112 186 18 147 156 121 69 117 56 135 89 113 128 25 50 203 176 133 38 200 8 149 199 32 210 189 163 154 68 167 159 41 28 85 29 80 197 148 79 96 76 14 150 36 161 47 46 122 129 62 21 100 130 192 127 107 99 7 5 65 126 151 58 42 190

Table 12 continued

Instance	Best layout
p220	20 217 122 145 89 212 96 208 111 166 88 193 29 94 143 179 99 141 83 123 219 198 180 12 10 24 218 171 84 207 165 71 15 6 19 200 132 151 119 112 185 169 68 136 14 191 77 34 110 161 157 178 118 113 109 26 64 195 121 108 57 176 105 27 56 72 197 138 114 158 41 210 162 47 163 42 206 199 59 79 164 150 137 184 91 167 177 134 4 154 142 188 187 139 186 152 50 220 66 16 11655 67 25 168 58 202 81 76 30 86 28 52 61 215 53 17 124 216 209 78 11 172 82 213 63 40 18 100 133 3 104 44 211 170 102 69 117 125 43 37 49 75 22 149 155 203 160 39 21 33 74 107 174 5 62 1 98 80 103 85 148 31 32 92 70 23 8 95 181 201 65 175 131 36 7 135 173 101 214 13 93 97 54 45 183 46 106 189 120 159 140 87 60 48 126 73 2 129 51 194 115 38 130 153 35 205 147 144 9 128 204 156 90 196 190 192 127 146 182
p230	181 151 224 200 59 44 220 182 189 125 22 33 197 229 199 78 201 192 23 150 8 194 127 49 6 159 84 183 168 21 209 148 58 128 73 143 210 68 99 19 81 157 104 94 114 121 31 174 64 77 129 162 213 172 191 86 123 205 28 32 193 141 124 80 95 38 137 140 203 176 113 212 4 133 146 147 118 163 54 177 223 39 37 132 202 5 149 161 221 152 138 102 74 43 25 55 153 215 90 98 214 82 36 75 65 83 130 20 179 226 145 27 97 66 230 52 13 186 228 14 1 96 216 46 105 173 180 178 222 154 136 34 195 106 11 9 166 170 169 101 187 227 48 219 79 122 211 225 117 198 217 184 208 91 45 7 119 67 17 190 15 160 109 131 50 57 185 134 204 171 35 10 16 144 63 2 85 155 71 188 126 72 103 142 93 30 12 120 110 107 87 41 92 88 116 3 47 18 26 62 89 115 29 60 40 165 139 164 207 218 76 196 51 42 175 24 135 158 112 100 156 53 206 167 111 108 61 69 56 70
p240	145 44 240 99 3 147 45 110 64 234 9 203 96 112 144 130 131 215 139 217 195 65 115 30 42 86 59 109 161 229 134 22 49 158 140 116 121 235 106 124 73 68 6 132 232 41 159 77 177 233 172 52 79 108 83 190 224 24 51 63 184 61 227 226 17 137 191 97 27 209 92 176 2 7 220 20 80 154 13 152 165 127 166 204 221 101 211 136 141 210 219 76 167 138 11 133 88 199 70 129 129 111 238 120 74 122 194 14 126 182 39 71 25 85 57 40 214 28 23 32 205 188 231 125 8 218 168 156 173 98 193 187 114 94 200 104 239 180 149 46 186 78 163 95 216 34 100 198 237 26 228 160 135 230 146 87 212 4 15 36 75 38 185 207 157 197 202 29 60 117 48 208 89 82 55 31 102 181 143 62 148 175 179 223 84 162 12 183 105 47 113 54 206 66 123 201 236 21 1 35 90 118 58 174 50 119 103 16 19 151 93 150 169 170 81 196 171 37 164 10 5 222 189 178 56 43 142 107 69 72 67 91 53 33 155 153 128 18 225 213
p250	49 225 28 141 246 116 187 130 222 211 9 234 184 155 61 209 240 72 123 73 236 144 250 76 153 96 142 70 119 7 102 47 193 146 26 91 37 29 95 81 210 238 220 224 233 221 206 63 22 201 134 140 59 196 182 195 68 138 161 106 6 160 117 4 24 87 57 214 232 110 176 86 200 170 174 133 118 5 168 58 156 38 244 173 213 83 121 66 1 101 128 167 25 64 14 231 36 12 113 67 48 245 215 40 177 79 18 105 137 202 157 99 85 239 100 114 178 237 94 35 217 71 27 74 77 147 65 247 216 93 56 2 205 191 139 122 199 152 165 32 181 52 108 179 54 164 30 235 189 125 42 158 120 10 55 194 21 243 166 3 208 148 127 84 33 150 169 132 190 92 51 124 183 103 31 248 104 89 219 186 212 111 145 45 223 107 180 197 241 53 198 39 11 188 143 131 13 88 207 34 126 19 97 154 17 43 115 228 159 50 15 98 230 62 75 44 69 172 82 229 136 171 185 80 90 109 175 151 162 16 23 226 218 8 242 227 135 60 112 129 149 78 20 46 192 203 163 249 204 41
p260	141 180 26 48 260 222 258 165 29 229 153 57 233 245 96 250 185 33 22 95 53 35 257 121 103 111 151 208 168 144 87 143 188 113 243 220 155 67 209 56 239 150 238 232 88 62 136 43 15 138 148 9 179 210 134 174 142 45 197 41 217 112 172 55 101 132 75 225 223 162 122 78 193 159 255 115 74 128 120 198 23 79 154 37 160 205 18 201 211 189 4 145 82 60 20 204 51 59 140 40 102 19 212 187 10 32 47 186 195 2 25 30 227 127 170 133 108 226 106 114 72 24 116 70 139 218 166 167 110 200 152 118 251 230 234 173 235 237 61 206 156 248 49 202 50 65 192 99 190 224 17 236 109 73 83 129 196 171 175 52 69 107 228 207 256 1 93 214 135 66 164 215 8 16 137 13 125 89 36 38 97 246 216 213 105 203 247 98 6 76 240 5 199 254 86 68 124 14 123 126 77 92 219 80 81 177 7 158 130 119 131 194 34 169 104 231 21 46 147 249 244 163 146 71 242 90 161 54 183 12 182 184 252 94 241 11 149 100 84 259 27 31 58 28 63 42 253 178 191 85 64 181 157 176 39 117 91 44 221 3
p270	45 27 139 128 194 18 46 83 49 233 162 188 156 53 122 124 238 186 175 102 120 84 267 213 96 41 229 110 107 157 131 176 37 30 250 169 22 2 152 85 198 227 266 88 223 13 109 205 31 103 69 75 130 12 230 268 256 258 142 244 159 231 134 164 173 220 39 3 200 36 207 228 21 125 226 243 14 246 203 154 264 254 161 112 178 251 237 182 11 140 206 196 93 33 232 218 38 193 72 240 150 225 74 187 81 61 190 263 35 148 236 189 214 133 212 57 113 158 180 224 90 253 6 20 55 261 242 239 135 42 192 16 34 50 235 71 179 252 177 171 146 4 168 70 87 132 47 66 118 202 241 208 106 80 89 147 63 265 160 217 79 94 199 155 149 259 245 23 100 97 197 195 95 19 64 60 143 77 115 216 25 185 174 144 167 111 201 56 78 209 163 8 86 165 101 221 59 129 32 114 247 141 117 123 5 29 191 43 9 136 40 10 68 166 151 62 7 153 121 58 257 170 48 15 24 249 116 1 52 26 172 28 104 44 82 65 184 99 138 54 137 51 215 17 211 181 92 73 145 67 76 262 119 127 210 98 255 222 105 91 108 126 270 234 219 248 204 260 269 183
p280	243 197 63 195 27 185 95 85 248 73 254 181 190 261 104 52 182 221 238 2 38 126 217 123 198 30 94 166 79 163 234 279 204 12 164 31 23 119 236 205 11 183 56 106 156 20 55 227 256 158 114 176 203 110 199 124 62 97 136 26 224 235 202 60 44 270 146 48 231 122 92 45 54 53 89 39 87 209 29 258 250 184 147 189 145 100 128 88 188 121 228 141 71 72 99 24 149 107 127 269 257 131 46 262 8 230 68 74 174 232 61 213 148 187 151 50 168 117 157 186 58 196 129 249 22 134 220 16 66 211 276 33 139 90 135 96 214 206 167 137 280 219 49 201 242 78 194 111 14 17 13 10 222 160 125 47 86 21 84 240 277 34 7 191 138 244 165 264 271 265 193 175 103 65 255 192 59 101 180 162 116 170 64 260 9 144 226 80 215 3 200 216 70 233 18 172 32 102 5 266 179 208 118 177 155 263 152 247 81 267 15 83 225 268 105 93 1 77 154 218 120 67 253 36 113 76 159 161 150 130 4 278 259 51 91 98 210 6 140 275 173 142 28 207 252 273 82 251 246 37 229 109 40 108 112 57 69 212 272 25 43 143 35 245 153 223 133 132 169 237 171 75 42 274 115 239 19 241 178 41

Table 12 continued

Instance	Best layout
p290	265 36 278 51 100 58 34 192 151 54 290 287 176 271 170 141 59 243 17 14 245 143 285 180 85 80 118 144 224 248 64 67 117 125 55 102 156 12 121 18 200 223 281 252 214 78 209 5 275 289 226 242 33 147 32 9 69 218 157 57 101 150 139 140 122 31 167 188 255 279 221 160 286 38 4 174 276 73 158 137 232 246 266 95 113 75 227 153 162 25 264 148 230 146 109 24 231 107 171 204 216 247 173 274 82 191 210 284 42 92 145 76 98 277 132 50 41 212 186 134 182 272 103 229 63 205 155 65 249 177 77 152 288 213 261 104 46 124 108 273 19 66 56 81 123 259 97 6 23 189 39 263 133 240 179 90 116 217 15 270 45 169 250 110 228 35 71 138 215 126 1 20 269 48 190 135 235 61 237 11 106 254 154 53 79 130 94 159 49 256 70 268 262 105 199 91 30 257 29 68 195 193 220 166 251 62 164 60 13 27 225 202 258 96 26 142 241 149 120 128 183 114 93 260 112 127 8 239 88 129 44 16 10 83 21 87 119 165 234 197 206 136 99 244 168 115 283 203 219 163 40 43 111 222 280 89 211 201 208 161 187 47 131 84 233 22 86 172 198 194 7 178 28 196 282 207 238 72 184 236 175 267 185 253 52 181 37 3 74 2
p300	16 242 107 295 33 17 175 299 288 296 171 226 12 115 29 63 249 206 72 293 203 195 120 102 272 158 131 267 213 291 281 122 181 208 193 239 230 273 76 91 78 74 259 75 163 61 113 159 266 274 227 81 4 125 11 217 276 119 44 183 37 36 262 148 283 87 174 178 188 216 141 41 197 269 50 47 101 211 145 264 212 25 105 286 294 270 289 173 198 126 34 109 45 38 31 190 209 201 26 204 244 46 225 21 153 28 222 166 165 71 233 24 268 257 161 18 27 157 169 66 154 13 64 172 256 139 292 114 111 167 56 184 49 177 229 116 89 162 150 67 85 118 284 124 221 152 149 77 298 251 202 128 223 1 48 140 15 57 68 285 247 94 86 60 62 237 92 19 65 143 231 80 192 54 224 275 290 98 58 234 130 82 10 241 2 84 51 191 83 88 156 132 8 255 240 9 200 261 147 5 121 207 3 182 138 135 144 205 93 59 185 246 32 30 260 245 129 117 42 248 189 100 70 176 199 7 218 127 232 179 20 160 151 133 96 250 282 155 254 265 106 235 69 103 55 287 108 73 180 23 280 170 253 277 142 186 187 271 123 164 278 297 112 136 79 263 90 43 252 58 300 215 243 95 39 35 137 146 196 6 22 97 194 219 238 40 168 14 220 210 104 99 279 110 53 214 236 134 52 228

6. Conclusion

In this article, we have proposed a population-based improvement heuristic with local search for solving SRFLP. The proposed heuristic approach utilizes some local search techniques and improvement strategies during each iteration for faster convergence of the solution. The proposed heuristic works well also for solving the SREFLP. The performance of the proposed algorithm has been demonstrated on several benchmark data sets and its performance has been compared to those of existing exact algorithms based on mathematical programming as well as meta-heuristic approaches. The proposed algorithm has achieved the best known results for all the instances considered in this article and the computational time is reasonably comparable to the time mentioned in the literature.

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References

- [1] Simmons D M 1969 One-dimensional space allocation: an ordering algorithm. *Oper. Res.* 17(5): 812–826
- [2] Picard J-C and Queyranne M 1981 On the one-dimensional space allocation problem. *Oper. Res.* 29(2): 371–391
- [3] Beghin-Picavet M and Hansen P 1982 Deux problèmes d'affectation non linéaires. *RAIRO-Oper. Res.* 16(3): 263–276
- [4] Heragu S S and Kusiak A 1988 Machine layout problem in flexible manufacturing systems. *Oper. Res.* 36(2): 258–268
- [5] Suryanarayanan J K, Golden B L and Wang Q 1991 A new heuristic for the linear placement problem. *Comput. Oper. Res.* 18(3): 255–262
- [6] Díaz J, Petit J and Serna M 2002 A survey of graph layout problems. *ACM Comput. Surv. (CSUR)* 34(3): 313–356
- [7] Anjos M F and Yen G 2009 Provably near-optimal solutions for very large single-row facility layout problems. *Optim. Methods Softw.* 24(4–5): 805–817
- [8] Datta D, Amaral A R S and Figueira J R 2011 Single row facility layout problem using a permutation-based genetic algorithm. *Eur. J. Oper. Res.* 213(2): 388–394
- [9] Kothari Ravi and Ghosh Diptesh 2012 The single row facility layout problem: state of the art. *Opsearch.* 49(4): 442–462
- [10] Kothari R and Ghosh D 2013 Insertion based Lin–Kernighan heuristic for single row facility layout. *Comput. Oper. Res.* 40(1): 129–136
- [11] Amaral A R S and Letchford A N 2013 A polyhedral approach to the single row facility layout problem. *Math. Program.* 141(1–2): 453–477
- [12] Kothari R and Ghosh D 2013 Tabu search for the single row facility layout problem using exhaustive 2-opt and insertion neighborhoods. *Eur. J. Oper. Res.* 224(1): 93–100
- [13] Kothari R and Ghosh D 2014 An efficient genetic algorithm for single row facility layout. *Optim. Lett.* 8(2): 679–690
- [14] Hungerländer P 2014 Single-row equidistant facility layout as a special case of single-row facility layout. *Int. J. Prod. Res.* 52(5): 1257–1268

- [15] Palubeckis G 2015 Fast simulated annealing for single-row equidistant facility layout. *Appl. Math. Comput.* 263: 287–301
- [16] Sarker B R, Wilhelm W E and Hogg G L 1998 One-dimensional machine location problems in a multi-product flowline with equidistant locations. *Eur. J. Oper. Res.* 105(3): 401–426
- [17] Yu J, Sarker B R 2003 Directional decomposition heuristic for a linear machine-cell location problem. *Eur. J. Oper. Res.* 149(1): 142–184
- [18] Anjos M F and Liers F 2012 Global approaches for facility layout and VLSI floorplanning. In: *Handbook on Semidefinite, Conic and Polynomial Optimization*, pp 849–877. Springer, Berlin
- [19] Hungerländer P and Rendl F 2013 A computational study and survey of methods for the single-row facility layout problem. *Comput. Optim. Appl.* 55(1): 1–20
- [20] Keller B and Buscher U 2015 Single row layout models. *Eur. J. Oper. Res.* 245(3): 629–644
- [21] Anjos M F and Vieira M V C 2017 Mathematical optimization approaches for facility layout problems: the state-of-the-art and future research directions. *Eur. J. Oper. Res.* 261(1): 1–16
- [22] Hungerländer P and Rendl F 2013 Semidefinite relaxations of ordering problems. *Math. Program.* 140(1): 77–97
- [23] Palubeckis G 2012 A branch-and-bound algorithm for the single-row equidistant facility layout problem. *OR Spectr.* 34(1): 1–21
- [24] Ozelik F 2012 A hybrid genetic algorithm for the single row layout problem. *Int. J. Prod. Res.* 50(20): 5872–5886
- [25] Kothari R and Ghosh D 2014 A scatter search algorithm for the single row facility layout problem. *J. Heuristics* 20(2): 125–142
- [26] Palubeckis G 2015 Fast local search for single row facility layout. *Eur. J. Oper. Res.* 246(3): 800–814
- [27] Atta S, Mahapatra P R S and Mukhopadhyay A 2018 Solving maximal covering location problem using genetic algorithm with local refinement. *Soft Comput.* 22(12): 3891–3906
- [28] Atta S, Mahapatra P R S and Mukhopadhyay A 2018 Deterministic and randomized heuristic algorithms for uncapacitated facility location problem. In: *Information and Decision Sciences*, pp. 205–216. Springer, Berlin
- [29] Atta S, Mahapatra P R S and Mukhopadhyay A 2018 Solving uncapacitated facility location problem using monkey algorithm. In: *Intelligent Engineering Informatics*, pp. 71–78. Springer, Berlin
- [30] Atta S, Mahapatra P R S and Mukhopadhyay A 2019 Multi-objective uncapacitated facility location problem with customers preferences: Pareto-based and weighted sum ga-based approaches. *Soft Comput.* <https://doi.org/10.1007/s00500-019-03774-1>
- [31] Atta S, Mahapatra P R S and Mukhopadhyay A 2019 Solving uncapacitated facility location problem using heuristic algorithms. *Int. J. Nat. Comput. Res. (IJNCR)* 8(2): 18–50
- [32] Atta S, Sinha Mahapatra P R and Mukhopadhyay A 2019 Solving tool indexing problem using harmony search algorithm with harmony refinement. *Soft Comput.* 23(16): 7407–7423
- [33] Love R and Wong J 1976 On solving a one-dimensional space allocation problem with integer programming. *INFOR: Inf. Syst. Oper. Res.* 14(2): 139–143
- [34] Heragu S S and Kusiak A 1991 Efficient models for the facility layout problem. *Eur. J. Oper. Res.* 53(1): 1–13
- [35] Amaral A R S 2006 On the exact solution of a facility layout problem. *Eur. J. Oper. Res.* 173(2): 508–518
- [36] Amaral A R S 2008 An exact approach to the one-dimensional facility layout problem. *Oper. Res.* 56(4): 1026–1033
- [37] Amaral A R S 2009 A new lower bound for the single row facility layout problem. *Discrete Appl. Math.* 157(1): 183–190
- [38] Anjos M F, Kennings A and Vannelli A 2005 A semidefinite optimization approach for the single-row layout problem with unequal dimensions. *Discrete Optim.* 2(2): 113–122
- [39] Anjos M F and Vannelli A 2008 Computing globally optimal solutions for single-row layout problems using semidefinite programming and cutting planes. *INFORMS J. Comput.* 20(4): 611–617
- [40] Sanjeevi S and Kianfar K 2010 A polyhedral study of triplet formulation for single row facility layout problem. *Discrete Appl. Math.* 158(16): 1861–1867
- [41] Djellab H and Gourgand M 2001 A new heuristic procedure for the single-row facility layout problem. *Int. J. Comput. Integr. Manuf.* 14(3): 270–280
- [42] Kumar K R, Hadjinicola G C and Lin T 1995 A heuristic procedure for the single-row facility layout problem. *Eur. J. Oper. Res.* 87(1): 65–73
- [43] de Alvarenga A G, Negreiros-Gomes F J et al 2000 Metaheuristic methods for a class of the facility layout problem. *J. Intell. Manuf.* 11(4): 421–430
- [44] Samarghandi H and Eshghi K 2010 An efficient tabu algorithm for the single row facility layout problem. *Eur. J. Oper. Res.* 205(1): 98–105
- [45] Romero D, Sánchez-Flores A 1990 Methods for the one-dimensional space allocation problem. *Comput. Oper. Res.* 17(5): 465–473
- [46] Heragu S S and Alfa A S 1992 Experimental analysis of simulated annealing based algorithms for the layout problem. *Eur. J. Oper. Res.* 57(2): 190–202
- [47] Solimanpur M, Vrat P and Shankar R 2005 An ant algorithm for the single row layout problem in flexible manufacturing systems. *Comput. Oper. Res.* 32(3): 583–598
- [48] Satheesh K R M, Asokan P, Kumanan S and Varma B 2008 Scatter search algorithm for single row layout problem in FMS. *Adv. Prod. Eng. Manag.* 3: 193–204
- [49] Samarghandi H, Taabayan P and Jahantigh F F 2010 A particle swarm optimization for the single row facility layout problem. *Comput. Ind. Eng.* 58(4): 529–534
- [50] Ficko M, Brezocnik M and Balic J 2004 Designing the layout of single-and multiple-rows flexible manufacturing system by genetic algorithms. *J. Mater. Process. Technol.* 157: 150–158
- [51] Rubio-Sánchez M, Gallego M, Gortázar F and Duarte A 2016 GRASP with path relinking for the single row facility layout problem. *Knowl.-Based Syst.* 106: 1–13
- [52] Teo Y T and Ponnambalam S G 2008 A hybrid ACO/PSO heuristic to solve single row layout problem. In: *IEEE International Conference on Automation Science and Engineering, 2008. CASE 2008.* IEEE, pp. 597–602
- [53] Kunlei L, Chaoyong Z, Liang G and Xinyu S 1995 Single row facility layout problem using an imperialist competitive

- algorithm. In: *Proceedings of the 41st International Conference on Computers & Industrial Engineering*
- [54] Palubeckis G 2013 Single row facility layout. <https://www.personalas.ktu.lt/~ginpalu/srflp.html>
 - [55] Obata T 1979 Quadratic assignment problem: evaluation of exact and heuristic algorithms. Ph.D. thesis
 - [56] Sarker B R 1990 The amoebic matrix and one-dimensional machine location problems. *J. Oper. Manag.* 9(3): 439–440
 - [57] Nugent C E, Vollmann T E and Ruml J 1968 An experimental comparison of techniques for the assignment of facilities to locations experimental comparison of techniques for the assignment of facilities to locations. *Oper. Res.* 16(1): 150–173
 - [58] Skorin-Kapov J 1990 Tabu search applied to the quadratic assignment problem. *ORSA J. Comput.* 2(1): 33–45
 - [59] Loiola E M, de Abreu N M M, Boaventura-Netto P O, Hahn P and Querido T 2007 A survey for the quadratic assignment problem. *Eur. J. Oper. Res.* 176(2): 657–690
 - [60] Letchford A N and Amaral A 2011 A polyhedral approach to the single row facility layout problem. Technical Report 49043, The Department of Management Science, Lancaster University