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Research Article

Flexible Scheduling Model of Bus Services between Venues of the Beijing Winter Olympic Games

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Traditional buses travel on fixed routes and areas, which cannot satisfy the flexible demands of athletes in the context of COVID-19 and the closed-loop traffic management policy during the 2022 Beijing Winter Olympic Games (BWOG). This study predicts the travel demands based on the characteristics of athletes' daily travel demands and then presents a flexible bus service scheduling model for cross-region scheduling among Beijing, Yanqing, and Zhangjiakou to provide high-level service. The flexible bus service is point-to-point and avoids unnecessary contact, which reduces the risk of spreading COVID-19 and ensures athletes' safety. In this study, the flexible bus scheduling model is established to optimize scheduling schemes, whose object is to minimize the cost of the system based on some realistic constraints. These constraints consider not only the preferred time windows of athletes' demand but also the vehicle's capacity, depot, minimum load factor, total demands, etc. In addition, a genetic-simulated annealing hybrid algorithm (GSAHA) is designed to solve the model based on the characteristics of the genetic algorithm (GA) and simulated annealing. To assess the feasibility and efficiency of the model and algorithm, a case study is conducted in the Beijing-Yanqing area. Furthermore, the travel time of the flexible bus is compared to that of the traditional bus, according to the results of the case study. Moreover, the sensitivity of the model and algorithm are analyzed. The experimental results show that the proposed model and algorithm can dispatch buses with superior flexibility and high-level services during the BWOG.

1. Introduction

Since Beijing has become the host city of the 2022 Beijing Winter Olympic Games (BWOG), the management and dispatch of enormous demands have resulted in tremendous pressure and challenges for Beijing's transportation system. Although the Beijing municipal government has constructed multidimensional complementary transportation service facilities (high-speed railway, air, highway, subway, and local roads), the high-service-level traffic demands of specific groups, such as Olympic officials, athletes, and sponsors, cannot be satisfied because traditional transportation lacks flexibility, comfort, and has a long waiting time. Various host cities have taken active measures to meet the requirements of these specific groups in the past. During the 2000 Sydney Olympic Games, the government implemented a series of transportation measures, such as introducing a multimodal system, implementing transportation networks and resource planning strategies, and formulating institutional changes and transportation plans that satisfied the travel demands of different service objects during the Olympics [1]. During the 2004 Olympics in Athens, the government analyzed the pressure of public transport. It proposed an auxiliary service facility (named the responsive bus) to provide services for specific groups of people (such as the elderly, VIPs, and the disabled) [2]. During the 2012 Olympics in London, the government proposed a scheduling strategy. In the first stage, a predictive traffic demand model was built, while in the second stage, relied existing models were used, thus covering the entire London underground, ground, national railways, and port areas. London's light rail, tram, and bus services were fully integrated to collect and dispatch the enormous demand during the Olympics [3]. In the 2016 Rio Summer Olympics, Brazil already had the experience of organizing transportation services for mega-events such as the World Cup. Its capital city constructed four new bus rapid transit lines to provide transportation services for different demands by connecting Olympic venues [4].

Flexible public transportation implies that buses provide demand-response services in a specific area between fixed first and last stations. Some scholars have proposed various models, considering their objective functions. For example, Sultana et al. [5] considered the economic benefits and proposed a set of econometric models to enhance the decision-making process and determine the causal relationship related to demand-responsive transportation trips. Sun et al. [6] aimed to solve the optimal route of the flexible bus, minimizing the vehicles' running time and the passengers' travel time; they proposed a flexible bus route optimization model based on multitarget stations. Chu et al. [7] considered the instability and scatter in travel demand in remote areas and proposed a two-stage stochastic programming (SP) model for the integrated planning of a fixed-route-fixed-schedule bus service and dial-a-ride transportation. Huang et al. [8] established a two-stage framework model. In the first phase, information was collected, such as route, schedule, and client data, while in the second phase, three nonlinear programming models were established to optimize the routine based on the data from the first phase. Moreover, Lee et al. [9] investigated flexible bus services by minimizing the sum of ad hoc service costs and detour time costs by providing either regular or ad hoc services after demand realization. In addition, some scholars have investigated the constraints conditions. Horn [10] considered the time window constraint and designed an itinerary insertion model that yielded excellent customer service and vehicle deployment efficiency. Nelson et al. [11] proposed applying the most suitable vehicles to adapt to different environments in designing a flexible bus service system. Myungseob et al. [12] considered the stochastic variability in travel times and wait times of flexible buses and proposed probabilistic optimization models to integrate and coordinate bus transit services for one terminal and multiple local regions. Lee et al. [13] considered passenger demands' spatial (origin-destination) and stochastic variation of volume and developed a zonal-based flexible bus service. Tas [14] also focused on the flexible time window constraint, in which vehicles should serve customers before and after the earliest and latest time window boundaries, respectively. However, their studies did not establish the bus scheduling model for specific travel demands, such as those of an athlete. On the other hand, their research was limited to scheduling within one area, not between different areas.

Several scholars have developed various algorithms to optimize the strategy to solve the problem of a flexible public transportation system. Taş [15] proposed a solution approach in which routes were obtained by a column generation procedure and further improved by a linear programming model that optimized the penalty cost of the given paths. Also, Huang et al. [16] designed a dynamic genetic algorithm to generate a static initial travel path based on simulated annealing. The dynamic travel path was continuously updated to meet real-time demand. Moreover, Lee et al. [9] studied the constructive heuristics algorithm and introduced a method that combined the gradient-based solution approach with a greedy search solution approach and relaxed the formulations. But their approaches only consider the specific area, in which the road network is not highly complicated. Some studies also considered meta-heuristic algorithms. For instance, Chu et al. [7] proposed a hybrid algorithm to solve the two-stage stochastic programming problem; they developed a depth-first search algorithm based on a route enumeration tree and a heuristic algorithm in the first and second stages, respectively. Wang and Ma [17] also proposed a three-stage hybrid coding method based on the multiobjective genetic algorithm (NSGA-II) to solve the problem of flexible bus route calculation. However, their solution algorithms should satisfy specific conditions, such as one bus route dispatching and fixed travel demand. Some scholars have proposed algorithms to improve the efficiency of computation. For example, Liu [18] studied the classic improvement heuristics algorithm and proposed an improved A^* algorithm to prune the unnecessary path directions during path planning to improve search efficiency. Huang et al. [16] also proposed a real-time search algorithm to improve computational efficiency. However, their algorithms may not produce the most global optimal solutions. In addition, some researchers have adopted improved genetic algorithms and simulated annealing algorithms. For instance, Lin and Tang [19] built a model for the intelligent scheduling problem in public transport based on an enhanced quantum genetic algorithm to find the optimal timetable. Also, Wang et al. [20] studied a multidepot electric vehicle scheduling problem in public transit and proposed a genetic algorithm based on a column generation approach for the problem. But the coverage rate of trips of their genetic algorithms is slow. Additionally, Yu et al. [21] developed a simulated annealing (SA) algorithm to deal with vehicle routing problems with time windows, and Candido and de Souza [22] developed an algorithm based on simulated annealing and local search that uses a collection of packing heuristics to address the loading constraints. They also proposed three new heuristics. Also, their algorithms still have room for improvement, such as by proposing more sophisticated and superior routing and packing strategies. However, in solving such problems, the search area of these algorithms is relatively small, and their convergence speed is relatively slow.

In light of the review, although these scholars attempted to develop models considering various perspectives, there is limited relevant research on flexible bus cross-region scheduling for athletes' demands during the Olympic Games. Furthermore, the current algorithm cannot obtain the final solution quickly and accurately. Therefore, this study first analyzes the characteristics of athletes' travel demands, then forecasts their daily travel demands among various venues in different regions during the BWOG. To satisfy the demands, a flexible bus scheduling model is established by minimizing the total cost of the system with some realistic constraints. Additionally, the preferred time windows of athletes' demands are also considered when providing high-level service. The flexible bus system can provide point-to-point service for athletes according to their demands, which reduces unnecessary contact. Besides, it complies with the closed-loop traffic management policy and reduces the risk of spreading COVID-19, ensuring athletes' safety. Furthermore, a genetic-simulated annealing hybrid algorithm is designed to solve the model. On the one hand, the search area of the GSAHA is extended based on the characteristics of the simulated annealing algorithm (SAA); on the other hand, its convergence rate is improved with the characteristics of the GA. Furthermore, a real case study is conducted based on venues in the Beijing and Yanqing areas to investigate the validity and effectiveness of the proposed model and algorithm. Finally, the proposed model and algorithms' sensitivity are also analyzed.

The remainder of this study is organized as follows: Section 2 presents the framework of this study. Section 3 describes the analysis and forecasting of the travel demand of athletes during the BWOG. Section 4 illustrates the proposed flexible scheduling model and discusses the assumptions and constraints. Section 5 presents the proposed solution algorithm and compares it with the GA. Section 6 elaborates on the selected test case and details the experimental results. Section 7 presents the sensitivity analysis of the proposed model and the GSAHA. Finally, Section 8 gives the concluding remarks and future research directions on the proposed methodology.

2. Framework

This study focuses on providing a flexible dispatching strategy for athletes during the BWOG with high-level service; the specific workflow, which is divided into four parts, is described in Figure 1.

To satisfy the travel demands of athletes, first, the characteristics of their traffic demands are analyzed to predict their daily travel demands. Because obtaining data related to athletes is the most crucial part. After forecasting the demand, a model is proposed to dispatch these demands. The second step considers various constraints on providing high-level service to athletes. In the third step, a new hybrid algorithm is designed that combines the advantages of the GA and SAA to obtain the optimal strategy. Finally, a case in the Beijing and Yanqing areas is investigated to verify the model and algorithm. The travel times between flexible buses and the traditional bus are compared. Furthermore, sensitivity analysis is performed for the proposed model and algorithm.

3. Demand Analysis

3.1. Venues Distribution. The BWOG was held in Beijing, Zhangjiakou, and Yanqing districts; the distribution of venues, depots, and Olympic Villages is depicted in Figure 2. Among these, Beijing was responsible for hosting the ice project; Zhangjiakou was responsible for hosting the snow project; and Yanqing co-organized the snow project in Zhangjiakou. In detail, 11 venues, three depots, and three

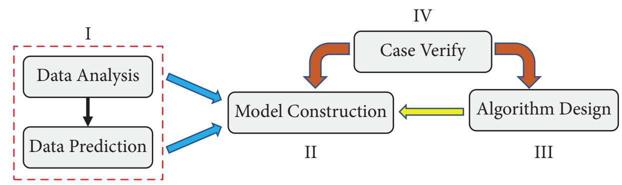


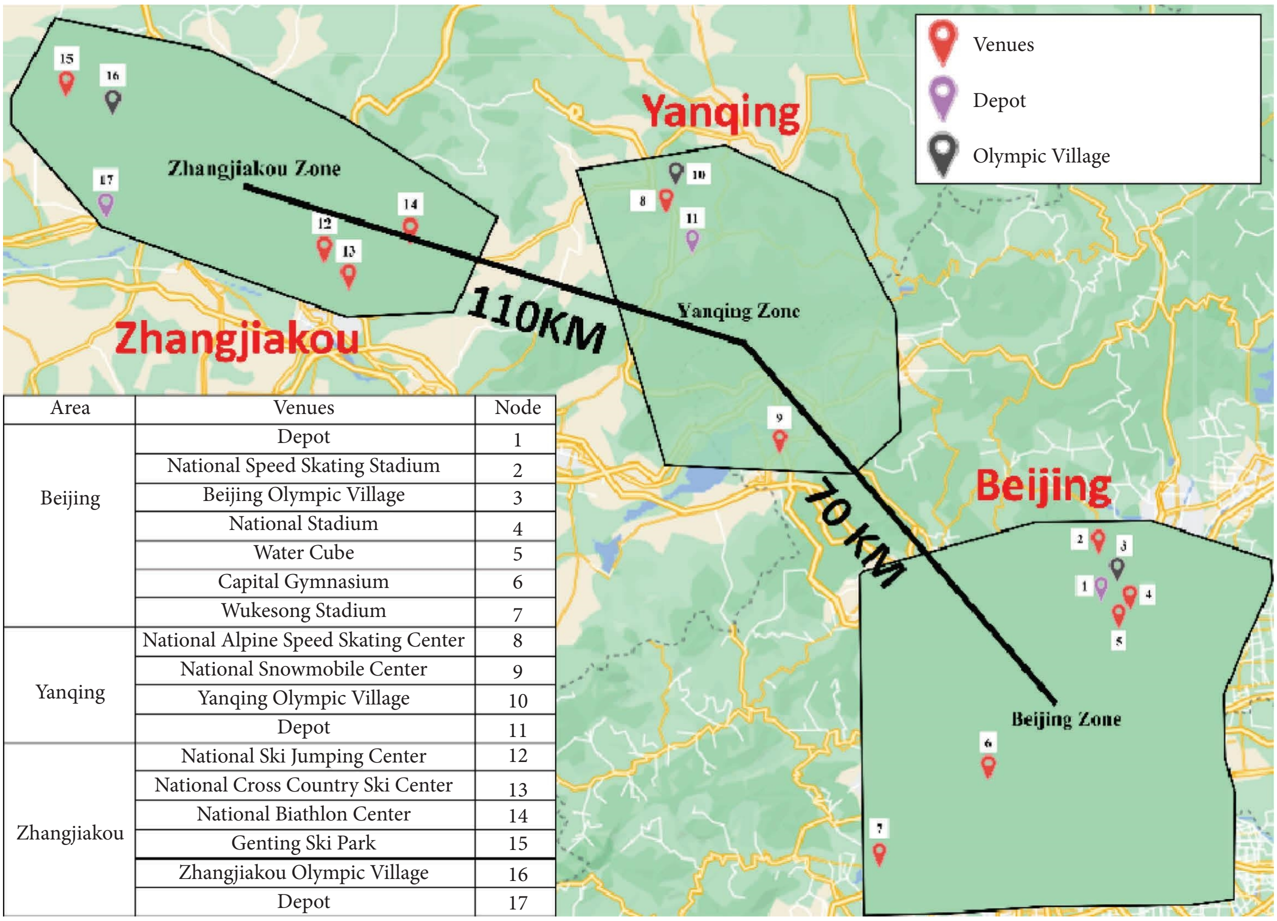
Figure 1: Framework.

Olympic Villages are distributed in Beijing, Yanqing, and Zhangjiakou; their geographical locations and names are depicted in Figure 2.

The distance between Beijing and Yanqing, as well as Yanqing and Zhangjiakou, is approximately 70 and 110 km, respectively. An Olympic-specific transportation system arranges and designates 4090 different types of vehicles to satisfy people's travel demands. In addition, the Beijing-Zhangjiakou high-speed railway and highways connect these three places tightly and facilitate travel for them.

3.2. Analysis of Travel Demand. As an international event, the BWOG attracted people from all over the world to participate. According to the official information of the Beijing Organizing Committee for the 2022 Olympics, the objects of travel mainly included the following categories: the Olympic family (athletes, volunteers), the National Olympic Committee, the media, the broadcaster, the market development partner, the audience, etc. Also, it was a considerable challenge for the Beijing Organizing Committee for the 2022 Olympics to satisfy the travel demands of the above people, especially when COVID-19 is still raging. To ensure the safety of athletes while meeting their daily travel demands, the government applied a particular traffic management policy, named closed-loop traffic management system, to reduce unnecessary contact and provided point-to-point transportation services with special transportation modes. Therefore, a flexible bus system is necessary and helpful to meet the flexible travel demands of athletes.

The travel demands of athletes generally involve (1) going to various training venues for daily training, which accounts for a large proportion of the demand; moreover, because the training time of athletes is not fixed, the travel time required can relatively change; (2) participation in formal competitions; the travel time associated with this is strict because each competition schedule is fixed in advance and athletes cannot be late; consequently, this type of demand requires a higher level of transportation service; (3) going back to the Olympic Village for rest; after training or participating in a competition, athletes usually return to the Olympic Village to rest; (4) participating in the opening and closing ceremonies or press conferences; this travel demand may be relatively high because athletes generally travel at the same time; and (5) daily life; this travel demand mainly happens in the Olympic Villages, and athletes go shopping, have meals, do exercise, etc. In addition, the detailed types of the athletes' travel demands are included in Table 1, based on the above analysis and three different influence factors such as sensitivity to a time window, willingness to wait for the bus, and service quality.



Area	Venues	Node
Beijing	Depot	1
	National Speed Skating Stadium	2
	Beijing Olympic Village	3
	National Stadium	4
	Water Cube	5
	Capital Gymnasium	6
	Wukesong Stadium	7
Yanqing	National Alpine Speed Skating Center	8
	National Snowmobile Center	9
	Yanqing Olympic Village	10
	Depot	11
Zhangjiakou	National Ski Jumping Center	12
	National Cross Country Ski Center	13
	National Biathlon Center	14
	Genting Ski Park	15
	Zhangjiakou Olympic Village	16
	Depot	17

Figure 2: Distribution of venues, depots, and Olympic Villages between Beijing, Yanqing, and Zhangjiakou districts.

Table 1: Types of travel demands and the influencing factors.

Types of travel demands	Sensitivity to the time window	Willing to wait for the bus	Service quality
Daily training	Middle	Wait for the bus within a short period	Less transfer
Attend the formal competitions	Very high	Won't wait for the bus	No transfer
Back to the Olympic Village	Low	Wait for the bus within a short period	Less transfer
Attend the opening and closing ceremonies	High	Won't wait for the bus	No transfer
Attend press conference	High	Won't wait for the bus	No transfer
Daily life	—	—	—

3.3. Demand Prediction of Athletes. The previous section analyzed the composition of athletes' travel demands during the BWOG. Next, the demands of athletes are predicted in the section. There are a total of 2892 athletes participating in the BWOG, according to the Beijing Winter Olympics Organizing Committee's official website information. Also, the traditional four-stage method of traffic demand prediction is adopted to systematically forecast the passenger flow of athletes based on Fang and Xu [23]. The traffic demand is forecasted as follows: first, the athlete population is allocated to these venues and Olympic Villages among Beijing, Yanqing, and Zhangjiakou according to the number of applicants and the venue of each competition event, and the population in each Olympic Village is the sum of the populations of venues in the same district. Second, the daily traffic generation is forecasted based on the following:

$$P_i = ax_i, \tag{1}$$

where P_i is the number of trips in the traffic area i; x_i is the population of the traffic area i; a is the travel ratio coefficient that athletes choose the flexible bus as their transportation mode. It is influenced by various factors, such as the weather, travel distance, and the local policy (the COVID-19 Prevention and Control Policy). During the Beijing Olympic Games in 2008, the proportion of people who chose to take public transportation (bus and subway) was 38.7%, based on Chen et al. [24]. Compared to the former, a is chosen as 0.5 in BWOG. Because of the closed-loop traffic management system, public transportation is forbidden to service these passengers, and athletes can only take designated transportation such as buses, taxis, and high-speed railways. Next, the daily passenger flow is forecasted. There were 7 major events and 109 subevents, such as snowmobiling, freestyle skiing, and alpine skiing, among the venues mentioned above during the Beijing Winter Olympics. Besides, an average of 10 hours of passenger flow is generated every day, and the average hourly passenger flow of athletes can be calculated. Finally, the mentioned-above estimated results are shown in Table 2.

4. Problem Description and Modeling

It is worth mentioning that a complete trip is defined as a bus starting from the pickup area, where the originating depot is located, and ending at its destination depot in the drop-off areas. Before responding to passenger demands, requests for buses should be sent. Figure 3 shows the specific process of the model schedule. First, the depot receives demand requests from passengers, and it sends a bus to respond to passengers, whose origin destinations are in the "pickup zone" under the constraints of the time window, and the time window refers explicitly to the pickup time window in this study; then, it responds to passengers whose destination is in the "drop-off zone." The pickup process is depicted by a pink dotted arrow in Figure 3. Once the number of cross-regional passengers meets the minimum load-carrying rate of the bus, it goes to the "drop-off zone." For the maximum utilization of vehicle resources, the bus also responds to the demands of the "drop-off zone" in sending passengers to their destination, implying that passengers can get on and off the bus during this process. For example, if the origin and destination of a passenger are both in the "pickup zone" or "drop-off zone," the bus also responds to the passenger's request. After addressing the requests of all passengers, the car finally returned to the depot; the red arrow in Figure 3 depicts this situation.

4.1. Notations. The problem is formulated as cross-region dispatching based on passenger demands with time window constraints. Next, some notations are defined. The network $G = (Z, N, R)$ is composed of zones, nodes, and routes, where $Z = O \cup D$ represents the zone, and it consists of the "pickup" zone $\{o_1, o_2, o_3\}$ and "drop-off" zone, $\{d_1, d_2, d_3\}$; $N = N^+ \cup N^- \cup W$ represents the nodes, where $N^+ = \{1, , , n\}$ (nodes in the pickup zone), $N^- = \{n+1, , , 2n\}$ (nodes in the drop-off zone), and $W = \{0, 2n+1\}$ (depots set); $R = \{(i, j) , , , \}$ represents the set of routes, where (i, j) represents a link from the node i to node j. Moreover, $K = \{1, , , k\}$ denotes the set of buses. The daily serving time of a bus, $[T_0, T_1]$, is divided into successive and continuous-time intervals $\{[t_0, t_1]_1, , , [t_0, t_1]_m\}$, where T_0 is the start time and T_1 is the end time. In addition, $M = \{1, , , m\}$ represents the order of a given time interval. Other variables and their domains and explanations are listed in Table 3.

4.2. Model Description. The objective of the proposed model is to minimize the total cost, and its formation is

$$\min Z = \sum_{m\in M} \left\{ c_v \left(\sum_{r\in R} \frac{\left(l^r_{i,j} y^m_{ij,k} \right)}{V} + \sum_{i\in N} s_i \right) + c_f \sum_{r\in R} u^m_k + c_p \sum_{i,j\in N^+, i\neq j} T_{\text{exceed}} \right\}, \quad (2)$$

$$T_{\text{exceed}} = LA_i \left[t^m_{i,a} - \left(T^{\text{leave}}_{i,k} + \sum_{i\neq j} \frac{\left(l^r_{i,j} y^m_{ij,k} \right)}{V} \right) \right] + LD_i \left[s_i - \left(t^m_{i,b} - t^m_{i,a} \right) \right]. \quad (3)$$

In equation (2), the total general cost is divided into three parts. The first part is the variable cost, which means the traveling time of the bus among these venues and the time used for passengers to board or alight the bus. It also includes fuel and tire costs. The second part is the fixed cost of each bus, which includes the vehicle depreciation, vehicle insurance, repair and maintenance costs, and the driver's salary. The last part is the penalty cost, which means the vehicle's arrival time at the scheduled node (or departure from the scheduled node after responding to demand) does not satisfy the scheduled time window of the passenger. Also, the exceeded time of a bus at the node i is calculated as equation (3). In equation (3), the former term refers to the time that the bus arrives at the node i earlier than the scheduled time, and the latter term refers to the time that the bus arrives at the node i later than the scheduled time.

Besides, the following equations express the various constraints related to the model:

$$\sum_{k\in K} x^m_{i,k} \leq 1 \quad \forall i \in N^+, \quad (4)$$

$$\sum_{k\in K} x^m_{i,k} \left(p^m_{i,j} + q^m_{i,on} - q^m_{i,off} \right) \leq Cap \quad \forall i \in N^+, \quad (5)$$

$$\sum_{k\in K} x^m_{i,k} \cdot p^m_{i,j} \geq \partial \cdot \text{Cap} \quad \forall m \in M, \quad (6)$$

$$\sum_{k\in K} u^m_k \geq 1 \quad \forall m \in M, \quad (7)$$

$$\text{Cap} \cdot \sum_{k\in K} u^m_k \geq Q^m \quad \forall m \in M, \quad (8)$$

Table 2: The demand for athletes using flexible buses to travel between these venues.

	Node label	Athlete population	Daily produced trips	Average hourly passenger flow
Beijing	2	166	108	11
	4	191	124	12
	5	156	101	10
	6	376	244	24
	7	382	248	25
	3	1271	826	83
Yanqing	8	305	198	20
	9	307	200	20
	10	612	398	40
Zhangjiakou	12	194	126	13
	13	214	139	14
	14	213	138	14
	15	388	252	25
	16	1009	656	66

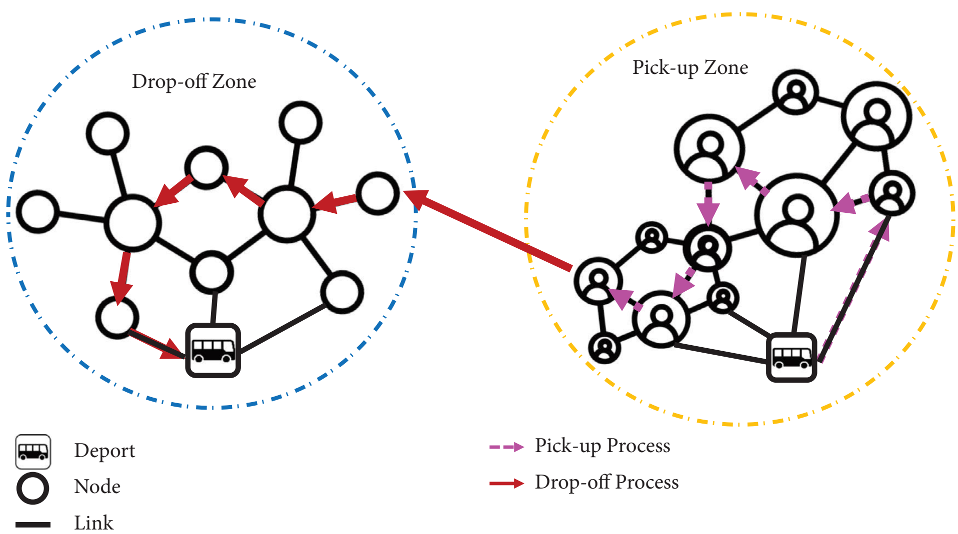


Figure 3: Dispatch mode of buses.

$$\mathrm{Cap}\cdot\sum_{k\in K} u_k^m \geq \sum_{i\in N^+}\left(p_{i,j}^m + q_{i,on}^m\right)\quad \forall m\in M, \tag{9}$$

$$\sum_{j\in N^+} y_{0j,k}^m \leq 1\quad \forall k\in K,\ m\in M, \tag{10}$$

$$\sum_{j\in N^-} y_{j,2n+1,k}^m = \sum_{j\in N^+} y_{0j,k}^m\quad \forall k\in K,\ m\in M, \tag{11}$$

$$y_{0j,k}^m = 0\quad \forall i\in N,\ k\in K,\ m\in M, \tag{12}$$

$$\sum_{j\in N^-} y_{j,2n+1,k}^m = 0\quad \forall i\in N,\ k\in K,\ m\in M, \tag{13}$$

$$\sum_{i\neq j}\frac{\left(l_{i,j}^r y_{ij,k}^m\right)}{V} + \sum_{i\in N^+}\left(p_{i,j}^m + q_{i,on}^m\right)\cdot t_{on} \leq \delta\quad \forall j\in N^-, \tag{14}$$

$$T_0 + m\cdot\delta = t_s^m\quad \forall m\in M, \tag{15}$$

$$t_s^m + \delta = t_e^m\quad \forall m\in M, \tag{16}$$

$$s_i = p_{i,j}^m\cdot t_{on} + \theta_i\cdot q_{i,on}^m + \left(1-\theta_i\right)\cdot q_{i,off}^m\quad \forall i, j\in N^+, \tag{17}$$

$$s_i \leq t_{j,b}^m - t_{j,a}^m, \tag{18}$$

$$T_{i,k}^{\text{leave}} = t_s^m + \sum_0^i\left(\frac{\left(l_{i,j}^r y_{ij,k}^m\right)}{V} + x_{i,k}^m s_i\right)\quad \forall i,\ j\in N^+, \tag{19}$$

$$T_{i,k}^{\text{leave}} + \sum_{i,i\neq j}^{j}\frac{\left(l_{i,j}^r y_{ij,k}^m\right)}{V} \geq t_{j,a}^m,\quad \forall i,\ j\in N^+,\ k\in K, \tag{20}$$

$$T_{j,k}^{\text{arrive}} - T_{i,k}^{\text{leave}} \leq T_{\max}\quad \forall i,\ j\in N,\ k\in K, \tag{21}$$

$$\sum_{j\in N, i\neq j} y_{ij,k}^m - \sum_{j\in N, i\neq j} y_{ji,k}^m = 0\quad \forall i\in N,\ k\in K, \tag{22}$$

Table 3: Problem variables and explanations.

Variable	Domain	Explanation
NS	$R+$	Maximum number of stations that people can accept during a trip
∂	(0, 1)	Minimum load factor of the bus
Cap	$R+$	The capacity of the bus
V	$R+$	The average speed of the bus
$l^r_{i,j}$	$R+$	Length of the link (i, j)
Q^m	$R+$	Total requests at the m-th time interval at zone O
$p^m_{i,j}$	$R+$	Number of passengers wanting to get on the bus at the i-th node
$q^m_{i,\text{on}}, q^m_{i,\text{off}}$	$R+$	Number of passengers wanting to get on/off at the i-th node for in-zonal passengers
t_{on}, t_{off}	$R+$	Average time for one passenger to get on or off the bus
s_i	$R+$	Actual serving time at the i-th node
$[t^m_{i,a}, t^m_{i,b}]$	$R+$	The time window for picking up passengers at the i-th node
$T^{\text{arrive}}_{i,k}$	$R+$	Actual arrival time at the i-th node for bus k
$T^{\text{leave}}_{i,k}$	$R+$	Actual leaving time at the i-th node for bus k
c_v, c_f, c_p	$R+$	Variable cost per bus, fixed cost per bus, and penalty cost for late time per minute
$T_{\max}$	$R+$	Maximum waiting time for a passenger
δ	$R+$	Time duration of each time interval
$x^m_{i,k}$	{0, 1}	1 if the k-th bus serves the i-th node at the m-th time interval; 0 otherwise
$y^m_{ij,k}$	{0, 1}	1 if the link is selected by bus k at the m-th time interval; 0 otherwise
u^m_k	{0, 1}	1 if the k-th bus is sent at the m-th time interval; 0 otherwise
θ_i	{0, 1}	1 if $q^m_{i,on} \geq q^m_{i,off}$; 0 otherwise
LA_i	{0, 1}	1 if the bus arrives at the i-th node earlier than the time window $[t^m_{i,a}, t^m_{i,b}]$; 0 otherwise
LD_i	{0, 1}	1 if the bus arrives at the i-th node later than the time window $[t^m_{i,a}, t^m_{i,b}]$; 0 otherwise

$$\sum_{j\in N} x^m_{i,k} \leq NS \quad \forall k \in K. \tag{23}$$

Constraint (4) ensures that each stop can be served by a selected bus at most once in the pickup process. Constraints (5) and (6) guarantee that demand cannot exceed the capacity of the bus, and the bus is not sent to the drop-off zone until it satisfies its minimum load factor. The minimum load factor is usually adjusted flexibly according to specific circumstances, especially during the BWOG; considering the impact of COVID-19, its value is usually set to a small value. Constraints (7) to (9) indicate that the bus should satisfy all passenger demands; the bus is not allowed to return from the drop-off depot to the pickup depot after finishing each pickup service. Constraints (10) to (13) ensure that the bus starts from the depot and must return to the depot. Constraint (14) implies that more than one bus can be sent to serve passengers if these demands exceed the bus capacity. Constraints (15) to (20) describe the bus's ability to dispatch passengers within the time window that passengers expect; the bus cannot be earlier than the time expected by the passengers nor later than the time expected by the passengers. Constraints (21) and (23) ensure that passengers do not spend too much time waiting for the bus and pass fewer intermediate stations during a trip. Constraint (22) captures the flow balance, i.e., during the pickup process, the vehicle k must leave after entering the reserved station to maintain flow conservation.

5. Algorithm Solution

5.1. Algorithm Development. Though many scholars have developed intelligent computing technologies such as genetic algorithms, tabu search, ant colony, and other methods to improve the quality and efficiency of the solution, these algorithms do not directly indicate that they can guarantee the global optimal solution but continuously improve the solution results [25–28]. To solve the model efficiently and accurately, a genetic-simulated annealing hybrid algorithm (GSAHA) that combines an SAA and a GA is proposed. In this algorithm, the GA is applied to group and encode the feasible paths of a single vehicle to facilitate subsequent genetic operations. Simultaneously, the SAA is used to expand the search area of the solution; meanwhile, the convergence rate is accelerated by reducing the difficulty of the selection. In addition, to improve and update the quality of the solution in each iteration, a storage device is added because it can remember and refresh the best result obtained during the calculation. Therefore, the GSAHA not only finds a satisfactory and feasible dispatching strategy quickly but also avoids local optimization.

The specific flow of the GSAHA is shown in the flowchart in Figure 4; the algorithm can be roughly divided into five steps. First, set the relevant variables and the fitness function. For example, set the maximum population number and initial temperature of the SAA, $t_z = t_0$;

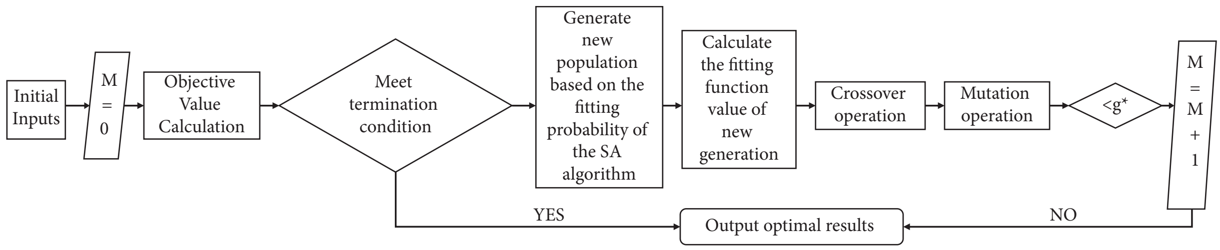


Figure 4: Flowchart of the GSAHA.

generate the initial population $P(m = 0)$; calculate its corresponding objective function value, $g(\lambda)$; and find the fitness function, $g_\lambda(t_m)$, with the smallest individual λ; set the storage variable, $g^*(\lambda^* = \lambda)$. Second, determine whether the termination condition is satisfied, if the optimal result is satisfied, g^* and λ^* denote the output. If it is not satisfied, randomly select other individuals around g^* for calculation and generate a new population according to the fitness probability of the SAA. Third, calculate the fitness function value corresponding to the new population. Fourth, perform the crossover and genetic operations for the GA according to the crossover and mutation probabilities, and generate a new population. Finally, in the new population, find the individual, λ, that minimizes the value of the fitness function, $g_\lambda(t_z)$. If the g is less than the storage variable g^*, then update the storage variables g^* and λ^* along with the simulated annealing temperature; simultaneously, update $m = m + 1$ and return to the second step. Otherwise, stop calculating and output the optimal feasible solution.

5.2. Algorithm Verification. A simple case is designed to verify the effectiveness of the GSAHA and the proposed model, whose network is depicted in Figure 5.

In Figure 5, the network has nine nodes, where nodes 1 and 9 are the depots. The medium blue dashed line divides the entire network into two areas: the right one is the pickup zone, and the left area is the drop-off zone. The distance between two adjacent nodes is attached to the link, and the distance between two nonadjacent nodes can also be calculated. The travel demand of every node except depots is simulated and generated within 60 min based on the Poisson distribution. The time windows of each node are also simulated, as shown in Table 4.

The simple case is modeled based on the proposed model first. Then, the GSAHA and GA are used to solve the case separately, and their optimal results are compared to validate the efficiency of the GSAHA. Next, some critical parameters of the proposed model are set. Assume that the flexible bus has a capacity of 15 people, its minimum load factor is 10%, its average operating speed is 15 km/h, the fixed cost of each bus is 800 yuan/bus, the variable cost is 1 yuan/km, and the average passengers' boarding and alighting times are both 1 minute. In addition, the critical parameters of the GSAHA are set as follows: the population is 80, the number of iterations is 200, the

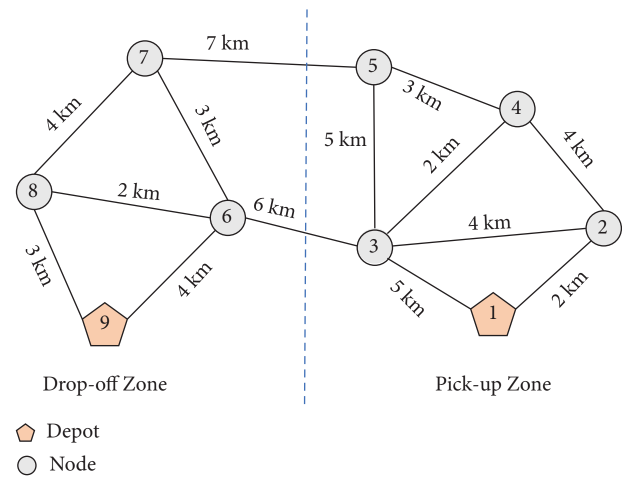


Figure 5: Network of a simple case.

probability of crossover is 0.9, the probability of mutation is 0.1, and the initial temperature of the SAA is 15. The same parameters are used for the GA. Furthermore, the Cplex solver is also used to solve the simple case. Next, their comparison results are shown in Figure 6.

In Figure 6, the left figure depicts optimal routines, and two buses are arranged to dispatch these demands. And the right figure shows the comparison results between the GSAHA, the GA, and the Cplex. It can be observed that the solution time, optimal value, and serving passengers of the GSAHA and the GA are 4.83 s, 1710.2 yuan, and 50 passengers; 3.48 s, 5232.4 yuan, and 50 passengers; and 0.05 s, 1712.5 yuan, and 50 passengers, respectively. Although the solving time of the GA is less than that of the GSAHA under the condition of dispatching the same travel demands, its optimal value is significantly larger than that of the GSAHA. Because the GSAHA spends more time searching for a larger solution space than the GA, it indicates that the optimal value of the GA may be a local optimal value instead of the optimal one. The GSAHA exhibits higher efficiency and accuracy in solving the proposed model compared to the GA. In addition, by comparing the results of the GSAHA and the Cplex, their objective values are basically the same, which shows the proposed GSAHA can solve such problems accurately and efficiently. Though the Cplex takes less time to solve the simple case, it is only suitable for small-scale networks and cannot be widely used. Therefore, the GSAHA can be applied to more scenarios and has better advantages.

Table 4: The simulated travel demand within 60 min for the simple network.

Node label	Demand		Time window	
	Pickup number (athletes)	Drop-off number (athletes)	Earliest arrival time (min)	Latest arrival time (min)
2	5	3	6	14
3	2	4	32	36
4	5	2	15	28
5	8	4	21	25
6	2	7	16	20
7	3	2	45	50
8	0	3	30	35
Total	25	25	—	—

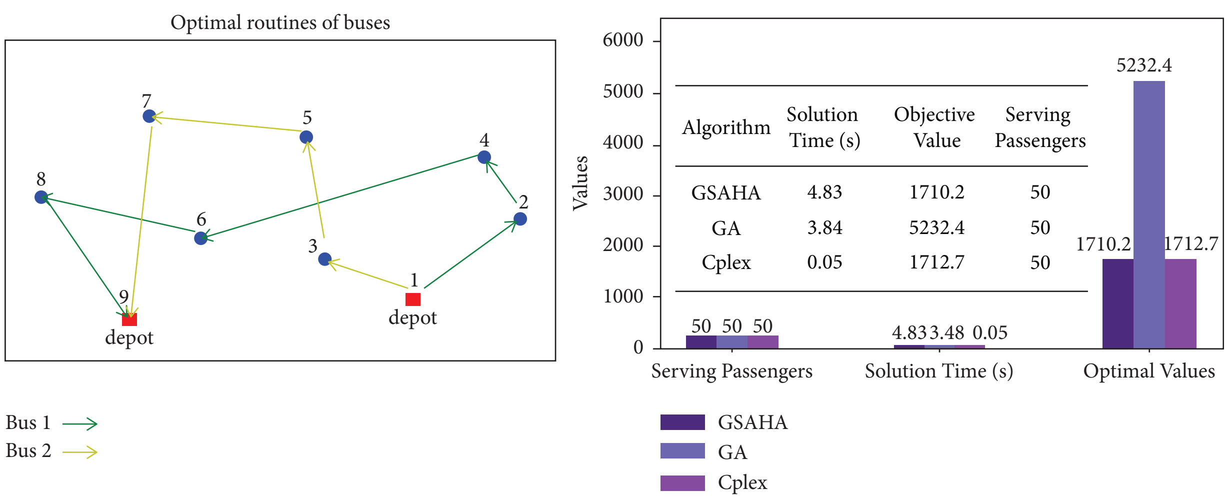


Figure 6: Comparison between the GSAHA and the GA based on the simple case.

6. Case Study

The previous section shows the effectiveness of the proposed model and the GSAHA. Next, a case study in the Beijing and Yanqing zones of the BWOG area (shown in Figure 2) was tested and analyzed. The dispatching efficiency is also compared between the flexible bus and the conventional bus to evaluate the application of this study in the real world.

6.1. Experimental Data. Previous Figure 2 gives the topology of nodes (venues and depots), and the exact distance between any two nodes is obtained from the Baidu map website. The distance matrix is shown in Table 5.

In addition, Section 3 has analyzed the travel demand of athletes and predicts their hourly demands during the BWOG. Assuming the athletes' arrival process follows a Poisson distribution, then the athlete demand during 9:00 AM–10:30 AM for among these venues is generated based on Table 1, presented in Table 6.

In addition, some key parameters are discussed. The capacity of a flexible bus is designed for 20 passengers. Considering the flexibility and comfortableness, a small-sized bus is more suitable. The vehicle's operating speed consists of in-zonal operating speed and cross-zonal operating speed: (1) when a bus operates in the Beijing or Yanqing zones, its operating speed is referred to as the average conventional bus operating speed in Beijing, which is 25 km/h; (2) when a bus operates from one zone to another zone, its operating speed is 90 km/h, which is the average operating speed of the Xingyan highway. Also, the minimum load factor is 20%. Other parameters refer to [16]. The fixed cost of each bus is mainly the vehicle depreciation cost, which is 2.28 yuan/vehicle·hour. Because

Table 5: Distance matrix among these nodes (unit: km).

Node labels	1	2	3	4	5	6	7	8	9	10	11
1	0	2.1	4	8	3.2	11	20	81	94	95	92
2	2.1	0	2.1	3.9	4.8	13	22	79	87	89	90
3	4	2.1	0	1.3	1.4	13	20	83	92	93	93
4	8	3.9	1.3	0	2	12	21	82	92	94	93
5	3.2	4.8	1.4	2	0	11	19	82	92	92	93
6	11	13	13	12	11	0	8.1	91	102	103	102
7	20	22	20	21	19	8.1	0	97	107	107	108
8	81	79	83	82	82	91	97	0	12	13	10
9	94	87	92	92	92	102	107	12	0	0.92	1.7
10	95	89	93	94	92	103	107	13	0.92	0	2.2
11	92	90	93	93	93	102	108	10	1.7	2.2	0

Table 6: Travel demand for athletes from various venues based on Table 1 within 9 : 00 AM–10 : 30 AM.

Node label	Demand		Time window	
	Pickup number (athletes)	Drop-off number (athletes)	Earliest arrival time	Latest arrival time
1	0	0	—	—
2	11	6	9:30	9:50
3	17	15	9:10	9:35
4	12	8	9:55	10:15
5	10	17	9:15	9:35
6	17	15	10:00	10:25
7	18	16	9:30	10:00
8	20	18	10:05	10:25
9	15	20	9:55	10:20
10	0	5	10:15	10:30
11	0	0	—	—
Total	120	120	—	—

the purchase cost of a medium bus is 0.2 million yuan and the average service life is 10 years. The variable cost of each bus refers to its fuel consumption cost. Considering the fuel consumption per 100 km for a medium bus is 20L, and the oil price is 6 yuan/L; therefore, it is 30 yuan/vehicle·hour. The penalty cost consists of arriving earlier and the penalty for arriving later. In this case, the bus is not allowed to arrive earlier, and its coefficient is set at 9,999,999 yuan/person·h. The coefficient of arriving later is according to the standard for the average salary that the Beijing Municipal Bureau of Statistics released in 2017, and it is 35.28 yuan/person·h. The parameters of the GSAHA are as follows: population (100), number of iterations (3000), probability of crossover (0.9), and probability of mutation (0.1). In addition, the initial temperature value of the SAA was 15.

Furthermore, when flexible buses are sent from the depot, they should obey a departure interval because it can reduce the vehicle occupancy rate on the road network at the same time and reduce traffic congestion. On the other hand, it can maximize vehicle resources and save costs for bus companies. For example, Zhu et al. [29] proposed a departure interval optimization model to optimize the departure intervals of public transit. In this study, the departure interval refers to [29] is 8 minutes.

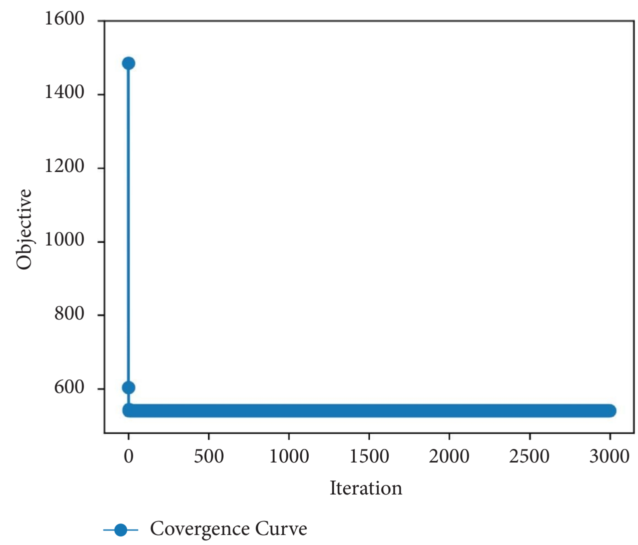


Figure 7: Convergence curve.

6.2. Experimental Results. To solve and evaluate the case, MATLAB version 2022 is used to program and execute the algorithm on a computer with an Intel i7-9570H processor. It takes 19.1 s to obtain the final results, and its convergence curve is depicted in Figure 7. The GSAHA quickly converges and stabilizes during the first few iterations, and its objective value remains the same during the following iterations. It demonstrates the fast efficiency of the GSAHA.

In this case, the path optimization results give a scheduling scheme to satisfy athletes' trip demands, as presented in Table 6. There are four original routes that are generated with fixed departure intervals as follows: (1) bus 1 path: 1-6-7-11; (2) bus 2 path: 1-3-2-8-11; (3) bus 3 path: 1-10-9-11; and (4)bus 4 path: 1-5-4-11. Figure 8 shows the path maps in the topology systems, which include the travel paths of buses 1–4.

In addition, the arrival times of flexible buses at various venues and the route lengths, travel time, and serving athletes for different paths are summarized in Table 7. Compared with the time window in Table 6, the arriving time in Table 7 can satisfy the constraint of the proposed model well. Besides, the scheduling scheme can quickly respond to athletes' travel demands because most time windows are well satisfied. Though few time windows are not satisfied, the athlete only waits a few minutes, which is acceptable based on the previous travel demand analysis in Table 1, which indicates the effectiveness of the proposed model.

The flexible bus is also compared with the traditional bus (TB) to evaluate its superiority. The travel time by TB is calculated based on the Baidu map app because it can significantly consider the local network, traffic situation, and passenger demand to determine the shortest path, and transfers are also included. The travel time by flexible bus is based on Table 7. According to Table 8, the flexible bus

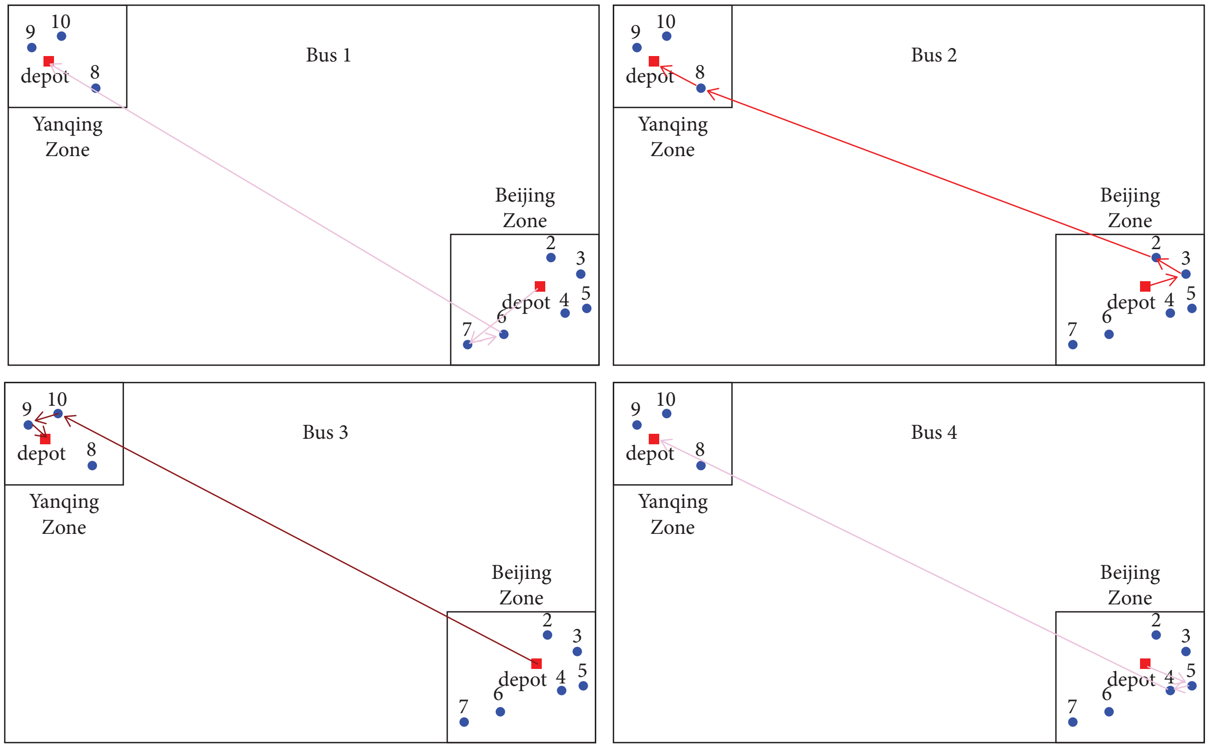


Figure 8: Travel route maps: bus 1, bus 2, bus 3, and bus 4.

Table 7: Path optimization results by the GSAHA.

Routes		Node label and arriving time					Route length (km)	Travel time (min)	Serving athletes
Route 1	Node label	1	7	6	11	—	130.1	164.9	35
	Arriving time	9 : 00	9:48	10:31	11 : 35	—			
Route 2	Node label	1	3	2	8	11	95.1	144.64	48
	Arriving time	9 : 08	9:18	9:45	10 : 34	11:25			
Route 3	Node label	1	10	9	11	—	97.6	107.3	15
	Arriving time	9 : 16	10:04	10 : 13	10 : 37	—			
Route 4	Node label	1	5	4	11	—	98.2	120.5	22
	Arriving time	9 : 24	9 : 32	10 : 02	11 : 01	—			

Table 8: Comparison of travel times between TB and FB services.

Node label	Travel time (min)		Save time (min)	Savings (%)
	TB	Flexible bus		
2	50	45	5	10.00
3	39	18	21	53.85
4	32	62	−39	−93.57
5	26	32	−6	−23.08
6	48	31	17	35.42
7	79	48	31	39.24
8	148	94	54	36.49
9	137	73	64	46.72
10	136	64	72	52.95
Average	76.2	51.9	25.3	17.54

shortens the average travel time by 17.54% compared with TB. For some stops, it can shorten the travel time by up to approximately 40%–50%. It is worth noting that the flexible bus takes more time to arrive at node 3 and node 4 compared with the TB. Because the athletes' expected bus arrival time at node 4 is 9:55–10:15 and the flexible bus cannot arrive too early. Furthermore, the time of bus 4 departing the depot is 9:24 instead of 9:00. Therefore, the

Table 9: Sensitivity analysis of the proposed model with various parameters.

Parameters	Group				
	1	2	3*	4	5
In-zonal speed (km/h)	15	20	25	30	35
Variable cost (yuan/vehicle·hour)	20	25	30	35	40
Late arrival penalty (yuan/p)	25	30	35	40	45

Table 10: Results of the sensitivity analysis of the proposed model with various parameters.

Parameters	Group									
	1		2		3*		4		5	
	Cost (yuan)	Total time (min)	Cost (yuan)	Total time (min)	Cost (yuan)	Total time (min)	Cost (yuan)	Total time (min)	Cost (yuan)	Total time (min)
In-zonal speed (km/h)	633.7	587.6	589.9	568.6	540.2	537.3	544.7	516.5	521.1	501.7
Variable cost (yuan/vehicle·hour)	481.2	537.3	532.1	537.3	540.2	537.3	591.1	537.3	684.8	537.3
Late arrival penalty (yuan/p)	456.5	537.3	508.9	537.3	540.2	537.3	580.9	537.3	617.0	537.3

flexible bus can save more time for athletes compared with TB. Hence, commuting time is substantially improved from the perspective of travel time.

7. Sensitivity Analysis

Sensitivity analysis is also performed for the critical parameters of the proposed model and the GSAHA. First, three critical parameters of the proposed model are selected: in-zone speed, variable cost, and penalty cost. Here, each parameter is divided into five groups; the other parameters remain the same, as shown in Table 9.

In Table 9, group 3* is the control group, and its parameters are mentioned in Section 6.1. The other four groups, group 1, group 2, group 4, and group 5, are experimental groups. For example, the first value of the "In-zonal speed" is as follows: 15 km/h, 20 km/h, 25 km/h (the control group), 30 km/h, and 35 km/h; other parameters are the same as in Section 6.1; then, the objective value (cost) and total time are calculated separately based on the proposed model and the GSAHA; finally, their results are compared. Therefore, a total of fifteen experiments were conducted, and their results are summarized in Table 10.

To compare the differences in results between the control and experimental groups, different levels of the confidence interval for the control group were also calculated. For example, in Table 10, the cost of the "In-zonal speed" of group 3* is 540.2 yuan. Its upper and lower 20% confidence intervals are calculated as $540.2 \times (1 + 20\%) = 648.24$, $540.2 * (1 - 20\%) = 432.16$, respectively. Similarly, other confidence intervals for other parameters are calculated based on Table 10, and their results are presented as the top and bottom boundaries of the yellow bands in Figure 9.

In Figure 9, the first three figures show the cost. It can be observed that the cost varies with different parameters. Figure 9.(1) reflects the faster the "In-zonal speed" is, the less the cost will be. Figure 9.(2) and Figure 9.(3) reflect the increasing trends with the increase of the "Variable cost" and "Late arrival penalty". The last three figures show the total time. Figure 9.(4) reveals that the total time decreases as the "In-zonal speed" increases, which is reasonable. The total time remains the same for different groups in Figure 9.(5) and Figure 9.(6), in which the "Variable cost" and "Late arrival penalty" hardly influence the final bus routes. Generally, most costs lie in the yellow bands and do not exceed the 20% confidence interval of group 3, and all total time also lies in the yellow bands and does not exceed the 10% confidence interval of group 3. It indicates the proposed model is not sensitive to different parameters.

In addition, a similar method is also used to test the GSAHA, and the probability of crossover, the probability of mutation, and the initial temperature are selected. These parameters are divided into five groups; group 3* is the control group, and the others are experimental groups, shown in Table 11.

Compared to the previous sensitivity analysis, the solution time of the GSAHA is chosen instead of the total time because it can reveal the efficiency of the GSAHA. Then, fifteen experiments are conducted with the parameters in Table 11, and their results are summarized in Table 12.

Similarly, different confidence interval levels for group 3* are also calculated based on Table 12, and their results are presented as the top and bottom boundaries of the light purple bands in Figure 10.

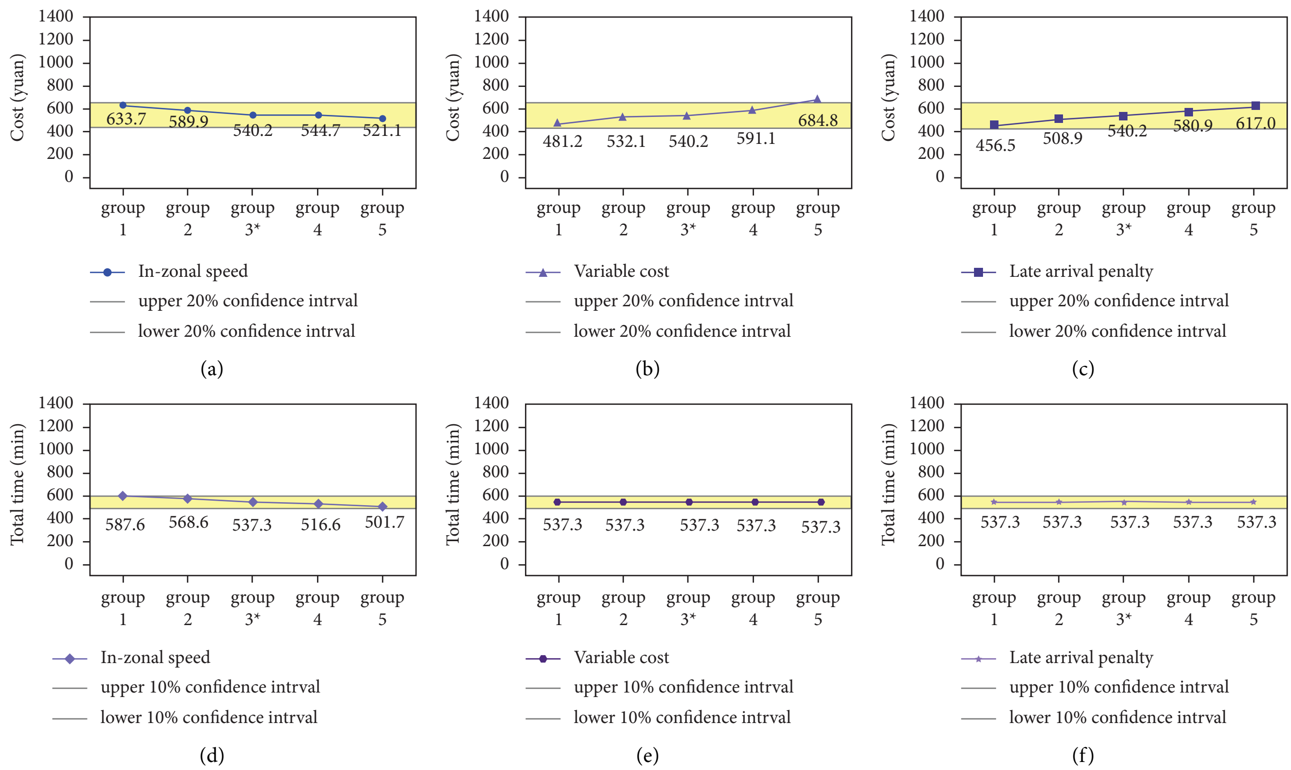


FIGURE 9: Figures of sensitivity analysis of the proposed model with various parameters: (1) cost with different "In-zonal speed"; (2) cost with different "Variable cost"; (3) cost with different "Late arrival penalty"; (4) total time with different "In-zonal speed"; (5) total time t with different "Variable cost"; (6) total time with different "Late arrival penalty."

TABLE 11: Sensitivity analysis of the GSAHA model with various parameters.

Parameters	Group				
	1	2	3*	4	5
Probability of crossover	0.1	0.5	0.9	0.95	0.99
Probability of mutation	0.01	0.05	0.1	0.4	0.7
Initial temperature	5	10	15	20	25

TABLE 12: Results of the sensitivity analysis of the GSAHA with various parameters.

Parameters	Group									
	1		2		3*		4		5	
	Cost (yuan)	Solution time (s)	Cost (yuan)	Solution time (s)	Cost (yuan)	Solution time (s)	Cost (yuan)	Solution time (s)	Cost (yuan)	Solution time (s)
Probability of crossover	606.5	17.3	582.9	17.9	540.2	19.1	540.2	19.5	540.2	20.0
Probability of mutation	540.2	19.0	582.9	18.3	540.2	19.1	582.9	19.5	582.9	18.9
Initial temperature	540.2	19.4	582.9	18.9	540.2	19.1	582.9	19.9	582.9	19.7

In Figure 10, the first three figures show the cost. It can be observed that the cost varies with different parameters. Though the cost varies with different "Probability of crossover," "Probability of mutation," and "Initial temperature," its values still lie in the light purple bands. They do not exceed the 15% confidence interval of group 3 in Figure 10.(1), Figure 10.(2), and Figure 10.(3). Besides, the values of solution times also lie in the light purple bands and do not exceed the 10% confidence interval of group 3. It indicates the GSAHA is not sensitive to different parameters.

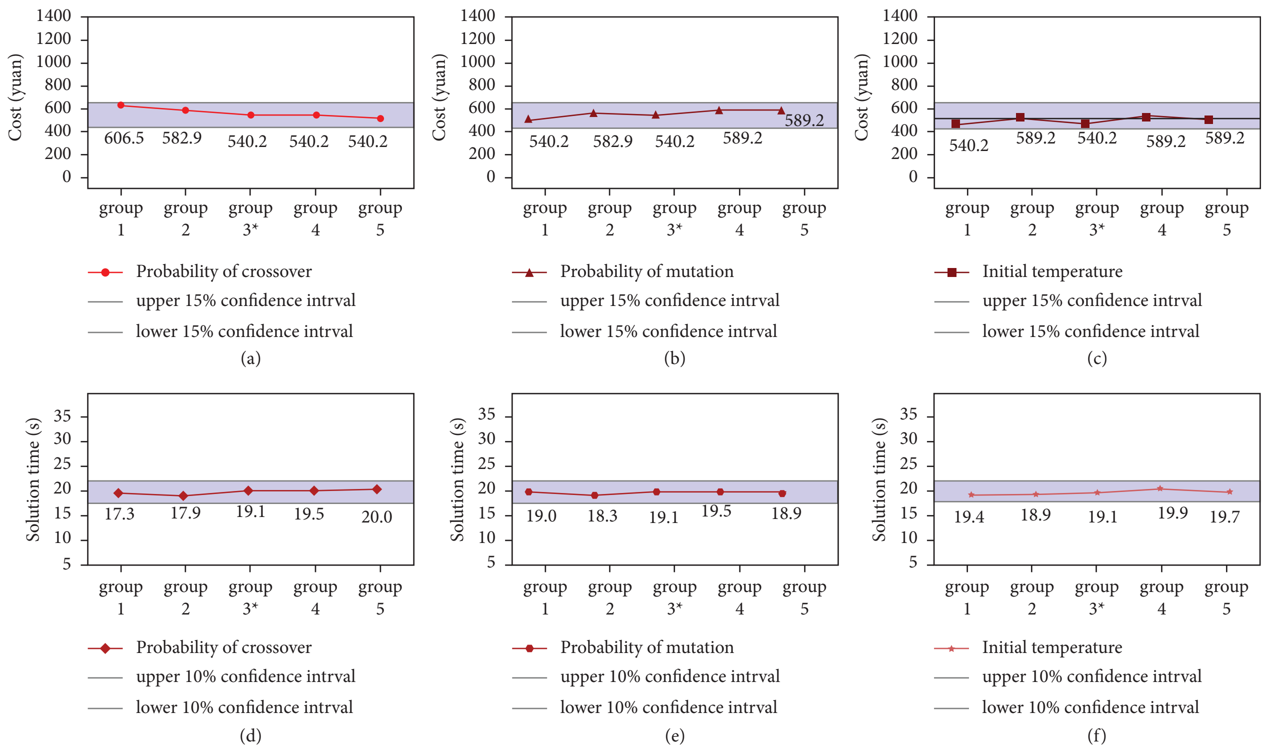


Figure 10: Figures of sensitivity analysis of the GSAHA with various parameters: (1) cost with different “In-zonal speed”; (2) cost with different “Variable cost”; (3) cost with different “Late arrival penalty”; (4) solution time with different “In-zonal speed”; (5) solution time with different “Variable cost”; (6) solution time with different “Late arrival penalty.”

8. Conclusion

To provide high-level and safer public transit service for athletes of the BWOG in the context of COVID-19, this study predicts the travel demands based on the characteristics of athletes’ daily travel demands and then proposes a flexible bus service scheduling model for cross-region scheduling among Beijing, Yanqing, and Zhangjiakou to provide high-level service. The service is point-to-point, which can satisfy their flexible demands and reduce unnecessary contact. The model is established to optimize scheduling schemes, whose object is to minimize the cost of the system based on some realistic constraints. To solve the model, the GSAHA is proposed by considering the GA and the SA. This study conducts a case study in the Beijing-Yanqing area to evaluate the feasibility and significance of the proposed model and the GSAHA. Moreover, the sensitivity of the proposed model and algorithm are analyzed. In summary, it is concluded that flexible bus service is a reasonable and effective public transit system, especially in the context of COVID-19. The experimental results also demonstrate that the proposed model and GSAHA can satisfy the athletes’ flexible demands and are also very robust. Hence, the flexible bus service is applicable in BWOG.

However, there are some limitations to this study . This study assumes the vehicle has the same capacity and fixed operating speeds. In addition, athletes’ demands are predicted based on the four-stage method, but it cannot find hidden characteristics of travel demands. In the future, mixed types of vehicles and real-time operating speeds will be considered. Also, a complex scheme of demand prediction should be designed to improve accuracy.

Data Availability

The data generated or used during the current study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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