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Abstract:

We consider facility planning and design in the single-row facility layout problem (SRFLP) for double-floor spaces to minimize land and material handling costs by efficiently arranging facilities along a given transport side of double-floor spaces. Previously, this problem has been solved based on a mixed-integer linear programming formulation. Our fast (1+1) EA operates by initially constructing a solution that aligns with the characteristics of SRFLP. It then proceeds to determine mutations using a heavy-tailed distribution function. To generate new solutions, we employ local insert and swap operators and incorporate a restart strategy into the process. We demonstrate the practical value of the fast (1+1) EA for DF-SRFLP on numerical experiments (9-80 facility-scale datasets) and real-world instances, including assembly workshops (size 14) and footwear manufacturing workshops (size 54). The experimental results show that under the numerical experiments: the solve time of the MILP solver (GUROBI 10.0.1) grows exponentially with the problem size, while (1+1) EA is relatively stable. And the large-scale, MILP solver is not able to give suitable values in a reasonable time. In a practical application involving a 14-scale assembly line shop, the 1+1 EA achieves a layout that reduces material handling costs by 24 % compared to the original layout form. Furthermore, in the context of a 54-scale shoe factory, our proposed algorithm not only successfully addresses the DF-SRFLP but also offers a valuable reference for establishing an improved layout.

Keywords: facilities planning and design; Double-floor Single-row facility layout Problem; Mixed-integer linear programming; Fast evolution algorithm; Real-life cases.

1 Introduction

The Facility Layout Problem (FLP) aims to find the optimal facility layout to optimize production or service objectives while meeting practical constraints (Pourvaziri et al., 2021). An efficient manufacturing layout improves system efficiency, and an unreasonable layout increases the production cycle and delivery time. Material handling cost (MHC) is a crucial indicator, accounting for 20-50% of the total operating cost and 15-70% of the total manufacturing cost(Chwif et al., 1998). A reasonable layout can reduce these costs by 10-30%(Hosseini-Nasab et al., 2018), and unreasonable planning will increase operating costs, affecting the efficiency of the production system by more than 35% (Gong et al., 2021). Therefore, the FLP is essential in designing modern production systems and has been widely concerned by researchers and entrepreneurs.

Single-row facility layout problem (SRFLP) is a well-known facility layout problem (FLP) that seeks to rationalize several facilities to follow one side of a transport path to minimize the weighted sum of material handling cost (MHC) between facilities. Due to its simple and compact layout structure, SRFLP plays an essential role in industrial manufacturing and cellular environments (Keller & Buscher, 2015; Wang et al., 2001), such as semiconductor production line layout, multi-product flow line layout(Nagarajan et al., 2018), automated workshop layout guide car, and machine layout of flexible manufacturing system (Kothari & Ghosh, 2012; Tubaileh & Siam, 2017). In addition, some other fields are also widely used, such as hospitals, schools, office buildings (Simmons, 1969), supermarkets and warehouse layouts (Picard & Queyranne, 1981). However, when the scale of the facilities to be arranged is large, the single-row layout will occupy a large land area (The entire production line layout is too long). As the current land supply is expensive (Karateke et al., 2022), huge land cost overhead and limited land use area make the layout engineering of large-scale facility groups more difficult (Ahmadi et al., 2017). Therefore, more and more countries and regions have begun to consider double-floor or multi-floor layouts from the perspective of land cost and space utilization (Ahmadi & Akbari Jokar, 2016; Che et al., 2017). The application scenarios of

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multi-floor layout overlap with SRFLP, such as hospitals, office buildings, factories, and warehouses (Hahn et al., 2010).

As of now, SRFLP and multi-floor facility layout problem (MFLP) have been considered by designers or engineers, respectively, in many scenarios (C. Guan et al., 2021; C. Guan, Zhang, & Li, 2019; C. Guan, Zhang, Liu, et al., 2019; Izadinia & Eshghi, 2016; S. Liu, Zhang, Guan, Liu, et al., 2021; Zhu et al., 2020). Although the combination of the two layout modes has been applied in reality, the combined application of these two layouts has not been researching reported yet. In this study, we extend SRFLP to double-floor layouts (The particular type of the MFLP) and develop a model for the double-floor single-row facility layout problem (DF-SRFLP). Both DF-SRFLP and double-row facility layout problem (DRLP, which includes basic double-row facility layout problem, corridor allocation problem (CAP) (Amaral, 2012), and parallel row ordering problem (PROP) (Amaral, 2013)) arrange facilities in two rows in the space. DF-SRFLP extends the second row vertically, while the DRLP extends horizontally. However, the material handling structure of DF-SRFLP is very different. The interaction between the two rows (two floors) of DF-SRFLP is only through the elevator, while the layout of the DRLP is different. Although PROP can also be seen as a multi-floor form of SRFLP (Gong et al., 2021), the difference in its multi-floor form is that the type and number of facilities on each floor are fixed, and the elevator is located at the starting point of the facilities. This feature makes its problem complexity lower than that of DF-SRFLP. DF-SRFLP is not necessarily superior to the three forms of DRLP in material handling structure. However, within the limited layout area, DF-SRFLP has tremendous advantages. The application of DF-SRFLP is shown in (Figure. 1. (a)~(d)).

(a) production line (b) Warehousing (c) temperate office (d) teaching building

Figure 1. The actual application of the layout mode combined with SRFLP and MFLP.

SRFLP and the MFLP have been proven to be NP-hard problems (Tubaileh & Siam, 2017). The DF-SRFLP problem combined with the two also has the property of NP-hard. While proposing DF-SRFLP, we also considered the tools used vertically moving materials between the two floors. As a critical consideration in the multi-floor layout, we adopted a vertical conveyor (J. Liu et al., 2022) (reciprocating lifting freight elevators) to avoid congestion. However, this leads to existing multiple types of calculating material handling distances between facilities, making the large-scale problem-solving of DF-SRFLP challenging. To address this challenge, we design a (1+1) Evolutionary Algorithm based on the heavy-tailed variational probability that can be used to solve DF-SRFLP. The algorithm prototype is a fast genetic algorithm (FGA) proposed by Benjamin (Doerr et al., 2017). He proved the ability of FGA to accelerate the solution of combinatorial optimization problems, such as the minimum vertex cover problem in bipartite graphs. Therefore, the algorithm proposed in this study is called Fast Evolutionary Algorithm (FEA). Finally, in addition to solving numerical instances, this study applies DF-SRFLP to two production workshops to combine theory and practice better.

2 Problem Description

The DF-SRFLP aims to solve the problems of limited land area for facility layout and congestion and waiting time waste in a single vertical transport channel. This layout form arranges the given multiple facilities on double floors properly. Unlike the basic SRFLP, the DF-SRFLP starts with the middle of two elevators and arranges the facilities of each floor on both sides of the elevators in sequence. Two one-way reciprocating elevators are vertical transportation tools between the two floors. In this study, we minimized the MHC between facilities by minimizing the land area. In practical situations, the width of most facilities is usually kept consistent width, so the length of the facilities is used as a measure instead of area. The material handling route (MHR) under this layout is shown in Figure 2.

Figure 2 has two subgraphs, (a) and (b). The two subgraphs represent the MHRs and the route calculation method under different conditions. Figure 2 (a) shows the MHRs of the two facilities in different areas. This situation includes different areas on the same floor and different areas on different floors. Figure 2 (b) shows the MHRs between facilities in the same area. This situation is the same as in Figure 2 (a), with cases of the same or different floors. It can be seen from the calculation formula at the bottom of the picture that the most challenging situation to calculate is $\{F1, A2\} \rightarrow \{F2, A2\}$ because, compared with other situations, the material handling distance between facilities in this situation is asymmetric. At the bottom of the

Figure 2, different colours arrows indicate different MHRs. The red arrow indicates the running direction of the freight elevator. The height h between the two floors and the elevator width e is set as fixed values, and the corridor width is not considered. Based on the actual layout characteristics, the other basic assumptions of the DF-SRFLP as follows:

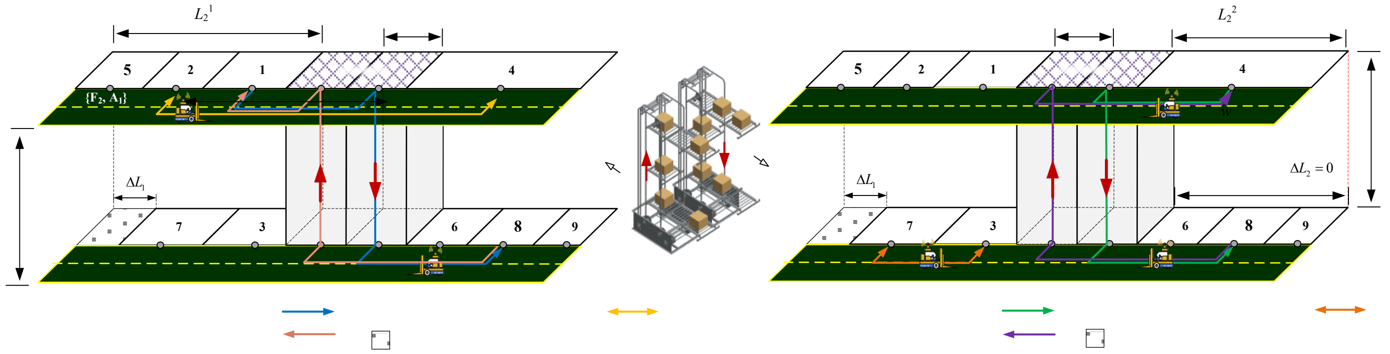


Figure 2. DF-SRFLP layout form, freight elevators and different types of material handling paths.

3 Fast evolution algorithm with Parallel frame

In order to efficiently obtain a better solution on a larger facility scale, we use FGA as the algorithm framework and continue to use its mutation strategy of heavy-tailed distribution in the algorithm. The proposed algorithm includes several steps: initial solution generation, neighbourhood search, and restart operation. Furthermore, a parallel computing framework was used to speed up the solving of DF-SRFLP. The original FGA has been shown to have a speed-up effect in combinatorial optimization problems. Based on this, we call the algorithm proposed in this paper FEA.

3.1 Encoding and decoding

In the basic SRFLP, encoding and decoding are represented by a non-repeating sequence of integers from 1 to n. In DF-SRFLP, according to the characteristics of the problem, the sequence is cut based on the basic SRFLP encoding, and we call the serial number of cut positions the split points. We need three split points because a sequence is to be divided into four fragments. That is the split point t between the upper and lower floors, the split point t_1 on the left and right sides of the elevator on the first floor, and the split point t_2 on the left and right sides of the elevator on the second floor. The specific meaning and operation of the split point are shown in Figure 3.

Taking the problem of the number of facilities n=9 as an example, a feasible solution Sol= [2 4 3 1 8 6 7 9 5], where t=5, t_1=2, t_2=2. That is, the sequence of facilities arranged on the left side of the elevator on the first floor is [2 4], and the sequence of facilities on the right side of the elevator on the first floor is [3 1]; the sequence of facilities arranged on the left side of the elevator on the second floor is [8 6], and the sequence of facilities arranged on the sequence of facilities on the right side of the elevator on the second floor is [7 9 5]. It should be noted that the starting point of all facility layouts is the midpoint between the two elevators. Therefore, the left area of the elevator on the first floor in Figure 3 is viewed as [4, 2] from left to right. Similarly, the visual order from left to right of the left area of the elevator on the second floor is [6, 8].

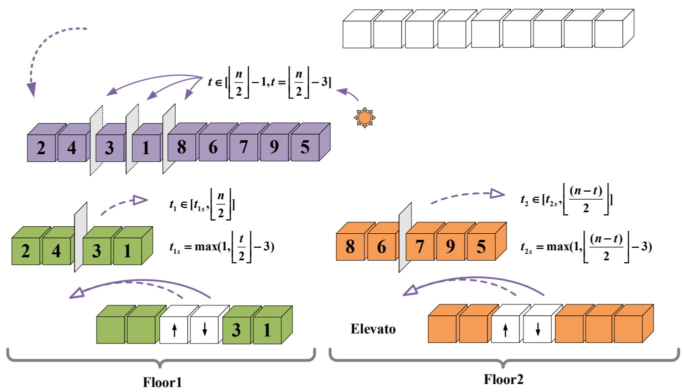


Figure 3. encoding and decoding of DF-SRFLP and SRFLP.

3.2 initial solution procedure

As we all know, an excellent initial solution can effectively improve the performance of an Algorithm and get high-quality solving results. According to the attribute of the objective function of the SRFLP, it is a good rule to make a pair of facilities with the smallest material handling volume (the best is zero) have the farthest material handling distance. Based on this, we design for initial solution generation in FEA.

According to the coding of DF-SRFLP, we construct a 1xn-dimensional empty array $Sol_{initial}$. We select the facility pair p-q with the smallest c_{ij} and place the facility pair p-q in the leftmost and rightmost two vacancies of unplaced facilities in $Sol_{initial}$ superior. But currently, there are two placement plans: p is placed at position i, q is placed at position n - i; q is placed at position j, and p is placed at position n-j. The two plans are compared by calculating the MHC between the facilities already placed. And the smallest MHC scheme is selected for placement. Then update the row p and column of c_{ij} in the selected matrix to inf until $Sol_{initial}$ has no vacancies. The initial solution generation process is shown in Figure 4.

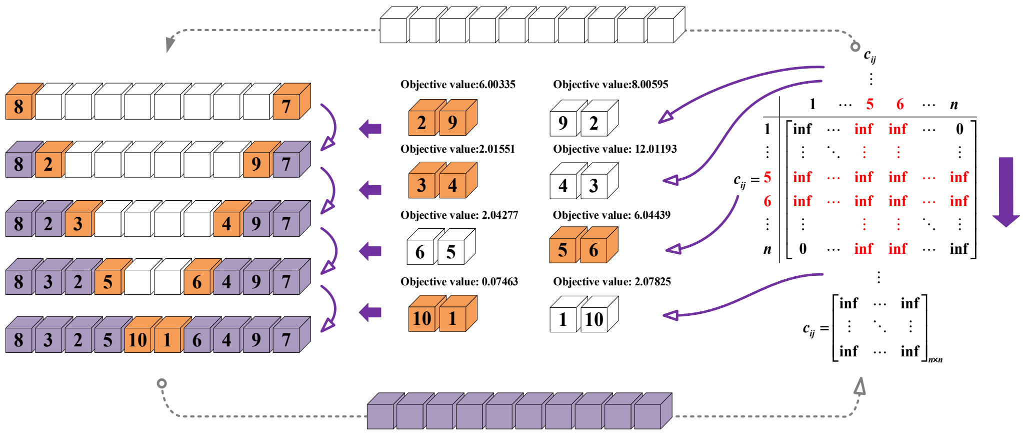


Figure 4. Initial solution generation process.

3.3 Local search with Heavy-Tailed Mutation Strategy

In the classic (1+1) EA, the mutation probability, or the number of mutations for local search is fixed, but this leads to the limitation that the algorithm cannot break through the local optimum. Therefore, in FEA, we randomly mutate the number of local searches each time according to a power law distribution with an exponent greater than 1. We use swap and insert as operators to search the neighbourhood, which are classic and highly effective mutation operations in SRFLP. We set the maximum number of iterations of the neighbourhood search as n/2. Note that setting the maximum number of iterations is only an upper limit for the times of the neighbourhood search in the local search operation, that is: loop iterations of mutation. The specific calculation method for the loop iterations of mutation is as follows:

The loop iterations of mutation is represented by ε, $\varepsilon \in [1, n/2]$. ε follows a power-law distribution function in a heavy-tailed distribution probability:

$$\mathrm{P}[\varepsilon=\phi]=\phi^{-\lambda}, \varepsilon=[1,2,\ldots,\frac{n}{2}] \tag{1}$$

$$P_{\varepsilon}=\mathrm{P}[\varepsilon=\phi] / (\sum_{\varepsilon=1}^{n/2} \mathrm{Pr}[\varepsilon=\phi]) \tag{2}$$

The normalization process is performed according to the power law distribution probability, and the processing formula is as Eq. (1). In Eq. (1), P[ε=φ] represents the power-law distribution probability of any number of ε. In Eq. (2), $P\varepsilon$ represents the normalized probability of P[ε=φ] at ε times. Then generate a random r in the [0,1] interval. If r satisfies $P_{\varepsilon\text{-}1}<r<P_{\varepsilon}$, the number of local search operations is ε.

3.4 Neighbourhood search operator and restart strategy

(A) Neighbourhood search operator

We have established a specific relationship between e and two operations, we call these operations Swap_ε and Insert_ε. At each iteration within the maximum number of loops ε, both operations have a 50% probability of being selected. The rules for finding neighbourhood solutions for the two procedures are as follows:

Swap refers to the mobile exchange of facilities at a and b positions. In Swap_ε, a=ε, …, n; b=1, 2, 3, …, n; $a \neq b$. The positions of a and b are exchanged once to generate a new solution.

Insert usually refers to the movement of the facility from position a to position b. In Insert_ε, a=ε, …, n; b=1, 2, 3, …, n; $a \neq b$. a position facility moves b position once to generate a new solution.

After searching the neighbourhood solutions for each operation, find the best solution in the neighbourhood solutions as the input solution for the following process.

(B) Restart strategy

One of the primary challenges faced by the FEA is overcoming local optima. The inherent structure of FEA results in a relatively limited capacity to overcome local optima. To enhance the overall performance of FEA, a restart operation has been incorporated. The restart operation follows specific rules: when the number of iterations, denoted as re, reaches the maximum threshold Re without any changes in the solution, the k rand permutation operation is applied to mutate the best parent solution, X_{parent}, obtained in the current search. Subsequently, the generated solution replaces the initial solution of the current parent solution, facilitating the subsequent restart process.

3.5 Parallel computing structure

DF-SRFLP encoding and decoding are described in Section 3.1. There are three key problem parameters, t, t_1, and t_2. The settings of these three parameters significantly impact the speed and quality of the algorithm. Usually, the split point parameter is used as a loop, and such three parameters form three loop nests to form a serial structure. Because of this, the solution speed of the algorithm is also significantly reduced. In our current research. We use t as the allocation parameter of workers in parallel computing, and the specific parallel framework is shown in Figure 5. The parallel operation of this framework is like parallel feature extraction, and the method has been well applied in similar hyper-heuristic methods for solving FLP (J. Liu et al., 2023).

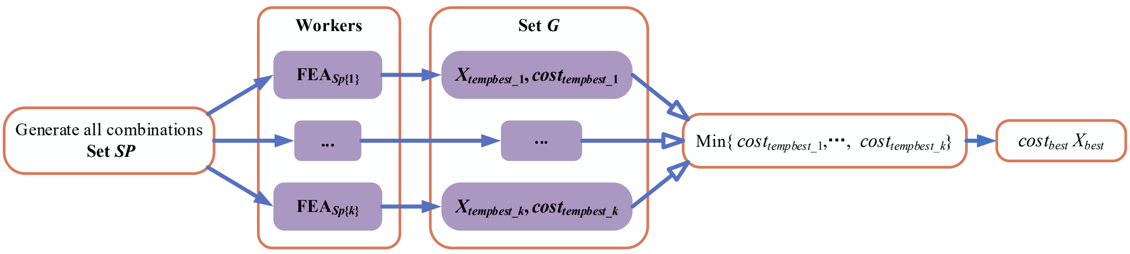


Figure 5. parallel computing frame.

The Pseudocode of Generating the Set ***Sp*** of Separation Point Parameter Combination in Parallel Computing.

Pseudo-code of set ***Sp*** generation
k_t←1
Create a set ***Sp***
/* *The set **Sp** holds the combination of separation points* [t, t_1, t_2] */
for t=floor(n/2)-2: floor(n/2)
t_{1_start}=max (1, floor(t/2)-3)
t_{2_start}=max (1, floor((n-t)/2)-3)
for t_1= t_{1_start}: floor(n/2)
for t_2= t_{2_start}: floor((n-t)/2)
Sp(k_t)= [t, t_1, t_2]
k_t ←k_t+1
end
end
end

4.6 Algorithm flow

The complete algorithm flow chart is shown below.

Pseudo-code of FEA
Input c_{ij}, l_i, θ, t_{max}, n, Re,
Generate the set ***Sp***
/* *num_Sp* is the number of separation points stored in ***Sp*** */
parfor count=1: *num_Sp* -1
[t, t_1, t_2] ←***Sp***(count)

Initialization parameters $re \leftarrow 1$.
Initialization set $\boldsymbol{X_{PARENT}}$.
/* $\boldsymbol{X_{PARENT}}$ is an empty set, $\boldsymbol{X_{PARENT}}$ is used to store the best-known facility sequence and cost before the restart operation for each combination of parameters ***/**
Generate initial solution X_{parent} ($Sol_{initial,}$ The symbol used in the Sect 4.1 is $Sol_{initial,}$) and $cost_{parent}$
while $time< t_{max}$
  while $re<Re$
    $X\leftarrow X_{parent}$;
    Determine the parameter ε according to Eqs. (29)and (30)
    While $k<\varepsilon$
      r←rand;
      if r<0.5
        Execute Swap_ε operation for X, generate $X_{offspring}$
      else
        Execute insert_ε operation for X, generate $X_{offspring}$
      end
      $k\leftarrow k+1$
      $X \leftarrow X_{offspring}$
    end
    If $cost_{offspring} < cost_{parent}$
      $cost_{parent} \leftarrow cost_{offspring}$
      $X_{parent} \leftarrow X_{offspring}$
      $re\leftarrow 1$
    else
      $re\leftarrow re+1$
    end
  end
  $\boldsymbol{X_{PARENT}} = [\ \boldsymbol{X_{PARENT}}\ ; X_{parent}\ ,cost_{parent}]$;
  Execute the restart operation /* $n/2$ rand permutation operation for X_{parent} */
  $re\leftarrow 1$
  Update *time*

end
Filtering the best solution $cost_{tempbest}$ and $X_{tempbest}$ from $\boldsymbol{X_{PARENT}}$
$\boldsymbol{G}$(count)=[$X_{tempbest}$, $cost_{tempbest}$];
End
Filtering the best solution $cost_{best}$ and X_{best} from $\boldsymbol{G}$
Output $cost_{best}$ X_{best}

4 Computational experiments

The FEA proposed in this study is implemented using Matlab. The experiments were conducted on a 13th Gen Intel(R) Core (TM) i5-13400 2.50 GHz 16G 10-core processor. The experimental evaluation consists of two parts. Firstly, we verified the accuracy and stability of the FEA algorithm through numerical instances, comparing it with SRFLP in terms of layout schemes and MHC, revealing their distinctions. In the second part, we applied DF-SRFLP to two real-life cases to explore its practical application value.

The algorithm parameters used in this study were determined through a combination of established values and a trial-and-error method. For instance, the parameter β was set to 1.5 based on previous studies on FEA. However, adjusting other parameters involved conducting extensive experiments to optimize their values. It is important to note that the primary focus of this study was to introduce the FEA algorithm to address the facility layout problem, specifically DF-SRFLP. Despite efforts to fine-tune the parameters, the stochastic nature of the simulated data introduces a level of uncertainty, and complete optimality of the parameters cannot be guaranteed. Each instance was tested ten times to mitigate the impact of accidental errors.

4.1 FEA for solving the benchmark instance of DF-SRFLP

(A) Experiments with instances of size $9 \leq n \leq 15$

We utilized the FEA algorithm to solve the five test instances in Table 1. The resulting solutions obtained from the FEA algorithm are summarized and presented in Table 1. Columns 4 to 10 in Table 1 detail the FEA solution results. For problem instances of size $n \leq 15$, the algorithm parameters are set to Re=3, t_{max} =10.

Table 1. The solution results of S9, S10, S11, Am13a, Am15 instances solving by FEA.

instacnce	Gurobi		EA						
	f		*f*	max	Avg	*num_Sp*	*SD*	Time/s	Global facility sequence
S9	0.05563	10.38	0.05563	0.05563	0.05563	10	0	10.05	5 8 | 3 2 | 1 9 |6 7 4
S10	0.06147	23.03	0.06147	0.06147	0.06147	13	0	20.05	8 | 1 3 9 | 2 6 | 4 5 10 7
S11	1.014033	247.84	1.014033	1.014033	1.014033	16	0	20.05	7 2 |5 6 11 | 1 10 9 | 4 3 8
Am13a	1.008997	456.44	1.008997	1.008997	1.008997	25	0	30.11	11 5 10 | 12 2 1 | 6 7 9 | 3 8 4 13
Am15	1.01178	31147.17	1.01178	1.01178	1.01178	32	0	40.10	12 11 9 | 13 2 1 | 8 4 3 |14 7 5 6 15 10

Table 1 demonstrates that the FEA algorithm can obtain objective values same as optimal global solutions within a reasonable amount of time, comparable to the solutions obtained by the exact solution optimizer. The result indicates the correctness of the algorithm's solution results. The Standard Deviation values (*SD*) for all ten solution instances are recorded as 0, indicating that FEA exhibits high stability in solving DF-SRFLP. Moreover, it is evident from the solution times that FEA holds a significant advantage over the exact algorithm. The solution time of FEA is not only affected by the parameters considered to be set but also by the number of combinations *num_Sp* in the split point set SP. For example, in the S9, *num_Sp* is 10, and the operating environment is ten cores, so the solution time is 10.05s. The floating is mainly due to the transmission of data information within the computer. Other scales can be deduced like this. Subsequently, we conducted tests on calculation instances of varying scales.

(B) Experiments with instances of size $30 \leq n \leq 49$

Considering that DF-SRFLP has yet to be reported, FEA cannot make comparison with other algorithms. After verifying the correctness of the designed FEA, we solved the calculation instances of two DF-SRFLP layout modes between scales 30 and 49 to observe the influence of different facility types on the solution results. The first type involved equal facility lengths, called Single-row Equidistant Facility Layout Problem (SREFLP). Thus, in the proposed double-floor layout mode, we referred to it as the double-floor single-row Equidistant facility layout problem (DF-SREFLP). In N-30-01, Ste36-01, N-40-01, Sko42-01, and Sko49-01, the facility lengths were equal to 1. The second type consisted of benchmark instances with varying facility lengths, termed the double-floor layout for DF-SRFLP (Double-floor Facility Single-row Facility Length Problem). For the DF-SREFLP benchmark instances, where the facility length is 1, we can infer that the distances difference between the upper and lower floor is either 0 or 1. Consequently, the t value in ***Sp*** is fixed at floor(n/2). The results of FEA solving these two calculation instances are presented in Table 3. The problem sizes range from $25<n<49$, and the algorithm parameters are Re=10 and t_{max}=30.

Table 2. Results of FEA solving for instances of size $30 \leq n \leq 49$ in DF-SREFLP and DF-SRFLP.

DFSREFLP						DFSREFLP					
Instance	*f_min*	△	MHC	MHC-*SD*	Time/s	Insatance	*f_min*	△	MHC	MHC-*SD*	Time/s
N25-01	1.013132	1	13132	0	62.30	N25-05	0.027264	0	27264	0	158.25
N-30-01	0.021558	0	21558	0	71.02	N-30-05	1.015724	1	157240	0	154.06
Ste36-01	0.00027586	0	27586	0	62.97	Ste36-05	0.000148379	0	148379	505.92	157.74
Sko42-01	0.055774	0	55774	70.20	65.18	Sko42-05	1.0322703	1	322703	210.62	173.93
Sko49-01	1.008359	1	83592	75.67	75.67	Sko49-05	1.00874954	1	874954	584.4	157.72

It can be seen from the table that for DF-SREFLP, the *SD* values of MHC in the solution results of N25-01, N-30-01, and Ste36-01 are all 0, and the *SD* values of SKo-42 and Sko-49 are both 70 about. This shows that FEA is relatively stable in solving the DFSREFLP. For DF-SRFLP, the *SD* values of MHC in the solution results of N25-01 and N-30-01 are all 0, but the *SD* values of Ste36-05, SKo-42 and Sko-49 fluctuate. However, because the magnitude of MHC is relatively large, the magnitude of *SD* of MHC is within an acceptable range. In terms of time, the solution time of DF-SREFLP at the same scale is significantly less than that of DF-SRFLP, which is consistent with the conclusion in Table 1; that is, the *num_Sp* has a significant influence on the solution time of the algorithm. The two examples of DFSREFLP and DFSREFLP provide a reference for the case solution in the case study.

(C) Experiments with instances of size $60 \leq n \leq 80$

After verifying the accuracy and stability of the algorithm, to prove the potential of the proposed algorithm in solving large-scale instances of DFSRFLP and to illustrate that FEA is also effective in essential SRFLP instances, 12 slightly larger-scale Benchmark instances are solved ($60<n<80$). The solution results are shown in Table 3. In most previous SRFLP works, c_{ij} and d_{ij} are symmetric in the objective function. Therefore, the range of facility i and facility j is $1\leq i<j\leq n$. For DF-SRFLP, the material handling distance from i to j maybe differs from its reverse distance. Therefore, the range between facility i and

facility j is $1 \le i, j \le n$. To better compare the difference between DF-SRFLP and SRFLP, we put the two times the value of the best SRFLP target obtained by FEA in the fifth column of Table 3. The optimal permutation sequence obtained by solving DF-SRFLP is placed in Appendix.1. The solution parameters of this algorithm are Re=10; t_{max}=60.

Table 3. Results of FEA solving for instances of size $60 \le n \le 80$ in SRFLP and DF-SRFLP.

		SRFLP			DRSFLP		
No.	Instance	Best -know value	FEA-solutions	$MHC^{SRFLP}_{Double\ direction}$	f_{min}	MHC_{DRSFLP}	Reduce %
1	A-60-01	1477834	1477834	2955668	0.01854872	1854872	37.24
2	A-60-02	841776	841776	1683552	1.0106214	1062140	36.91
3	A-60-03	648337.5	648337.5	1296675	1.00804719	804719	37.94
4	A-60-04	398406	398406	796812	0.00509792	509792	36.02
5	A-60-05	318805	318805	637610	1.00406924	406924	36.18
6	A-70-01	1528537	1528537	3057074	1.0190548	1905480	37.67
7	A-70-02	1441028	1441028	2882056	0.01771776	1771776	38.52
8	A-70-03	1518993.5	1518993.5	3037987	0.01878941	1878941	38.15
9	A-70-04	968796	968796	1937592	1.01223536	1223536	36.85
10	A-70-05	4218002.5	4218002.5	8436005	0.005212165	5212165	38.22
11	A-80-01	2069097.5	2069097.5	4138195	0.002593043	2593043	37.34
12	A-80-05	1588885	1588885	3177770	1.02002642	2002642	36.98

Best -know value come from the report of Gintaras Palubeckis. (Palubeckis, 2017)

Numerical results in Table 4 show that for the SRFLP instances of 60<n< 80, the proposed algorithm achieves the best-known values in current public reports. At the same time, we found that the overall MHC of SRFLP instance can be up to 38.52% (Reduce = ($MHC^{SRFLP}_{Double\ direction}$ -MHC_{DRSFLP})/ MHC_{SRFLP}*100%) less than that of SRFLP compared with DF-SRFLP. This is attributed to the problem of the layout structure in DF-SRFLP. It is evident that the double-floor layout greatly folds the space and reduces the material handling distance between some facilities. However, it is because of this structure that the calculation of the model and the solution of the algorithm are difficult to solve by SRFLP.

4.2 Simulation Test of DRSRFLP on Existing Cases

In this section, we investigate two types of manufacturing cases derived from the assembly line workshop(Kovács, 2020) and the shoe factory case. The prototype of the first instance is an unequal area instance, while the prototype of the second instance is a dynamic layout instance(Ulutas & Islier, 2015). After processing the facility lengths, the first instance is classified as a DF-SRFLP in Section 5.1 (B), while the second instance is classified as a DF-SREFLP in Section 5.1 (B) based on equal facility lengths -SREFLP problem.

(A) Automotive assembly case

The first case is a manufacturer of auto parts assembly. The workshop contains 14 workstations. For this, we drew Figure 6 concerning its original workshop layout. In Figure 6, we use arrows to represent the flow of materials between different workstations. The length of the facility and the unit material handling cost between the facilities are shown in Table 4 and Table 5 Because the scale of 14 is relatively small, we use FEA to solve it. At the same time, GUROBI is used for solving. The solution results of this layout are placed in Table 7, and the layout diagram of DF-SRFLP is drawn, as shown in Figure 6.

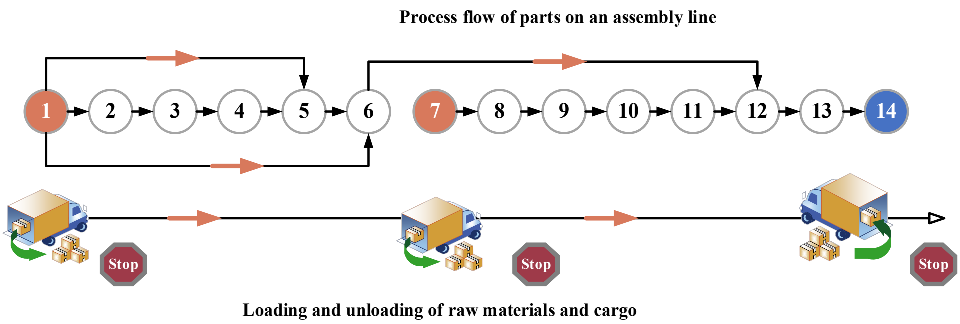


Figure 6. Materials handling direction between different workstations.

Table 4. Facility length.

Workstation	Dimensions (m × m)	Workstation	Dimensions (m × m)

1, 2, 3, 4, 6, 8, 10, 11, 13	2×1	7, 9	1×1
5, 14	4×1	12	1×3

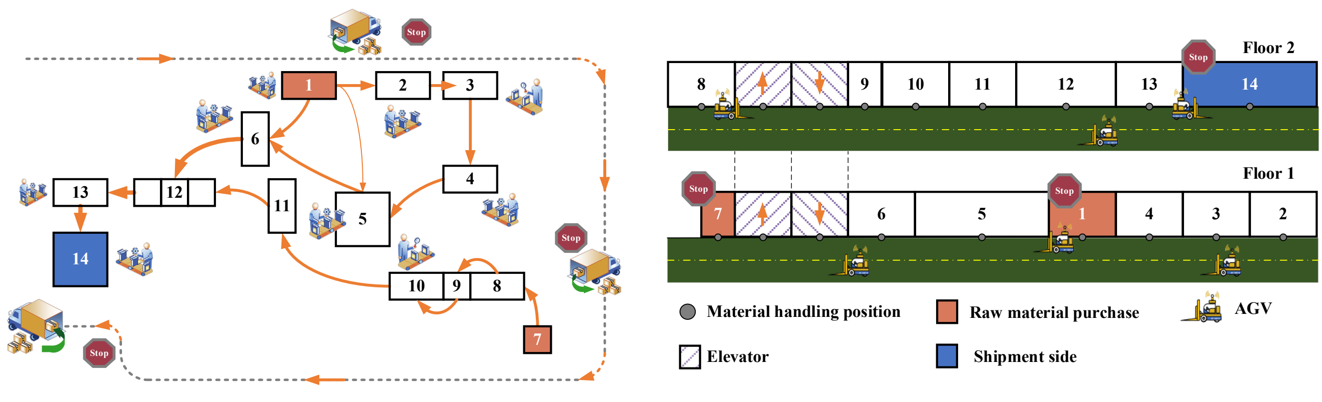
Table 5. Material handling flow of auto parts assembly.

From to Table - Material Handling Flow. (m, n) c m: Initial facilities; n: Terminal facilities; c: flow;							
(1,2) 5	(1,5) 1	(1,6) 5	(2,3) 5	(3,4) 5	(4,5) 5	(5,6) 6	(6,12) 11
(7,8) 4	(8,9) 4	(9,10) 4	(10,11) 4	(11,12) 4	(12,13) 15	(13,14) 15	(Others m, Others n) 0

Table 6. Results of the optimized auto parts assembly line layout case.

Objective value	MHC	θ	Area	Sequence		Gurobi Time/s	FEA Time/s	*SD*
1.002765	276.5	10000	1	7 | 6 5 1 4 3 2 | 8 | 9 10 11 12 13 14	365	297.61	11.27	0

It can be seen from Table 6 that the value of Gurobi and the solution value of FEA are both 276.5. Furthermore, the difference between the layout length of the upper floor and the lower floor is 1. Overall, MHC is reduced by 24% relative to the original layout. The layout of DF-SRFLP is successful. Combining Figure 7 (a) and Figure 7 (b), in DF-SRFLP, the location of Facility 1 is between Facility 2 and Facility 6 because Facility 1 has a strong logistics relationship with Facility 2 to Facility 6. Although facility 7 is far from facilities 8~10, facility 7 is close to the elevator entrance. This optimization result is due to our limited floor space.



(a) The original layout MHC=356

(b) DFSRFLP MHC=276.5

Figure 7. The original layout and DF-SRFLP for auto parts assembly cases.

(B) shoe manufacturer

The second case is provided by Ulutas B (Ulutas & Islier, 2015).. The actual application scenario of this case is a shoe factory. The original layout of this case was a static layout, which was designed as a dynamic layout in 2015 after optimization. Compared with large-scale equipment used in heavy industry, it is more suitable for the light industry to exist in the form of the double floor layout or MFLP. Here we use it as a static layout for DF-SRFLP design. The main goal of the layout remains to minimize MHC while keeping the area to a minimum. The general shoemaking process is as follows: Clicking, Closing, Bottom stock preparation, Lasting, Making and Finishing. The direction of material flow and the names of facilities are shown in Figure 8.

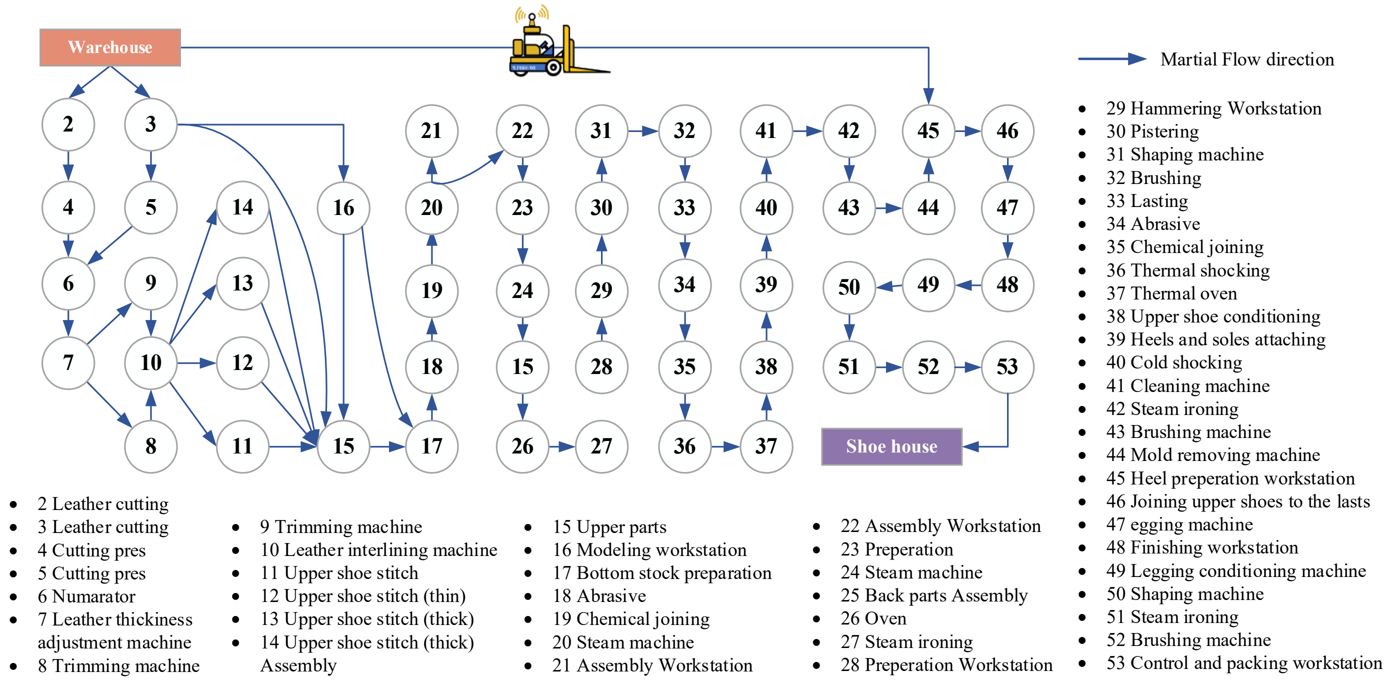


Figure 8. Material handling flow direction in shoe manufacturer.

Table 7 presents the values of c_{ij}, representing the Unit transportation cost per unit distance for material handling between facilities in the footwear factory. As the facilities in the factory have the same area, we assume they have the same length as the elevator. Due to the complexity of the problem, the exact algorithm cannot handle a case of size 54 within a reasonable timeframe. Hence, we employed the FEA algorithm to solve this case. The results obtained from the FEA algorithm are summarized in Table 8. To better display the layout results, we draw the optimized layout diagram. The algorithm parameters used for this calculation instance align with those applied to the 60-scale instance discussed in Section 5.1 (B).

Table 7. Table material handling flow for the shoe factory.

From to Table - Material Handling Flow. (m, n) c m: Initial facilities; n: Terminal facilities; c: flow;								*100
(W, 2) 43.5	(W, 3) 18.5	(W, 15) 302	(W, 16) 345	(W, 45) 49	(2, 4) 43.5	(3, 5) 18.5	(4, 6) 45	(5, 6) 40
(6, 7) 85	(7, 8) 42.5	(7, 9) 42.5	(8, 10) 85	(9, 10) 27	(10, 11) 10	(10, 12) 10	(10, 13) 5	(10, 14) 4
(11, 15) 4.5	(12, 15) 29	(13, 15) 22.5	(14, 15) 51.5	(15, 17) 302	(16, 17) 34.5	(17, 18) 34.5	(18, 19) 262	(19, 20) 262
(20, 21) 262	(20, 22) 262	(22, 23) 262	(23, 24) 262	(24, 25) 262	(25, 26) 345	(26, 27) 345	(27, 28) 262	(28, 29) 113
(29, 30) 262	(30, 31) 262	(31, 32) 257	(32, 33) 345	(33, 34) 262	(34, 35) 345	(35, 36) 262	(36, 37) 144	(37, 38) 144
(38, 39) 281	(39, 40) 220	(40, 41) 323	(41, 42) 345	(42, 43) 345	(43, 44) 345	(44, 45) 345	(45,46) 49	(46, 47) 345
(47, 48) 70	(48, 49) 345	(49, 50) 70	(50, 51) 262	(51, 52) 345	(52, 53) 345	(53, S) 345	(Others *m*, Others *n*) 0	

Table 8. Table material handling flow for the shoe factory.

Objective value	MHC	Sequence [Floor, Area]
0.000039899	3989900	{1, 1} = [28 27 26 25 24 23 22 21 20 19 18 17 16 1 15 14 12]; {1, 2} = [13 37 38 39 40 41 42 43 44 45]. {2, 1} = [29 30 31 32 33 34 35 36 2 4 5 6 7 9 8 10 11]; {2, 2} = [3 46 47 48 49 50 51 52 53 54].

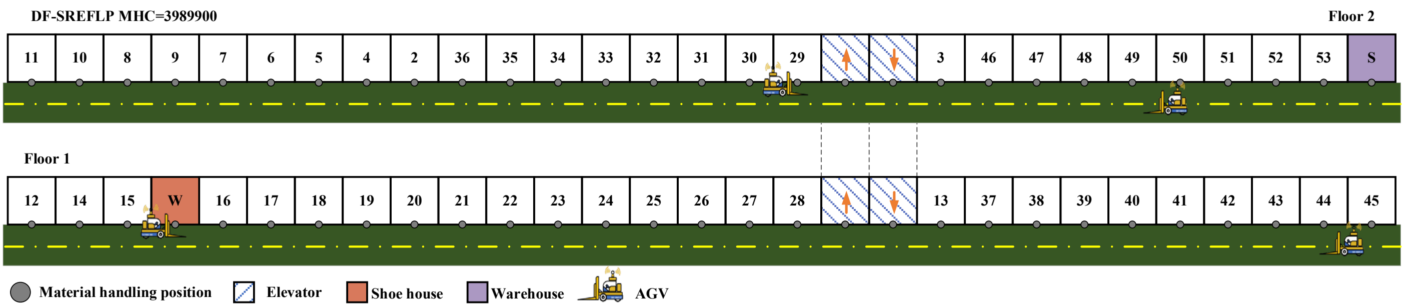


Figure 9. optimized layout diagram for shoe manufacturer.

We can analyse Figure 9 by combining Table 7, Table 8, and Figure 8. From Figure 9, it can be observed that facilities 15 and 16 are arranged around the warehouse. This is because, among the direct material receiving facilities (2, 3, 15, 16, and 45) on the level below the warehouse, facilities 15 and 16 have significantly higher c_{ij} than other facilities. Facility 3 is not put together with Facility 5 because the layout area of the facility should be reduced as much as possible, but Facility 3 is placed at the entrance of the freight elevator, on the same floor as Facility 5, so that it is convenient to receive materials from Facility 1 and the transportation between Facility 3 and Facility 5 also become more convenient. It is also the influence of these factors that facility 28 and facility 29 are distributed on two floors, but both facilities are placed next to the freight elevator, so the cost of material handling is reduced to a certain extent. Overall, it is reasonable for DF-SRFLP.

5 Conclusion

This study establishes an application framework for DF-SRFLP considering key factors such as building Area and Longitudinal freight tools. In this framework, the mixed integer linear programming model of DF-SRFLP is developed, and the constraint scale relationship of the model is analysed. To solve this layout problem faster, a fast evolutionary algorithm is introduced, which has been proven to perform well in solving similar problems. We successfully solved 27 benchmark instances ($9<n<80$) by applying the algorithm. The application of this method provides new ideas and tools for solving the double-floor single-row layout problem. Meanwhile, the framework was successfully applied to two actual cases: a small case of an assembly line (14 facilities) and a larger-scale case of a shoe factory (54 facilities). By solving these actual cases, the applicability and practicability of the framework for DF-SRFLP and in actual scenarios are further verified, and it also provides a valuable reference for layout decisions in actual manufacturing.

Although this research has made progress in the double-floor single-row layout, there are still directions for further exploration and improvement. Future research can further optimize the model and explore effective exact solving algorithms and strategies to improve the problem-solving effect. Second, the fast evolution algorithm is improved and extended to increase its performance and adaptability in facility layout problems. Also, consider introducing more practical constraints, such as facility dependencies and process flow, to simulate actual production environments more accurately. At the same time, the research focus is shifted to the multi-objective double-floor single-row layout problem, and how to optimize the design while satisfying multiple performance indicators is explored. This will further enhance the practicality and scope of application of the double-floor single-row layout.

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