Bi-level Programming Model to Solve Facility Configuration and Layout Problems in Railway Stations

Junsheng Huang, Huanping Huang, Xiaoping Guang, Rong Li and Jianshu Zhu

Abstract — **The facility configuration and layout design of hub stations play an essential role in building a practical and cost-efficient hub station system. In general practice, bi-level programming models are implemented based on specific objectives and constraints. In this study, an upper-level model is used to solve the facility configuration problem, which is constructed based on the predetermined facility types to calculate the quantity of each facility by three objectives, including the number of passengers queueing in line, passengers' average waiting time in the queueing system and the cost of facilities. A genetic simulated annealing (GSA) algorithm based on the ε-constraints method is presented to optimize the upper-level model. A lower-level model is used to solve the facility layout problem. An optimization solver, named CPLEX, is applied in the lower-level model to calculate the abscissas and ordinates of the facility location after determining the facility configuration in the upper-level model. A case study of the Lanzhou West station in Northern China is demonstrated to verify the efficiency of the optimal solution from the bi-level model by using a commercial pedestrian simulation software, MASSMOTION. This study reveals an innovative method for optimizing station facility configuration and layout by using the heuristic novel algorithm, a discrete event simulation technology and effective utilization of the Building Information Model (BIM) data.**

Index Terms - **facility configuration and layout problem; bi-level programming model; genetic simulated annealing algorithm; Lanzhou West Station**

I. INTRODUCTION

The facility configuration and layout problem (FCLP) was firstly introduced to facilitate production activities. The facility configuration problem is to determine the quantity of facilities needed in order to increase the facility service level. The traditional facility layout problem determines the placement of facilities in a system to get the most effective arrangement by some objectives and different constraints. Nowadays, designing an effective facility configuration and layout in a manufacturing system attracts the attention of both manufacturers and station decision-makers. A poor layout may lead to longer queues and inefficient passenger flow [1]. On the contrary, good placement of facilities has a direct contribution to the overall efficiency of operations [2] after considering facility configuration. It was proposed that 43% of the total operating cost would be reduced by an effective facilities arrangement once the data has been analyzed [3], [4].

It is critical to design an efficient facility configuration and layout in a railway hub station system under the background of multiple passenger flow [5] and an inefficient facility level of service in the railway system [6].

[7] - [9] were described from the aspect of facility configuration. The methodology of estimating the number of fare collection systems in Beijing South Railway Station was presented by using the queueing theory model [7]. The sharing rate of ticket counters and ticket machines was considered in evaluating their efficiency [8]. The randomness of passenger behavior was considered in the metro station to determine the optimal number of ticket machines [9]. However, facility configuration design in the hub station is affected by several factors (including passenger satisfaction and facility cost), which means any one of these factors is not explanatory enough when it comes to the design. Meanwhile, the purpose of designing a multi-objective model in most research [10], [11] and [12], is to generate efficient alternatives which can be provided to the decision-makers so that they can select the best facility layout alternative while conflicting and non-commensurate objectives are considered. Thus, it is necessary to design a multi-objective model to determine the facility configuration, and in this study, the model contains three objectives to determine the level of facility service.

[13], [14] described the facility layout from the passenger flow aspect. Placement of the facility in the metro station or railway station has a close relationship with passengers' walking efficiency [13], [14]. Thus, the facility layout is well arranged only when passengers' walking behavior is fully considered. [15] combined queueing-delay on congested facilities with minimization network-wide travel times in the

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bi-level programming model.

After considering the NP-hardness of the facility configuration and layout problem, various heuristic evolutionary algorithms are designed for solving the problem. The hybrid multi-population genetic algorithm [16], [17] separated solution space into small parts to improve the accuracy of the searching ability. A genetic algorithm [18] was developed to deal with the problem of planning and constructing logistic parks in functional areas. With the development of simulation technology, the simulation-based approach is now prevalent. To analyze the impact of facility size on the project time and cost, [19] adopted a hybrid discrete-continuous simulation technique.

In general, facility configuration and layout problems are now prevalent in, not only manufacturing systems, but also railway hub stations. But nowadays passenger behavior preferences change rapidly. Therefore, suggested configuration and layout in the hub station were beneficial at that time, but after a period as the demands of passengers increase, they lose their effectiveness. Thus, it is essential to identify and solve the facility configuration and layout problem in time as the conditions change in the hub station, which gives the decision-maker satisfying alternative options.

In this study, all facilities are set on a single floor, and our focus is on problem description, mathematical model designing, and its optimization approach. Thus several contributions can be summarized as follows: (1) a new bi-level model is adopted to present the relationship between the facility configuration and facility layout; (2) the upper-level model contains three objectives, aiming to determine facility configuration which considers the number of passengers queueing in line, passengers' average waiting time and operation cost simultaneously; (3) the lower-level is to solve the facility layout from passengers' walking efficiency; (4) a heuristic method, the GSA algorithm based on the ε-constraints method is utilized to solve the upper-level model, and 6 pareto solutions are acquired; (5) an optimization solver, CPLEX, is to solve the facility layout in the lower-level model; (6) finally, a simulation experiment is conducted in MASSMOTION to verify the efficiency of the solution.

The rest of the paper is organized as follows:

The types of facilities used in this paper are discussed in Section 2.

The bi-level programming model is developed in Section 3 based on facility configuration and facility layout.

For solving the bi-level programming model, some solution techniques are created in Section 4.

Simulation verification and discussion are included in Section 5.

Finally, the conclusion is presented in Section 6.

II. FACILITY DESCRIPTIONS

In this section, to provide feasible regional space to the upper-level programming model, types of facilities in the hub station should be proposed in advance, and the estimation of the facility number is used in this part according to the queueing theory model.

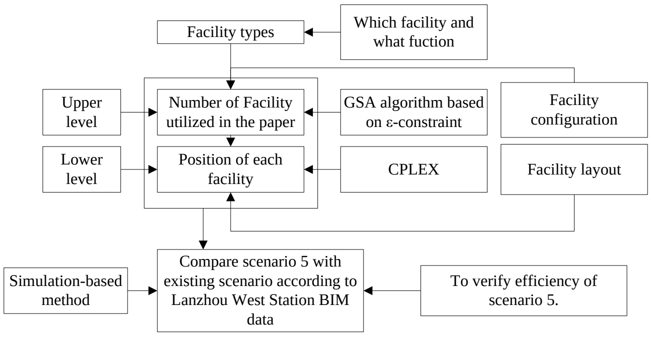

Fig. 1. Paper structure

A. *Types of Facility*

The facilities of this study are mainly separated into two parts, the universal hall and the waiting room, which are classified according to their specific locations in the hub station. TABLE I lists the subitems of each part.

TABLE I
THE FUNCTION OF EACH FACILITY

Type	Specific Separation	Function
Universal Hall	Security check machine	Checks the identification of passengers, and ensures safety and security in the hub station.
	Ticket lobby	Includes ticket counters and ticket machines, and provides passengers with travel proofs.
Waiting Room	Waiting hall	Provides seating for passengers waiting for target trains.

In practical experience, inefficient passenger flow and long queues always happen in the universal hall. Meanwhile, the operation efficiency of a railway hub station depends very much on the universal hall and in this study, our focus is on designing efficient facility configuration and layout in this area. The security check machine, ticket machine, and ticket counter are respectively considered in this paper.

B. *Queueing Theory Models*

The queueing theory is for studying waiting in all its various guises [20]. It provides various formulas for each model to indicate how the corresponding queueing system should perform. In this study, the facility configuration problem mainly considers and discusses how to design the most suitable quantity of security check machines, ticket machines, and ticket counters when passengers are queueing. Thus, the number and waiting time of passengers in queue should be defined according to mature queueing theory.

Before building the queueing theory models, several assumptions (a-d) should be made, including service time, service disciplines, etc.

a. Define the passengers' average arrival rate as λ (person/s), complying with the Poisson's distribution;

b. Define the average service rate of a single service as μ (person/s), complying with the negative exponential distribution;

c. The service discipline is first in and first out;

d. Define the utilization factor for the service facility as ρ ($\rho=\lambda/(C\mu)\leq 1$), and the quantity of each service counter facility is C.

Furthermore, formulas of each notation in queueing models should be provided under the background of multiple service counters (M/M/C).

$$L_s = L_q + \frac{\lambda}{\mu} \quad (1)$$

L_s represents the expected number of customers in the queueing system;

$$L_q = \frac{(c\rho)^c \rho}{c!(1-\rho)^2} p_0 \quad (2)$$

L_q represents the expected queue length (excludes customers being served);

$$W_s = \frac{L_s}{\lambda} \quad (3)$$

W_s represents the waiting time in the system (includes service time) for each customer;

$$W_q = \frac{L_q}{\lambda} \quad (4)$$

W_q represents the waiting time in queue (excludes service time) for each customer;

$$p_0 = [\sum_{k=0}^{c-1} \frac{1}{k!}(\frac{\lambda}{\mu})^k + \frac{1}{c!} \bullet \frac{1}{1-\rho} \bullet (\frac{\lambda}{\mu})^c]^{-1} \quad (5)$$

p_0 represents the probability of each service counter under idle state;

$$p_n = \frac{1}{n!}(\frac{\lambda}{\mu})^n p_0, n \le C \quad (6)$$

$$p_n = \frac{1}{c!c^{n-c}}(\frac{\lambda}{\mu})^n p_0, n > C \quad (7)$$

p_n represents the probability of exactly n passengers in the queueing system.

C. Determination Number of Facilities

The queueing discipline is M/M/C, and the arrival rate of passengers complies with the Poisson's distribution; the service time of each service counter satisfies the negative exponential distribution.

Related information in TABLE II is obtained by practical investigation towards the Lanzhou West Station after statistics.

TABLE II
SERVICE TIME FOR EACH MACHINE

Service time	Ticket counter	Ticket machine	Security check machine
μ	20s/person	60s/person	3s/person
ν	3person/min	1person/min	20person/min

The determination of the ticket machine number is captured as an example under the background of 5000 persons per peak hour. (Provided 20% of passengers in peak hours using the ticket machine, the quantity of ticket machines is estimated according to the queueing theory model)

The number of security check machines and ticket counters can also be obtained in a similar manner.

TABLE III
ESTIMATING QUANTITY OF TICKET MACHINES AT PEAK HOUR

Passengers	Quantity	L_q	L_s	W_s (min)	W_q (min)	P_0
5000*20%	17	Not meet requirements				
	18	12.63	29.63	1.73	0.74	0.00
	19	4.59	21.60	1.26	0.27	0.00
	20	2.17	19.17	1.13	0.13	0.00
	...	...	...	...	...	...

III. BI-LEVEL PROGRAMMING MODEL

A. Problem description

Nowadays, railway administration is focusing more on operational details with regard to facility configuration and layout problems. Before designing a facility layout in a railway hub station, it is necessary to decide the facility configuration according to the passenger volume at peak hours. However, facility cost and passenger satisfaction have a close relationship with the facility configuration, which indicates that effective facility configuration will lead to higher passenger satisfaction and higher operation costs simultaneously. Thus, it is contradictory when the cost of operation and passenger satisfaction are considered together. To overcome these challenges, it is necessary to design a multi-objective model towards the facility configuration problem to ensure minimization of the total cost of the facility in the hub station and the passenger waiting time while queuing.

On the other hand, corresponding micro-walking efficiency, which directs passengers to walk among facilities in the shortest distance, will be fully considered after determining the quantity of facilities.

The internal relationship between facility configuration and facility layout meets the requirement of the bi-level programming model and the planning logit. Thus, the bi-level programming model is proposed to consider facility configuration and layout based on the discussed facilities in section 2.

Several assumptions are generalized according to the bi-level programming model:

a. All facilities are set on a single floor;

b. The same kind of facility has the same area and radius;

c. Different to [21], the facility in this paper is considered as a circle. Meanwhile, the origin and destination of a passenger walking route are set at the center of the circle;

d. All kinds of facilities numbers are determined under the condition of 5000 passengers per peak hour;

e. The area of facilities is much smaller than the area of the railway station;

f. The coordinate origin is set at the northeast of the Lanzhou West Station;

g. The horizontal projection of the Lanzhou West Station is approximately a rectangle.

B. Upper-level Model

The upper-level is designed from the queueing theory model perspective, which is composed of three objectives, including the expected number of passengers in the queueing system (L_{si}), the average waiting time of passengers in the queueing system (W_{si}) and the cost of facilities and employees (C_i). Security check machine (n_1), ticket machine (n_2) and ticket counter (n_3) are respectively considered in the upper-level model. The number of security check machines, ticket machines, and ticket counters should strictly satisfy the basic constraint $\rho=\lambda/(C\mu)\leq 1$ ($C\in\{n_1, n_2, n_3\}$).

The specific formula of L_{si} and W_{si} are explained in (1) - (4). The purchasing price of each machine (C_1, C_2) is set to 12800RMB, supposing its service life span for ten years, and the worker's monthly salary (C_3) is set to 3210RMB according to a survey.

Based on these targets, the multi-objective model of the upper lever is formulated as the formula (8):

$$F_{up}(n_1,n_2,n_3)=\begin{cases}\min n_1L_{s1}+n_2L_{s2}+n_3L_{s3}\\ \min n_1W_{s1}+n_2W_{s2}+n_3W_{s3}\\ \min n_1C_1+n_2C_2+n_3C_3\end{cases} \quad (8)$$

C. Lower-level Model

The lower-level programming is to direct passengers walking in the shortest distance after determining the quantity of all facilities. The direction of passenger flow should be first determined according to the daily routine. Before entering the waiting hall in the hub station, passengers should pick up the ticket from the ticket counter or ticket machine, then receive the security check service. The reverse direction is not allowed in our study.

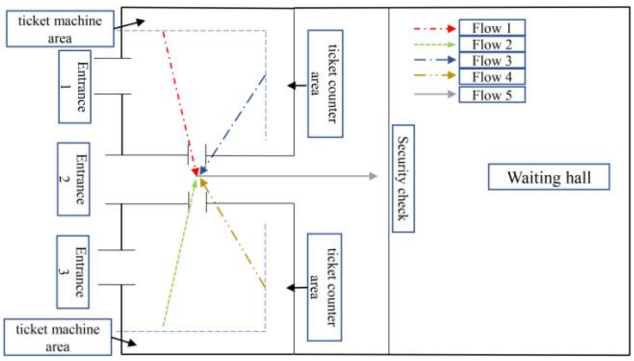

Fig. 2. Specific passenger flows

In the lower-level model, specific five passenger flows are considered as:

$$flow_1=\sum_{1\leq j\leq N^1} c_{21}^1 z_2^1\left(\sqrt{(x_{2j}^1-x_c)^2+(y_{2j}^1-y_c)^2}\right) \quad (9)$$

$$flow_2=\sum_{1\leq j\leq N^2} c_{21}^2 z_2^2\left(\sqrt{(x_{2j}^2-x_c)^2+(y_{2j}^2-y_c)^2}\right) \quad (10)$$

$$flow_3=\sum_{1\leq j\leq N^3} c_{31}^3 z_3^3\left(\sqrt{(x_{3j}^3-x_c)^2+(y_{3j}^3-y_c)^2}\right) \quad (11)$$

$$flow_4=\sum_{1\leq j\leq N^4} c_{31}^4 z_3^4\left(\sqrt{(x_{3j}^4-x_c)^2+(y_{3j}^4-y_c)^2}\right) \quad (12)$$

$$flow_5=\sum_{1\leq j\leq N^5} \left(\sqrt{(x_{1j}^5-x_c)^2+(y_{1j}^5-y_c)^2}\right) \quad (13)$$

Thus, the lower-level model is designed in the formula (14) to ensure the minimum passenger walking distance:

$$F_{low}(x_i,x_j,y_i,y_j)=\min(flow_1+flow_2+flow_3+flow_4+flow_5) \quad (14)$$

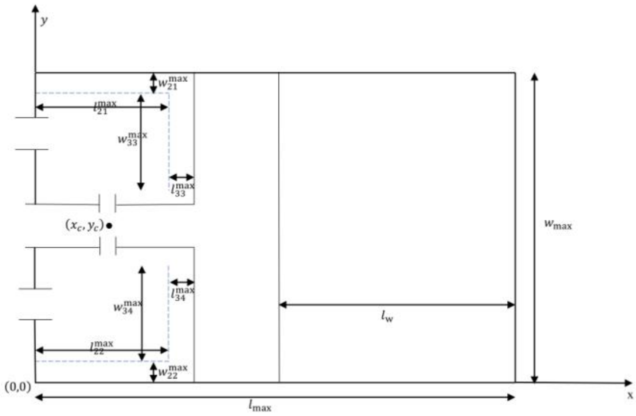

Fig. 3. Scheme of the Lanzhou West Station

In this study, the logit model presented in (15) – (18) is to determine the sharing rate of ticket machines and ticket counters:

$$z_{21}^1=p_{hour}\exp(c_{21}^1)/(\exp(c_{21}^1)+\exp(c_{21}^2)+\exp(c_{31}^3)+\exp(c_{31}^4)) \quad (15)$$

$$z_{21}^2=p_{hour}\exp(c_{21}^2)/(\exp(c_{21}^1)+\exp(c_{21}^2)+\exp(c_{31}^3)+\exp(c_{31}^4)) \quad (16)$$

$$z_{31}^3=p_{hour}\exp(c_{31}^3)/(\exp(c_{21}^1)+\exp(c_{21}^2)+\exp(c_{31}^3)+\exp(c_{31}^4)) \quad (17)$$

$$z_{31}^4=p_{hour}\exp(c_{31}^4)/(\exp(c_{21}^1)+\exp(c_{21}^2)+\exp(c_{31}^3)+\exp(c_{31}^4)) \quad (18)$$

Related constraints (19) - (37) in the lower-level model are shown as follows:

$$\sqrt{(x_{ij}^k-x_{i(j+1)}^k)^2+(y_{ij}^k-y_{i(j+1)}^k)^2}\geq 2r_i \quad (19)$$

The constraint (19) ensures that there is no overlap between any two facilities.

$$r_i=\sqrt{\frac{S_i}{\pi}} \quad (20)$$

For each facility, an infinite boundary of a facility should be avoided. Constraint (21) – (40) ensures that each facility is assigned within the boundary of its corresponding area.

$$x_{2j}^1+r_2\leq l_{21}^{\max} \quad (21)$$

$$y_{2j}^1+r_2\leq w_{\max} \quad (22)$$

$$x_{2j}^1-r_2\geq 0 \quad (23)$$

$$y_{2j}^1-r_2\geq w_{\max}-w_{21}^{\max} \quad (24)$$

$$x_{2j}^2+r_2\leq l_{22}^{\max} \quad (25)$$

$$y_{2j}^1+r_2\leq w_{22}^{\max} \quad (26)$$

$$x_{2j}^2-r_2\geq 0 \quad (27)$$

$$y_{2j}^1-r_2\geq 0 \quad (28)$$

$$x_{3j}^3+r_3\leq l_{21}^{\max}+l_{33}^{\max} \quad (29)$$

$$y_{3j}^3+r_3\leq w_{\max}-w_{21}^{\max} \quad (30)$$

$$x_{3j}^3-r_3\geq l_{21}^{\max} \quad (31)$$

$$y_{3j}^3-r_3\geq w_{\max}-w_{21}^{\max}-w_{33}^{\max} \quad (32)$$

$$x_{3j}^{4}+r_3\le l_{22}^{\max}+l_{34}^{\max} \quad (33)$$

$$y_{3j}^{4}+r_3\le w_{22}^{\max}+w_{34}^{\max} \quad (34)$$

$$x_{3j}^{4}-r_3\ge l_{22}^{\max} \quad (35)$$

$$y_{3j}^{4}-r_3\ge w_{22}^{\max} \quad (36)$$

$$x_{1j}^{5}+r_1\le l_{\max}-l_w \quad (37)$$

$$y_{1j}^{5}+r_1\le w_{\max} \quad (38)$$

$$x_{1j}^{5}-r_1\le \max\{l_{21}^{\max}+l_{33}^{\max},l_{22}^{\max}+l_{34}^{\max}\} \quad (39)$$

$$y_{1j}^{5}-r_1\ge 0 \quad (40)$$

D. Notation Explanation

(1) x_{ij}^{k} means the abscissa of the j[th] facility i through the flow k; (i∈{1,2,3}, facility 1 means the security check; facility 2 means the ticket machine; facility 3 means the ticket counter);

(2) y_{ij}^{k} means the ordinate of the j[th] facility i through the flow k;

(3) z_{ij}^{k} means the number of passengers who use the j[th] facility i through the flow k;

(4) x_c means the center abscissa of the ticket lobby;

(5) y_c means the center ordinate of the ticket lobby;

(6) r_i means the radius of the facility i;

(7) $l_{21}^{\max}$ means the maximum length of the ticket machine (i=2) area through the flow 1;

(8) $w_{21}^{\max}$ means the maximum width of the ticket machine (i=2) area through the flow 1;

(9) $l_{22}^{\max}$ means the maximum length of the ticket machine (i=2) area through the flow 2;

(10) $w_{22}^{\max}$ means the maximum width of the ticket machine (i=2) area through the flow 2;

(11) $l_{33}^{\max}$ means the maximum length of the ticket counter (i=3) area through the flow 3;

(12) $w_{33}^{\max}$ means the maximum width of the ticket counter (i=3) area through the flow 3;

(13) $l_{34}^{\max}$ means the maximum length of the ticket counter (i=3) area through the flow 4;

(14) $w_{34}^{\max}$ means the maximum width of the ticket counter (i=3) area through the flow 4;

(15) l_{max}, w_{max} mean the maximum length and width of the rectangle;

(16) l_w means the length of the waiting hall;

(17) c_{ij}^{k} means the generalized cost for a passenger moving from the j[th] facility i through the flow k;

(18) p_{hour} means the number of passengers in peak hours;

(19) S_i means the area of the facility i.

IV. SOLUTION TECHNIQUES FOR BI-LEVEL MODEL

A. GSA Algorithm Based on the ε-constraints method for solving the Upper-Level Model

To solve the multi-objective problem in the upper-level model, the ε-constraints method was introduced [22]. In this method, only one of the objective functions is regarded as the primary objective function, and the other two objective functions are transformed into its constraints. In this way, three objects in the upper-level model can be converted into three single-objective models, named model 1, model 2 and model 3. Moreover, by varying different ε values within an appropriate interval, a set of Pareto solutions can be obtained.

Model 1:

$$\min f_1=n_1L_{s1}+n_2L_{s2}+n_3L_{s3} \quad (41)$$

$$\text{s.t. } n_1W_{s1}+n_2W_{s2}+n_3W_{s3}\le\varepsilon_w,\varepsilon_w\in(\underline{\varepsilon_w},\overline{\varepsilon_w}) \quad (42)$$

$$n_1C_1+n_2C_2+n_3C_3\le\varepsilon_C,\varepsilon_C\in(\underline{\varepsilon_C},\overline{\varepsilon_C}) \quad (43)$$

Model 2:

$$\min f_2=n_1W_{s1}+n_2W_{s2}+n_3W_{s3} \quad (44)$$

$$\text{s.t. } n_1L_{s1}+n_2L_{s2}+n_3L_{s3}\le\varepsilon_s,\varepsilon_s\in(\underline{\varepsilon_s},\overline{\varepsilon_s}) \quad (45)$$

$$n_1C_1+n_2C_2+n_3C_3\le\varepsilon_C,\varepsilon_C\in(\underline{\varepsilon_C},\overline{\varepsilon_C}) \quad (46)$$

Model 3:

$$\min f_3=n_1C_1+n_2C_2+n_3C_3 \quad (47)$$

$$\text{s.t. } n_1L_{s1}+n_2L_{s2}+n_3L_{s3}\le\varepsilon_s,\varepsilon_s\in(\underline{\varepsilon_s},\overline{\varepsilon_s}) \quad (48)$$

$$n_1W_{s1}+n_2W_{s2}+n_3W_{s3}\le\varepsilon_w,\varepsilon_w\in(\underline{\varepsilon_w},\overline{\varepsilon_w}) \quad (49)$$

Because facility configuration problem can be classified as a kind of combinatorial optimization problem, some stochastic search algorithm should be utilized to find the solution. The simulated annealing method imitates the physical annealing of a solid. It is well known that, in practical annealing, a solid is heated until it melts and then with a proper annealing schedule it becomes colder until it reaches the least energy point. “The least energy point” is also called the satisfactory solution in an optimization problem. Similar to the simulated annealing algorithm, the genetic algorithm is commonly used in the combinatorial optimization problem. Crossover and mutation operations in the genetic algorithm will enlarge the solution space to find a near-optimal solution. Thus, to get a better solution, a genetic simulated annealing algorithm is put forward to solve each single-objective model (1,2,3) in the upper-level model.

It should also be mentioned that the crossover and mutation operation can generate feasible alternatives concerning constraints (ρ=λ/(Cμ)≤1). The basic crossover and mutation operation [23] applied in the GSA algorithm are shown in Fig.4.

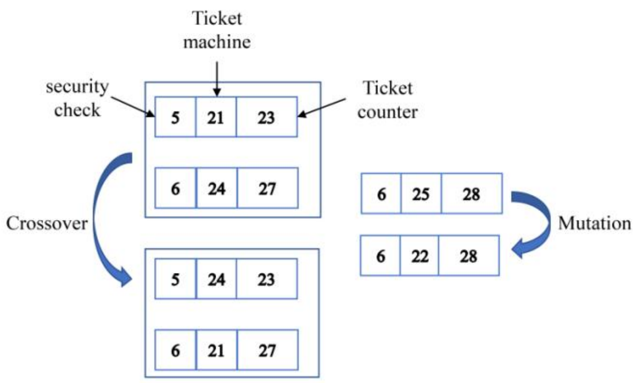

Fig. 4. Crossover and mutation operation

Moreover, the pseudo-code of GSA for solving model 1 is summarized as follows:

Step 1: Initialization

1.1 Set the lower bound of n_1, n_2, and n_3 as 1, 1, 1. Set the sufficiently large upper bound of n_1, n_2, and n_3 as 10, 30, 40. $\underline{\varepsilon_s}, \overline{\varepsilon_s}, \underline{\varepsilon_w}, \overline{\varepsilon_w}, \underline{\varepsilon_C}, \overline{\varepsilon_C}$ will be calculated.

1.2 Set some input parameters in GSA: the start temperature $sT = 100$, the cooling efficient $w = 0.9$, the outer iteration $OT = 1000$, the inner iteration $IN = 55$, the searching iteration $SN = 5000$,the mutation probability $p_m = 0.05$, the crossover probability $p_c = 0.9$, the searching iteration $z = 1$.

1.3 Generate a random value $\varepsilon_w \in [\underline{\varepsilon_w}, \overline{\varepsilon_w}]$; $\varepsilon_C \in [\underline{\varepsilon_C}, \overline{\varepsilon_C}]$.

1.4 Generate three feasible solutions to satisfy $\rho/(n_i * \mu) < 1$. Let the temperature $T = sT$. Calculate the value $z_1 = f_1$. Set the outer iteration $i = 1$.

Step 2: During the current temperature T

2.1 Set the inner iteration $j = 1$.

2.2 Generate a random number a, if $a > p_m$, then generate three new feasible solutions by a mutation operation, and the mutation position is set randomly; generate another random number b, if $b > p_c$,then generate three new feasible solutions by a crossover operation. Then calculate the value $z_2 = f_1$.

2.3 Calculate $\Delta = z_2 - z_1$, if $\Delta < 0$, then $z_1 = z_2$; if $\Delta > 0$, then calculate $\rho = \exp(-\Delta/T)$, generate another random number c, if $c > \rho$, then $z_1 = z_2$.

2.4 if $j = IN$, then go to Step 3; otherwise $j = j + 1$, then go to 2.2.

Step 3: Terminate or not

3.1 if $i = OT$, then output the value and computing time, then go to 3.2; otherwise $T = T \times 0.9$, $i = i + 1$, then go to Step 2.

3.2 if $z = SN$, then terminate; otherwise $z = z + 1$, then go to 1.3.

Likewise, solutions of model 2 and model 3 are found according to the GSA algorithm. And TABLE IV shows six Pareto solutions forming 6 scenarios.

TABLE IV
THE SPECIFIC QUANTITY OF EACH FACILITY

	n_1	n_2	n_3
Scenario1	5	19	23
Scenario2	5	19	24
Scenario3	5	19	25
scenario4	5	20	25
Scenario5	6	20	25
Scenario6	7	20	25

B. *Solving the Lower-Level Model Based on CPLEX*

Dominated solutions of the upper-level are the constraints to the lower-level model; $n_1 = 6$, $n_2 = 20$, $n_3 = 25$ (Scenario 5) is taken as the practical example, to calculate the abscissa and ordinate of each facility according to the lower-level model. And the other scenario coordinates will also be found in the same manner.

CPLEX is considered as one of the most advanced mathematical programming solvers. The lower-level model is tested using CPLEX solver 12.5 on a personal computer with an Intel Core i5-6200u, 2.3 GHz CPU and 12GB RAM. After solving the non-linear model of the lower-level, the coordinates of each facility in scenario 5 are obtained:

TABLE V
THE SPECIFIC COORDINATES OF FACILITIES ON SCENARIO 5

Facility		Abscissa(m)	Ordinate(m)
Security check	1st	62.57	151.635
	2nd	62.57	151.175
	3rd	62.57	150.715
	4th	62.57	152.555
	5th	62.57	153.015
	6th	62.57	153.475
Ticket machine	1st	41.56	270.775
	2nd	41.56	21.775
	…	…	…
Ticket counter	1st	43.2	150.455
	2nd	43.2	153.735
	…	…	…

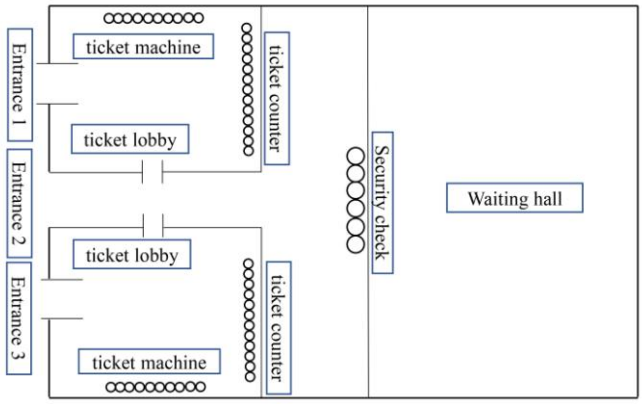

Fig. 5. Specific facility layout of scenario 5

Moreover, passengers' average walking time among facilities can be calculated to decide which scenario (1,2,3,4,5,6) is the most suitable for the Lanzhou West Station under the background of 5000 passengers per peak hour.

TABLE VI
RANKING OF EACH SCENARIO BASED ON AVERAGE WALKING TIME

Pareto solution of the upper-level	n_1	n_2	n_3	Passengers' average walking time in the lower-level (s)	Ranking
Scenario 1	5	19	23	274.0	6th
Scenario 2	5	19	24	273.4	5th
Scenario 3	5	19	25	273.1	4th
Scenario 4	5	20	25	225.6	2nd
Scenario 5	6	20	25	225.5	1st
Scenario 6	7	20	25	225.6	2nd

The difference among scenarios is easily quantified by passengers' walking efficiency. Since passengers' walking behavior is added to the lower-level model, some scenarios solved by the upper-level model will become more competitive. It can be concluded from TABLE VI that the optimal quantity of security check machines, ticket machines, and ticket counters is 6, 20, 25 respectively under the background of 5000 passengers per peak hour in the Lanzhou West Station.

V. SIMULATION VERIFYING AND DISCUSSION

A. Simulation Verification

It is widely accepted that simulation is an effective solution for evaluating facility layouts efficiency. In our study, MASSMOTION is applied to verify our solution. MASSMOTION is an agent-based pedestrian simulation software which integrates 3D environments and behavioral profiles to analyze various pedestrian movements and different route choices [24]. In this section, the Lanzhou West Station BIM model is imported to the MASSMOTION to verify the efficiency of scenario 5.

In our simulation model, each passenger makes a series of choices to arrive at their destination based on their advanced O-D pair and behavior profile.

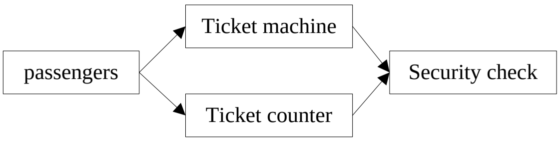

Fig. 6. Service processes

For validation, a simplified evaluation method for passengers' average route cost is provided in Equation (50) which considers the facility configuration and the facility layout simultaneously:

$$\cos t = \sum_{p \in P} (W_D \cdot (D_p / V) + W_Q \cdot Q) / T_p \qquad (50)$$

Where W_D is the distance weight, D_p is a passenger total distance from the origin to the destination, V is the passenger's desired velocity, W_Q is the weight of the queue, Q is the expected time for passenger queueing in line, P is the total passenger set. T_p is the total passengers in peak hours.

At present, the quantity of security check machines, ticket machines and ticket counters in the Lanzhou West Station is 4, 12, 14 respectively. After simulation, the comparison between the current scenario and scenario 5 is given in Fig.7.

It can be seen in Fig.7, that the current scenario is no longer efficient when the number of passengers in peak hours increases. Meanwhile, passengers' average route cost increases rapidly in the current scenario when the number of passengers at peak time reaches 5000. On the contrary, scenario 5 shows its superiority when the number of passengers in peak hour increases. Unlike the current scenario, passengers' average route cost increases slowly in scenario 5. Meanwhile, passengers' average route cost is strictly limited within a reasonable boundary in scenario 5.

Therefore, this simulation experiment verifies the efficiency of scenario 5. Decision-makers can decide on the most efficient scenario when today's changing passenger requirements are taken into account in the future.

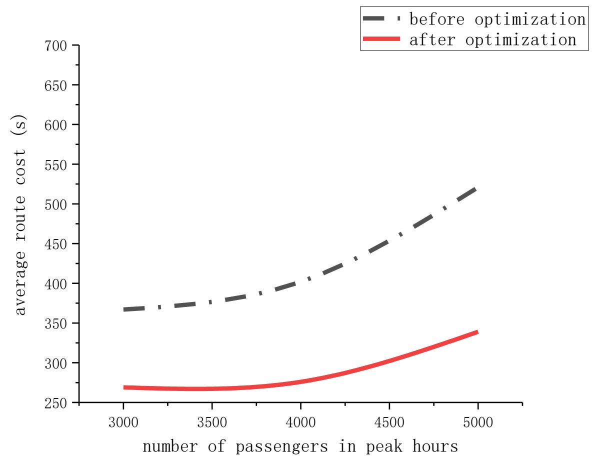

Fig. 7. Comparison curve between existing scenario and scenario 5

B. Discussion

Some effective and interesting information will also be obtained to discuss the inner relationship of the facility configuration and facility layout in TABLE VI.

When the number of ticket counters increases, passengers' average walking time in scenario 1 to 3 decreases gradually. As the number of ticket machines increases from 19 to 20, passengers' average walking time drops down immediately. This result shows passenger behavior preferences when they are making choices. When the number of ticket machines increase, passengers are more willing to pick up their tickets from the ticket machine due to its high efficiency. The crowded dissipates more quickly and the volume of passenger flows will be reduced, which means that the cost for passengers moving from the ticket machine to the security check will be less than that from the ticket counter to the security check. Thus, passengers' average walking time will be less as well. On the other hand, although the number of ticket counters increases, the crowded dissipate slowly due to the poor efficiency of the ticket counter, and it indicates that passengers' average walking time decreases slowly. According to observation, this result corresponds closely to the actual situation.

Therefore, this will also enable the decision-makers to make better and more effective decisions depending on the efficiency of the ticket machine and ticket counter.

VI. CONCLUSIONS

This study presents a bi-level programming model to optimize facility configuration and layout problems in the hub station from the perspectives of passengers and railway administration. The GSA algorithm based on the ε-constraints method is developed in the upper-level programming model to deal with the facility configuration problem. After comparing with the passengers' average walking time of scenario 1,2,3,4,5,6, the optimal solution of the bi-level programming model can be discovered under the background of the Lanzhou West Station. A simulation verification experiment is conducted in MASSMOTION, which indicates that scenario 5 is more efficient than the current scenario in the Lanzhou West Station.

In this paper, the number of passengers per peak hour is set at 5000, the quantity of corresponding facilities and their locations will be obtained according to the method presented. And if the number of passengers per peak hour is set as 10000 or more in the future, corresponding solutions will also be obtained in time for the decision-makers. The approach used in solving the facility configuration and layout problems in this paper gives a new research methodology for studying this subject with regard to the hub station.

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