ISSN 1648-4142 / eISSN 1648-3480

VILNIUS TECH
Vilnius Gediminas Technical University

TRANSPORT

2024
Volume 39
Issue 3
Pages 240–249
https://doi.org/10.3846/transport.2024.20522

*Original Article*

# OPTIMAL INTEGRATED LOCATION AND DISPATCHING DECISIONS FOR FEEDER BUS ROUTE DESIGN PROBLEM

Bo SUN[1,2]✉, Ming WEI[2,3], Chunfeng YANG[1]

[1] *College of Civil Engineering, Hebei University of Technology, Tianjin, China*
[2] *School of Transportation, Nantong University, Nantong, China*
[3] *Nantong Research Institute for Advanced Communication Technologies, Nantong, China*

**Highlights:**

- an integrated mixed-integer-programming model is presented to joint location and dispatching decisions for FBRD to improve scheduling efficiency;
- this objective of this model is to simultaneously minimize the total construction cost of selected dispatch centres and the total operational cost of designed feeder bus system;
- an improved double population bacterial foraging algorithm is designed to efficiently yield the acceptable solution to the proposed model;
- a real-world case for designing a feeder bus system in Nanjing (China) is used to illustrate the correctness of proposed methodology.

**Article History:**

- submitted 24 May 2018;
- resubmitted 16 December 2018, 25 January 2019;
- accepted 6 April 2019.

**Abstract.** Dispatch centres are an important part of the feeder bus network, and their location affects the design process of the feeder route. In some remote areas with weak transport infrastructure, it is very important to find an effective tool to simultaneously select the optimal location of the dispatch centre as well as transit routing process, which could improve the performance of the feeder bus system. The purpose of this article is to present an integrated optimization model for joint location and dispatching decisions for Feeder Bus Route Design (FBRD). The proposed methodology can select a number of best dispatch centres in alternative sets and calculate the order of the demand points visited by the feeder route. The objective of the model is to simultaneously minimize the total construction cost of selected dispatch centres and the total operational cost of the designed feeder bus system. The methodology facilitates obtaining solutions using the design of an improved double population Bacterial Foraging Optimization (BFO) algorithm. For example, it redefines the solution coding and the heuristic used to randomly initialize the initial population. When applied to the design of a feeder bus system for a station at Nanjing (China), the results reveal that a reduced budget may lead to change in the location of the dispatch centre; a more distant centre is required, which may increase the total mileage cost of all feeder routes. A detailed comparison of the improved and standard BFO and CPLEX shows that the difference between solutions is acceptable. However, the calculation time is greatly reduced, thus proving the effectiveness of the proposed algorithm.

**Keywords:** feeder bus route design, dispatch centre location, integrated optimization model, bacterial foraging optimization.

✉Corresponding author. E-mail: *bosun@cauc.edu.cn*

## Notations

BFO – bacterial foraging optimization;
CPLEX – IBM ILOG CPLEX optimization studio (*https://www.ibm.com/products/ilog-cplex-optimization-studio*);
GIS – geographic information system;
FBRD – feeder bus route design;
IBFO – improved BFO;
LD-FBRD – location and dispatching FBRD;
M-to-M – many-to-many;
M-to-1 – many-to-one;
VRP – vehicle routing problem.

## 1. Introduction

The feeder bus, which provides "last mile" access service to link urban rail transit and residential areas, could shift the majority of passengers from car traffic to public transport and further enhance urban connectivity (Errico *et al.* 2013). Typically, feeder bus routes often consist of a set of nodes and a set of links. These nodes represent bus stops, dispatch centres, and rail stations. The links between 2 adjacent nodes are treated as bus route segments. The demand points are mostly centred on workplaces and/or residences located near bus stops, wherein passengers are to be transported from pick-up locations to rail stations.

The rationality of FBRD is one of the main challenges faced by traffic management personnel. Dispatch centres are an important part of the feeder bus network. Existing research mainly focuses on assigning vehicles to visit these nodes based on the premise that dispatch centres are built in advance during the feeder bus network design process. However, dispatch centres may not be constructed in some remote areas with weak transport infrastructure. In this case, the location of the dispatch centre affects the design process of the feeder route, especially when considering the nature of land required for the candidates and total budget for selected dispatch centres. Non-integration of dispatch centre selection and FBRD will result in inconvenience to passengers and high operation costs for the bus company. Thus, similar to location-routing problems (Capelle *et al.* 2019), it is very important to study how location jointing and dispatching decisions affect FBRD (henceforth referred to as "LD-FBRD" in this article).

In an attempt to fill the gaps in existing studies on FBRD, the main contribution of this article is to create an integrated optimization framework for LD-FBRD by identifying an optimal relationship between the process of designing a feeder bus route and the locations of dispatch centres. The following research tasks are considered critical in this regard:

- coordination of location selection of the dispatch centres and feeder transit routing process to balance residents' travel convenience, operation costs for the bus company, and construction cost of the selected dispatch centres;
- development of an improved BFO algorithm to efficiently obtain the acceptable solution to such a nondeterministic polynomial-time-hard (NP-hard) problem;
- use of a case study to illustrate the proposed methodology and identifying factors influencing parameter sensitivity of the scheduling result, to find optimal locations of dispatch centres and finalize the corresponding feeder bus route plan in the real world.

The remainder of this article is structured as follows. Section 1 is introduction. A summary of related literature on FBRD is provided in the Section 2. In Section 3, we present our methodology and the integrated optimization model. The Section 4 provides an improved BFO algorithm; we discuss the experimental results and case study in Section 5. Finally, in the Section 6 we present the conclusions.

## 2. Literature review

FBRD is an extension of the well-known VPR, and various types of applications in relation to FBRD have been widely reported by academicians. As studies on FBRD is associated with 2 major areas, namely, optimization modelling and the solution algorithm, the literature review concentrates on these aspects.

At present, many network-programming approaches exist to handle FBRD. They decompose the traffic network into a set of demand points, rail transit stations, dispatch centres, and links between them (i.e., bus route segments). Based on these developed methodologies, most mathematical models are based on either the M-to-1 or M-to-M demand pattern (Kuah, Perl 1989; Martins, Vaz Pato 1998; Li *et al.* 2018). Ciaffi *et al.* (2012) presented a 2-phase mode to conduct FBRD, which 1st finds some feasible routes and then uses the associated frequencies to identify sub-optimal routes. Deng *et al.* (2013) proposed a novel model for the M-to-M feeder bus network based on a multi-level cost structure, which included passengers' costs and operators' costs. Pan *et al.* (2015) employed a bi-level model to reveal the optimal relationship between the number of residents picked up by the vehicles and the operation cost for transit operators. Quental *et al.* (2018) established a design model for a rail transit network to study the difference between the total costs of rail transit and other non-rail transit systems. Deng *et al.* (2013) presented a model for designing transit networks based on irregularly shaped streets. Kim & Schonfeld (2014) studied the bus transit optimization model considering transfer time. Qiu *et al.* (2014, 2015a; 2015b) established a 2-stage vehicle scheduling model that addresses both booking and real-time requirements. Shen *et al.* (2017) proposed an integrated model for vehicle routing and scheduling of demand-responsive connectors with on-demand stations. Li *et al.* (2018) proposed a model to optimize total cost by choosing the best pick-up locations and feeder bus routes. Sun *et al.* (2018a, 2018b) presented a mixed-integer-programming model to establish coordination between rail and bus lines while considering passengers' multiple time windows and their satisfaction.

The solution algorithms for FBRD are mainly divided into 2 general categories, namely, exact methods and heuristic algorithms (El-Sherbeny 2010). The exact methods are further sub-divided into 3 groups: (1) Lagrangian relaxation-based techniques (Kohl, Madsen 1997), (2) column generation methods (Desaulniers *et al.* 1998), and (3) dynamic programming methods (Christofides, Beasley 1984). Since the problem is NP-hard, exact methods are unable to solve large-scale instances due to their poor computational efficiency (Calvete *et al.* 2007; El-Sherbeny 2010; Ma *et al.* 2018), and heuristic algorithms are thus preferred. Heuristic algorithms allow route-building by generating several feasible routes at 1st, and then refining the search. Thus, they fine-tune the initial solutions according to the proposed constraints at a reasonable computational cost (Solomon *et al.* 1992; Li *et al.* 2018). Besides these route-building methods, some widely used metaheuristics, such as the bat algorithm (Sun *et al.* 2018b), ant colony algorithm (Mohaymany, Gholami 2010), and genetic algorithms (Tang *et al.* 2017; Sun *et al.* 2018a), are often used to resolve problems in this area.

Although the reviewed literature presents a variety of models and solution algorithms on FBRD, the following critical issues deserve attention during the process of designing a feeder bus network:

- a number of studies have presented a variety of FBRDs, but only a few have taken the locations of dispatch centres into account. The basic input to traditional models is based on the premise of dispatch centres being built in advance during the process of feeder bus network design. However, dispatch centres may be not under construction in some remote areas with weak transport infrastructure. Thus, the selection of dispatch centre locations (which guides the feed routes to the selected dispatch centres) and routing transits (which guides transit from these demand points to the rail station) has not been integrated, which may inconvenience passengers and lead to high operation costs;

- FBRD is an NP-hard problem as it is an extension of the classic VRP. Thus, it is a more complex issue, which is not treated as such by traditional modelling. The proposed methodology fills this gap by considering the integration of dispatch centre locations and route designs of the feeder bus routes, and hence is more suited to real-life situations. Hence, the traditional methods lack the means to solve such a problem.

## 3. Methodology

### 3.1. Research framework

This article proposes an integrated model that is capable of seamlessly and simultaneously coordinating locations of dispatch centres and the feeder transit routing process when designing the feeder bus network. The core input to the model consists of the number of passengers at demand points, dispatch centre candidates, travel distance, and time matrix between demand points, dispatch centres, and rail stations in the study area. Real distribution of travel demand, involving pick-up locations and number of passengers, could be obtained using cell phone data. A set of candidate dispatch centres with their locations, construction cost, and capacities (i.e., area) are provided by the relevant transportation departments. Further, the travel distance and time matrix based on actual traffic conditions are obtained using an open GIS tool. This is designed to meet realistic constraints, such as total budget, capacity and, route length. To reveal the optimal relationship in FBRD efficiency between centre locations and dispatching decisions, integrated mixed-integer-programming is formulated to select the most appropriate locations of dispatch centres as candidates as well as guide routes starting from the selected dispatch centres and ending at a rail station, to transport residents from the demand points (home address or workplace) to the rail station. These key components, including the model's input and output, are illustrated in Figure 1.

Figure 2 explains the principle and scope of the proposed mixed-integer-programming. It shows 1 rail station (M), 5 demand points (C1...C5), and 3 candidate dispatch centres (D1...D3) in the feeder bus system. The number below each demand point (C*i*, where *i* =1, 2, ..., 5) denotes the number of passengers at this pick-up location. The 2 numbers within parentheses below each dispatch centre (D*i*, where *i* =1, 2, ..., 3) denote the construction cost and maximum number of routes for this centre. The 2 numbers within the parentheses for vehicles travelling between adjacent nodes denote travel distance and time. For instance, this value is 4 for C2 in Figure 2, which means that 4 people will board the bus at this location. The numbers within parentheses, that is, (40, 2), near D1 mean that the construction cost is 40 million, and at most, 2 routes can be located at the depot. The 2 numbers between C4 and C3, that is, [5, 4], denote that the travel distance and time taken for the travel are 5 km and 4 min, respectively. In this example, the optimization process yields the following optimal plan. 2 candidates, D1 and D2, are finally selected for 3 dispatch centres of the feeder bus route, and these example routes are described as D1–C5–M, D1–D4–D3–M, and D2–C2–C1–M. For example, vehicle 3 departs from D2, and arrives at demand points C2 and C1 to pick-up 4 and 6 people, respectively, before finally returning to M. Thus, the total travel time and distance are 11 km and 12 min, respectively. In this case, the total construction cost is 90 million. The reduction in the total budget from 90 million to 85 million would render both D1 and D2 unfeasible, and these centres can be replaced by D3 to change the feeder routes. Thus, the location of the dispatch centre affects the design process of the feeder route.

The aim of the proposed model is to simultaneously minimize the total cost of constructing selected dispatch centres and operating designed feeder routes. To ensure real-world application of the proposed methodology, the

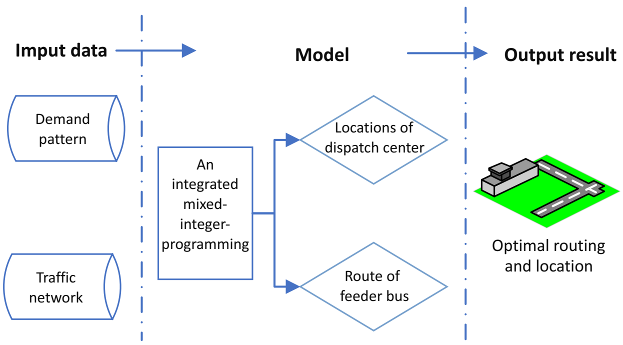


**Figure 1.** Key components of the research framework

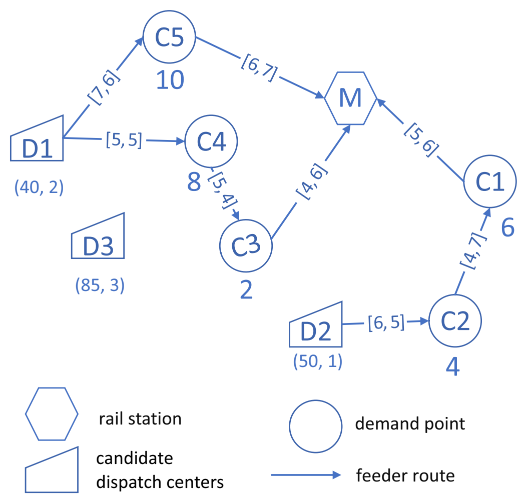


**Figure 2.** Graphical representation of LD-FBRD

model is based on the following assumptions/requires the following inputs:

- the nature of land use as well as the locations and construction costs of a series of candidate dispatch centres;
- real distribution of passenger demand between demand points and the rail station is obtained using cell phone data. However, a few passengers between different demand points may be ignored;
- actual travel distance or the time matrix between these vehicle nodes, based on the real traffic flow conditions, can be calculated using the open GIS tool.

## 3.2. Mathematical model

### 3.2.1. Definitions of variables

The notations used in the model are listed in Table 1.

### 3.2.2. Formulation

The proposed methodology can be formulated as an integrated mixed-integer-programming:

minimize:

$$\min f = c_0 \cdot \sum_{\forall i,\, j \in I \cup M \cup D} \sum_{\forall k \in K} x_{ij}^k \cdot d_{ij} + \sum_{\forall i \in D} z_i \cdot c_i \quad (1)$$

subject to:

$$\sum_{\forall i \in D} z_i \le N; \quad (2)$$

$$\sum_{\forall i \in D} z_i \cdot c_i \le C; \quad (3)$$

$$x_{ij}^k \le z_i,\ \forall j \in I,\ \forall i \in D,\ \forall k \in K; \quad (4)$$

$$\sum_{\forall k \in K} \sum_{\forall j \in I} x_{ij}^k \le R_i,\ \forall i \in D; \quad (5)$$

$$\sum_{\forall j \in I \cup M} x_{ij}^k = \sum_{\forall j \in I \cup D} x_{ji}^k = 1,\ \forall k \in K,\ \forall i \in I; \quad (6)$$

$$U_{ik} - U_{jk} + |I \cup D \cup M| \cdot x_{ij}^k \ge |I \cup D \cup M| - 1,$$
$$\forall k \in K,\ \forall i, j \in D \cup I \cup M; \quad (7)$$

$$\sum_{\forall j \in I} x_{ji}^k = 1,\ \forall k \in K,\ \forall i \in M; \quad (8a)$$

$$\sum_{\forall j \in I} x_{ij}^k = 0,\ \forall k \in K,\ \forall i \in M; \quad (8b)$$

$$\sum_{\forall j \in I} x_{ji}^k = 0,\ \forall k \in K,\ \forall i \in D; \quad (9a)$$

$$\sum_{\forall j \in I} x_{ij}^k = 1,\ \forall k \in K,\ \forall i \in D; \quad (9b)$$

$$q_i^k + p_i - \left(1 - x_{ij}^k\right) \cdot H \le q_j^k,$$
$$\forall i \in I,\ \forall j \in I \cup M,\ \forall k \in K; \quad (10a)$$

$$q_i^k + p_i + \left(1 - x_{ij}^k\right) \cdot H \ge q_j^k,$$
$$\forall i \in I,\ \forall j \in I \cup M,\ \forall k \in K; \quad (10b)$$

$$q_i^k \le \mathrm{Q},\ \forall k \in K,\ \forall i \in I; \quad (11)$$

$$q_i^k = 0,\ \forall k \in K,\ \forall i \in D; \quad (12)$$

**Table 1.** Parameters and variables of LD-FBRD

| | |
|---|---|
| *Indices* | |
| $i, j$ | node (i.e., demand point, candidate dispatch centre, or rail station) index |
| $k$ | route index |
| *Sets* | |
| $I$ | set of demand points |
| $K$ | set of routes |
| $D$ | set of candidate dispatch centres |
| $M$ | set of rail stations |
| *Parameters* | |
| $p_i$ | number of residents at pick-up location $i$; $\forall i \in I$ |
| $c_i$ | construction cost of dispatch centre $i$; $\forall i \in D$ |
| $c_0$ | operational cost per km |
| $C$ | budget for building dispatch centres |
| $R_i$ | maximum capacity of dispatch centre $i$; $\forall i \in D$ |
| $N$ | maximum number of dispatch centres |
| $Q$ | maximum route capacity |
| $D_{\max}$ | maximum route length |
| $T_{\min}$ | minimum travel time of each route |
| $d_{ij}$ | travel distance matrix between route node $i$ and $j$; $\forall i, j \in D \cup I \cup M$ |
| $t_{ij}$ | travel time matrix between route node $i$ and $j$; $\forall i, j \in D \cup I \cup M$ |
| $H$ | a very big constant |
| *Decision variables* | |
| $x_{ij}^k$ | whether adjacent nodes $i$ and $j$ are visited by route $k$ or not; $\forall k \in K$, $\forall i, j \in D \cup I \cup M$ |
| $z_i$ | whether dispatch centre $m$ is selected or not; $\forall i \in D$ |
| $q_i^k$ | number of passengers on route $k$ visiting demand point $i$; $\forall k \in K$, $\forall i \in I$ |
| $U_{ik}$ | auxiliary variable for sub-tour elimination constraint in route $k$; $\forall k \in K$, $\forall i \in I$ |

$$\sum_{\forall i, j \in I \cup D \cup M} x_{ij}^k \cdot d_{ij} \le D_{\max},$$
$$\forall i, j \in D \cup I \cup M,\ \forall k \in K; \quad (13)$$

$$\sum_{\forall i,\, j \in I \cup D \cup M} x_{ij}^k \cdot t_{ij} \ge T_{\min},$$
$$\forall i, j \in D \cup I \cup M,\ \forall k \in K. \quad (14)$$

In the formulation, the objective function of the proposed model is given by Equation (1) to minimize total cost, including the operation cost for different feeder routes and the construction cost of the selected dispatch centres. Constraint (2) indicates that the number of selected dispatch centres should be no more than the allowed maximum number. Constraint (3) indicates that construction cost for the selected dispatch centre should be no more than the allowed budget. Constraints (4) and (5) guarantee each feeder bus route originates from the selected dispatch centre and the number of feeder bus routes is limited. Constraints (6) and (7) guarantee network flow constraints, that is, each demand point is covered by 1 feeder route only, starting at the dispatch centre and ending at the rail station. Constraints (8) and (9) guarantee that the line departs from the dispatch centre and arrives at the orbital station. Constraint (10) shows the relationship between the flow rates of cross-sections between the adjacent demand points $i$ and $j$. Constraint (11) indicates the number of passengers on the route visiting the demand point does not exceed the route's capacity. Constraint (12) indicates that vehicles can leave the dispatch centre with no passengers. Constraints (13) and (14) show that the total travel distance and time for all feeder bus routes should satisfy their minimum and maximum values.

## 4. Improved BFO to solve LD-FBRD

LD-FBRD is an NP-hard problem, which requires integrating the vehicle route and site location optimization problem. Large-scale instances cannot be solved within an acceptable time using an accurate algorithm. BFO is a novel nature-inspired algorithm that simulates the social foraging behaviour of *E. coli* bacteria (Wei *et al.* 2015). Similar to other intelligent algorithms, BFO displays immature convergence mainly due to the neglect of the required exchange between the bacteria and the environment during their propagation and migration, which may result in the elite bacteria dying off and failure to maintain population diversity. In order to overcome some of the disadvantages of BFO, this article proposes a 2-population improved BFO method for solving LD-FBRD, by designing a coding scheme of solutions, the heuristic method to produce the initial population, and foraging behaviour.

### 4.1. Coding scheme of an individual bacterium

Using the real number encoding method, the position vector $X_k = \left(x_1, \ldots, x_{|D|}, x_{|D|+1}, \ldots, x_{|I|+|D|+|K|}\right)$ of the bacteria $k$ represents a solution to the problem. Here, each element $x_i$ ranges from 0 to 1. The vector includes 2 parts. Element $x_i\left(1 \le i \le |D|\right)$ indicates whether the dispatch centre is selected (if $x_i > 0.5$,the said centre is selected). Element $x_i\left(|D|+1 \le i \le |I|+|D|+|K|\right)$ presents the position of routes and demand points, where the sorted position of element $x_i\left(|D|+|I|+1 \le i \le |I|+|D|+|K|\right)$ is the position of route $i-|D|-|I|$ and the sorted position of element $x_i\left(|D|+1 \le i \le |I|+|D|\right)$ is the position of demand point $i-|D|$. Depending on the value of $x_i$, the positions of different feeder routes and their demand points are found, and the sequence of demand points visited by each feeder route is determined.

For example, 1 solution vector involving 2 dispatching centres, 2 routes, and 4 demand points, is denoted as $X = \left(0.2, 0.6, 0.2, 0.8, 0.3, 1.1, 0.7, 0.1\right)$, wherein the value of the element for dispatch centre 2 is set as 0.6. Thus, this centre is selected. The sorted positions of all demand points and routes are $\left[2\,5\,3\,6\,4\,1\right]$. Thus, the 2 selected routes are 2–4 and 1–3.

### 4.2. Evaluation function of the individual bacterium

In this article, we use the objective function $f$ as the evaluation function fit ($f$) = $f$ of an individual bacterium to estimate the strengths and weaknesses of the individual and find the optimal solution.

### 4.3. Heuristic algorithm for generating the initial population

Some factors of LD-FBRD are extremely complicated. It is very difficult for BFO to randomly find a set of feasible individuals to generate the initial population. Hence, the heuristic algorithm used to generate some feasible solutions is presented as follows:

- *Step 1*: initialize operating parameters for the dispatch centre and feeder route, such as $C$, $R_m$, $m$, $N$, $Q$, $D_{\max}$, and $T_{\min}$;
- *Step 2*: randomly select the dispatch centre $m$ (i.e., $z_m = 1$) by satisfying $\sum_{\forall m \in D} z_m \le N$ and $\sum_{\forall m \in D} z_m \cdot c_m \le C$. Let $i = m$ and $N' = N$, and randomly choose feeder route $k$;
- *Step 3*: according to $q_i^k \le Q$, $\sum_{\forall i,\, j \in I \cup M_s} x_{ij}^k \cdot d_{ij} \le D_{\max}$, and $\sum_{\forall i,\, j \in I \cup M_s} x_{ij}^k \cdot t_{ij} \ge T_{\min}$, find the set $N''$ of feasible demand points in set $N'$ covered by feeder route $k$ for the route arriving at demand point $i$, and randomly choose $j \in N''$ as the next demand point to be visited (i.e., $x_{ij}^k = 1$). If $N'' = \varnothing$, let $j \in M$ and go to Step 2. Otherwise, go to Step 4;
- *Step 4*: let $N' = N' - \{j\}$. If $N' = \varnothing$, output the result. Otherwise, go to Step 3.

### 4.4. Bacteria foraging behaviour

In the BFO, each bacterium's foraging behaviour consists of 3 operations: chemotaxis, reproduction, and migration. When each bacterium completes 1 cycle of chemotaxis, it would multiply and then migrate. To enhance the global search capability of the algorithm, this article aims to overcome the defect of the single-population BFO, wherein the diversity of the population is maintained by the exchange of information between 2 different populations of bacteria. The main improvements are as follows.

In chemotaxis, the concept of "gradient" is introduced in the moving step in order to speed up the convergence. The $i$th bacteria completes the actions involving overturning, going forward, and stopping towards a high-fitness bacterium $k$. There is a certain probability σ to move to a new location, gradually approaching the best bacterial location $X^*\left(j, r, l\right)$ to complete the foraging behaviour. The overturning and moving position of the $i$th bacterium is updated according to the following formula:

$$X_i\left(j+1, r, l\right) = \begin{cases} X_i\left(j, r, l\right) + C\left(i\right)\angle\phi\left(j\right), & rand \le \sigma; \\ X^*\left(j, r, l\right) + C\left(i\right)\angle\phi\left(j\right), & rand > \sigma, \end{cases} \tag{15}$$

where: $X_i\left(j,r,l\right)$ is the location of the $i$th bacterium in the process of the $j$th chemotaxis; $r$th reproduction; $l$th migration; *rand* is a random number;

$$C\left(i\right)=\frac{X_k\left(j,r,l\right)-X_i\left(j,r,l\right)}{\sqrt{\left(X_k\left(j,r,l\right)-X_i\left(j,r,l\right)\right)^{\Gamma}\cdot\left(X_k\left(j,r,l\right)-X_i\left(j,r,l\right)\right)}}$$

denotes step length; $\angle\phi\left(j\right)$ denotes the random direction angle of the bacterium going forward in the $j$th step.

The fitness of all bacteria in the reproduction operations was calculated to replicate bacteria of uniform fitness using the "retain the best bacteria" and "fitness wheel selection" strategies.

In the migration operation, individuals are exchange between different populations, and population diversity controls the size of the migration probability.

### 4.5. Algorithm steps

Given the basic principles of multi-population BFO, the general process used to solve the improved BFO problem is described in Figure 3. The data inputs for both populations are the same. After initializing their populations, they are run independently to complete each bacterium's foraging behaviour in each iteration. When the diversity of the population is reduced to a certain extent, the population will exchange information with the other population to produce a new generation of bacterial populations. In the case, the population with the highest diversity would gradually approach the optimal solution.

## 5. Case study

This section presents an example to verify the suitability/validity of the proposed algorithm. We develop a feeder bus system serving the population around Nanjing. As shown in Figure 4, the white square represents the rail station (M), the 6 red balloons represent the dispatch centres (D1...D6), and the 15 blue balloons represent passenger pick-up points (C1...C15) for this case study. Basic information pertaining to the passenger points and dispatch centres is described in Tables 2 and 3, respectively. The key input parameters of our model are as follows:

- maximum route capacity: 180 passengers;
- maximum route length: 10 km;
- minimum travel time per route: 15 min;
- operational cost per km: 6.5 million/km;
- budget for building dispatch centres: 80 million;
- maximum number of dispatch centres: 3.

The parameters for the improved BFO were sourced from Wei *et al.* (2015). The solutions were obtained using both BFO and CPLEX. Table 4 reveals the following:

- although the solution provided by the IBFO is about 5% worse than that of CPLEX, the calculation time is greatly reduced, and the algorithm is feasible;
- as the number of feeder routes increases, the total mileage costs also gradually increase, resulting in an increased number of dispatch centres between the starting and ending points, and more empty mileage;
- assuming that the selected dispatch centres have limited capacity, a higher number of feeder routes raises the

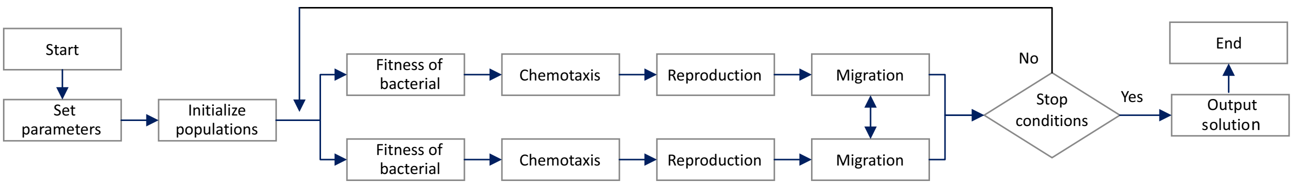


**Figure 3.** Flow chart of the improved BFO

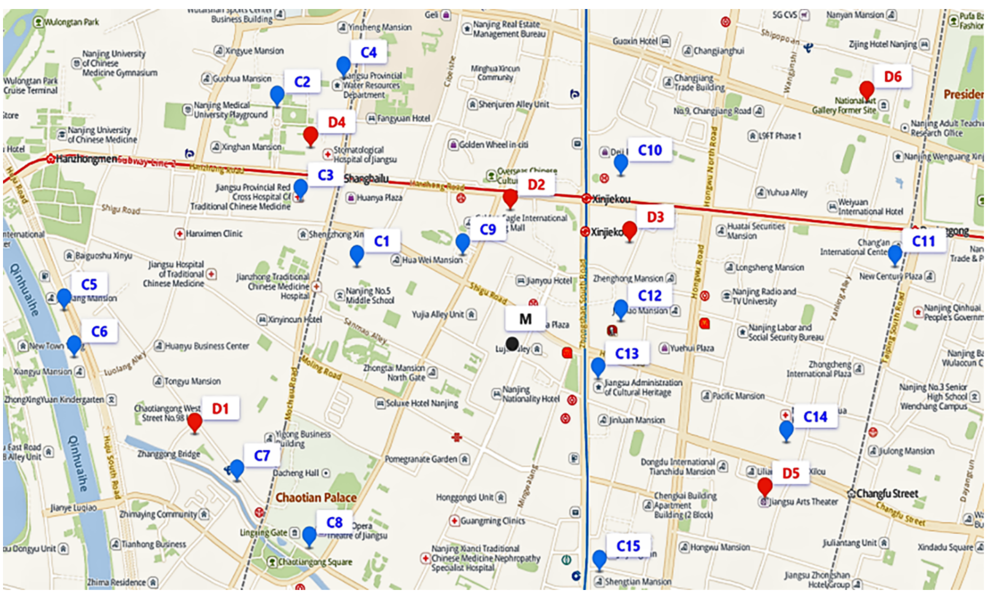


**Figure 4.** Spatial distribution of the routes visiting nodes

construction cost of the dispatch centres. Thus, 1 would need to choose a dispatch centre with a larger capacity to reduce the construction cost entailed by multiple dispatch centres.

Therefore, the total operation cost gradually rises as the number of feeder routes increases. The scheme with 3 feeder routes is the optimal. As shown in Table 5, candidate centre D3 is selected for route 2, and the candidate centre D5 is selected for routes 1 and 3. The total mileage and time for the 3 feeder bus routes are 9.685 km and 38.708 min, whereas their total operation cost is 112.9525 million.

**Table 2.** Information pertaining to demand points

| No | $q_i$ [passengers] |
|---|---|
| C1 | 23 |
| C2 | 36 |
| C3 | 20 |
| C4 | 37 |
| C5 | 22 |
| C6 | 37 |
| C7 | 21 |
| C8 | 25 |
| C9 | 32 |
| C10 | 41 |
| C11 | 30 |
| C12 | 37 |
| C13 | 38 |
| C14 | 34 |
| C15 | 35 |

We take 3 feeder routes as examples to analyse the impact of the unit cost of transportation, construction budget, and capacity of dispatch centres on the route-scheduling plan. The results displayed in Tables 6–8 reveal the following:

- as the total construction budget for the dispatching centres is reduced to a certain extent, the scheme may prefer a more distant dispatching centre to lower the construction cost. Thus, the mileage cost as well as total cost would increase. When the budget increases to more than a certain degree, the total cost remains unchanged due to the fact that there is no obvious improvement in the construction cost and the mileage changes depending on the selection of the dispatching centre;
- as the maximum number of dispatching centres increases, the scheme may choose the more expensive dispatching centres in the surrounding areas, but the cost of the commuting decreases, and thus, the total cost may also be reduced. When the maximum number of dispatch centres rises to a certain number, relocation options for dispatch centres and design of better feeder routes are no longer available/possible, and thus, the total cost will also remain unchanged;

**Table 3.** Information pertaining to dispatch centre candidates

| No | $c_m$ [million] | $R_m$ |
|---|---|---|
| D1 | 30 | 2 |
| D2 | 30 | 1 |
| D3 | 25 | 1 |
| D4 | 45 | 3 |
| D5 | 25 | 2 |
| D6 | 15 | 1 |

**Table 4.** Comparison of schemes for different numbers of feeder routes

| Number of routes | Objective value [million] | | Average calculation time [s] | | Mileage fees [million] | Construction costs [million] | Total mileage [km] | Total runtime [min] | Location of dispatching centres | Capacity of dispatching centres |
|---|---|---|---|---|---|---|---|---|---|---|
| | CPLEX | IBFO | CPLEX | IBFO | | | | | | |
| 3 | 112.9 | 118.4 | 487 | 48 | 62.9 | 50 | 9.7 | 38.7 | D3, D5 | 3 |
| 4 | 133.0 | 140.5 | 793 | 54 | 78.0 | 55 | 12.0 | 48.1 | D1, D5 | 4 |
| 5 | 177.7 | 188.7 | 1201 | 67 | 97.7 | 80 | 15.0 | 59.1 | D1, D3, D5 | 5 |

**Table 5.** Optimal locations of dispatch centres and feeder route design

| Route No | Sequence of nodes visited by feeder route | Run mileage [km] | Runtime [min] | Number of passengers |
|---|---|---|---|---|
| 1 | D5–C10–C4–C2–C3–C1–M | 3.092 | 12.41 | 157 |
| 2 | D3–C9–C5–C6–C7–C8–M | 3.560 | 14.214 | 137 |
| 3 | D5–C14–C11–C15–C13–C12–M | 3.033 | 12.084 | 174 |

**Table 6.** Impact of different total construction budgets for dispatch centres on feeder bus route design

| Construction budget [million] | Objective value [million] | Mileage fees [million] | Construction cost [million] | Total mileage [km] | Total runtime [min] | Location of dispatching centres |
|---|---|---|---|---|---|---|
| 40 | 113.3265 | 73.3265 | 40 | 11.281 | 38.304 | D5, D6 |
| 50 | 112.9525 | 62.9525 | 50 | 9.685 | 38.708 | D3, D5 |
| 60 | 112.9525 | 62.9525 | 50 | 9.685 | 38.708 | D3, D5 |

**Table 7.** Impact of different maximum number of dispatch centres on FBRD

| Number of dispatch centres | Objective value [million] | Mileage fees [million] | Construction cost [million] | Total mileage [km] | Total runtime [min] | Location of dispatching centres |
|---|---|---|---|---|---|---|
| 1 | 124.8265 | 79.8265 | 45 | 12.281 | 38.304 | D4 |
| 2 | 112.9525 | 62.9525 | 50 | 9.685 | 38.708 | D3, D5 |
| 3 | 112.9525 | 62.9525 | 50 | 9.685 | 38.708 | D3, D5 |

**Table 8.** Impact of different unit mileage values on FBRD

| Unit mileage [million/km] | Objective value [million] | Mileage fees [million] | Construction cost [million] | Total mileage [km] | Total runtime [min] | Location of dispatching centres |
|---|---|---|---|---|---|---|
| 6.5 | 112.9525 | 62.9525 | 50 | 9.685 | 38.708 | D3, D5 |
| 11.5 | 158.8105 | 103.8105 | 55 | 9.027 | 37.076 | D1, D3 |
| 16.5 | 203.9455 | 148.9455 | 55 | 9.027 | 37.076 | D1, D3 |

- as unit mileage costs increase, the scheme may choose the more expensive dispatch centre in the surrounding area, which will reduce the total length of the feeder route, and thus reduce the total cost. When the unit mileage costs increase to a certain extent, the mileage cost of the feeder route far exceeds the construction cost of the dispatch centre. Hence, the design of the feeder route tends to be stable.

To verify the validity of the algorithm, the differences in performance between the improved BFO and standard BFO are compared. As shown in Figure 5, we can see that improved and standard BFO iterate 114 and 171 times respectively on average to find their respective optimal solutions. The average difference between these iterations is 1.69%. This finding can be attributed to the fact that the improved BFO introduces the concept of "gradient" into the calculation by considering the information exchange among multiple groups. It not only converges quickly but also avoids the algorithm from reaching the local optimum. Thus, the improved BFO shows good robustness over its standard counterpart and proves that the technique is valid for the case at hand.

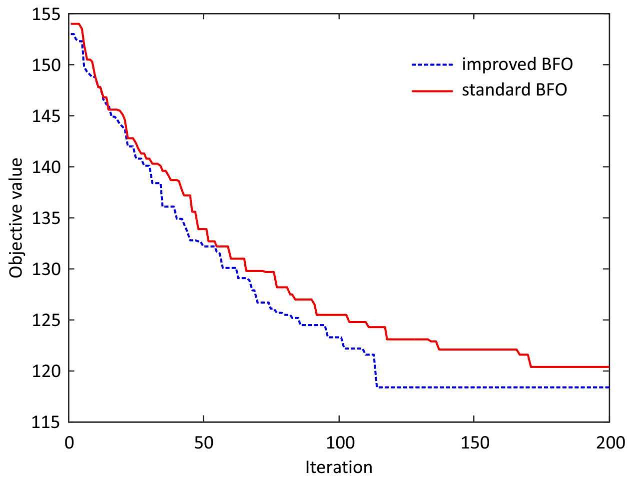


**Figure 5.** Comparison of different algorithms to ensure optimal performance

## 6. Conclusions

It is well-known that the location of the dispatch centre affects the design process of the feeder route. Some remote areas with weak transport infrastructure require a methodology that is capable of seamlessly and simultaneously selecting the optimal location of the dispatch centre and transit routing process, so as to improve the performance of the feeder bus system. This work extends Li *et al.* (2018) study on FBRD, by integrating location decisions of the dispatch centres to seek a balance between the interests of various stakeholders, namely, the government, businesses, and passengers. Unlike existing studies, the proposed methodology is unique in that (1) it presents an integrated model to find the optimal relationship between the process of designing a feeder bus route and the locations of its dispatch centres, and (2) it is an improved BFO-based heuristic algorithm, which redefines the solution code to generate an initial population and foraging behaviour based on the problem's features. The results show that a reduced construction budget would entail building a more remote dispatch centre, thereby reducing the total mileage. Obviously, if the reduction does not affect the location of the dispatch centre, the total mileage will remain unchanged. Changes in the number of dispatching centres and unit mileage costs have the same effect on LD-FBRD as changes in the construction budget. Hence, a balance needs to be obtained between designing the feeder bus route and the locations of dispatch centres, to even out the disparity between the construction cost of the dispatching centre and the operating mileage cost of the feeder route. These aspects are limited by the budget, maximum capacity of the dispatch centre, and unit mileage cost. Further, the difference between the proposed BFO and the exact solution is about 5%, and the calculation time is greatly reduced by the former, which proves the effectiveness and accuracy of the proposed algorithm.

Note that this study is based on 2 hypotheses: (1) the demand and travel time are stable, and (2) passengers board at the demand points only (i.e., bus stops). In the real world, however, random events such as traffic congestion and weather may cause fluctuations in the dynamics of passenger flow and travel time, which may not be reflected in the results of the proposed scheme. In addition, our study has neglected the fact that the selected demand points may not necessarily be the only passenger boarding points; at times, passengers board at left-turn only intersections as well. In this case, the design of the feeder bus network should integrate the assignment of demand points to boarding points selected by passengers. Therefore, extending our methodology to passenger-centric stop selection, that is, from the current static settings to dynamic and uncertain ones, as well as including time-varying traffic conditions, would be an important direction for further research.

## Funding

This article is funded by:
- the National Natural Science Foundation of China (Grant No 61503201);
- the Natural Science Foundation of the Jiangsu Province in China (Grant No BK20161280);
- the Humanities and Social Sciences Foundation of the Ministry of Education in China (Grant No 16YJCZH086);
- the Nantong Science and Technology Innovation Program (Grants No GY12016020, GY12016019);
- the Nantong University-Nantong Joint Research Centre for Intelligent Information Technology (Grant No KFK-T2017B08);
- the Project of excellent graduate innovation in Hebei Province (Grant No 2016348).

## Author contributions

*Bo Sun* and *Ming Wei* conceived the study and were responsible for the design and development of the data analysis.

*Bo Sun*, *Ming Wei* and *Chunfeng Yang* were responsible for data collection and analysis.

*Ming Wei* were responsible for data interpretation.

*Bo Sun* and *Ming Wei* wrote the 1st draft of the article.

## Disclosure statement

All authors declare we have no competing financial, professional, or personal interests from other parties.

## References

Calvete, H. I.; Galé, C.; Oliveros, M.-J.; Sánchez-Valverde, B. 2007. A goal programming approach to vehicle routing problems with soft time windows, *European Journal of Operational Research* 177(3): 1720–1733. https://doi.org/10.1016/j.ejor.2005.10.010

Capelle, T.; Cortés, C. E.; Gendreau, M.; Rey, P. A.; Rousseau, L.-M. 2019. A column generation approach for location-routing problems with pickup and delivery, *European Journal of Operational Research* 272(1): 121–131. https://doi.org/10.1016/j.ejor.2018.05.055

Christofides, N.; Beasley, J. E. 1984. The period routing problem, *Networks* 14(2): 237–256. https://doi.org/10.1002/net.3230140205

Ciaffi, F.; Cipriani, E.; Petrelli, M. 2012. Feeder bus network design problem: a new metaheuristic procedure and real size applications, *Procedia – Social and Behavioral Sciences* 54: 798–807. https://doi.org/10.1016/j.sbspro.2012.09.796

Deng, L.-B.; Gao, W.; Zhou, W.-L.; Lai, T. Z. 2013. Optimal design of feeder-bus network related to urban rail line based on transfer system, *Procedia – Social and Behavioral Sciences* 96: 2383–2394. https://doi.org/10.1016/j.sbspro.2013.08.267

Desaulniers, G.; Lavigne, J.; Soumis, F. 1998. Multi-depot vehicle scheduling problems with time windows and waiting costs, *European Journal of Operational Research* 111(3): 479–494. https://doi.org/10.1016/S0377-2217(97)00363-9

El-Sherbeny, N. A. 2010. Vehicle routing with time windows: an overview of exact, heuristic and metaheuristic methods, *Journal of King Saud University – Science* 22(3): 123–131. https://doi.org/10.1016/j.jksus.2010.03.002

Errico, F.; Crainic, T. G.; Malucelli, F.; Nonato, M. 2013. A survey on planning semi-flexible transit systems: methodological issues and a unifying framework, *Transportation Research Part C: Emerging Technologies* 36: 324–338. https://doi.org/10.1016/j.trc.2013.08.010

Kim, M.; Schonfeld, P. 2014. Integration of conventional and flexible bus services with timed transfers, *Transportation Research Part B: Methodological* 68: 76–97. https://doi.org/10.1016/j.trb.2014.05.017

Kohl, N.; Madsen, O. B. G. 1997. An optimization algorithm for the vehicle routing problem with time windows based on Lagrangian relaxation, *Operations Research* 45(3): 395–406. https://doi.org/10.1287/opre.45.3.395

Kuah, G. K.; Perl, J. 1989. The feeder-bus network-design problem, *Journal of the Operational Research Society* 40(8): 751–767. https://doi.org/10.1057/jors.1989.127

Li, X.; Wei, M.; Hu, J.; Yuan, Y.; Jiang, H. 2018. An agent-based model for dispatching real-time demand-responsive feeder bus, *Mathematical Problems in Engineering* 2018: 6925764. https://doi.org/10.1155/2018/6925764

Ma, C.; Hao, W.; He, R.; Jia, X.; Pan, F.; Fan, J.; Xiong, R. 2018. Distribution path robust optimization of electric vehicle with multiple distribution centres, *Plos One* 13(3): e0193789. https://doi.org/10.1371/journal.pone.0193789

Martins, C. L; Vaz Pato, M. V. 1998. Search strategies for the feeder bus network design problem, *European Journal of Operational Research* 106(2–3): 425–440. https://doi.org/10.1016/S0377-2217(97)00283-X

Mohaymany, A. S.; Gholami, A. 2010. Multimodal feeder network design problem: ant colony optimization approach, *Journal of Transportation Engineering* 136(4): 323–331. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000110

Pan, S.; Yu, J.; Yang, X.; Liu, Y.; Zou, N. 2015. Designing a flexible feeder transit system serving irregularly shaped and gated communities: determining service area and feeder route planning, *Journal of Urban Planning and Development* 141(3): 04014028. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000224

Qiu, F.; Li, W.; Haghani, A. 2015a. A methodology for choosing between fixed-route and flex-route policies for transit services, *Journal of Advanced Transportation* 49(3): 496–509. https://doi.org/10.1002/atr.1289

Qiu, F.; Li, W.; Haghani, A. 2015b. An exploration of the demand limit for flex-route as feeder transit services: a case study in Salt Lake City, *Public Transport* 7(2): 259–276. https://doi.org/10.1007/s12469-014-0097-9

Qiu, F.; Li, W.; Zhang, J. 2014. A dynamic station strategy to improve the performance of flex-route transit services, *Transportation Research Part C*: *Emerging Technologies* 48: 229–240. https://doi.org/10.1016/j.trc.2014.09.003

Quental, C.; Azevedo, M.; Azevedo, J.; Gonçalves, S. B.; Gonçalves, J. 2018. Influence of the musculotendon dynamics on the muscle force-sharing problem of the shoulder – a fully inverse dynamics approach, *Journal of Biomechanical Engineering* 140(7): 071005. https://doi.org/10.1115/1.4039675

Shen, J.; Yang, S.; Gao, X.; Qiu, F. 2017. Vehicle routing and scheduling of demand-responsive connector with on-demand stations, *Advances in Mechanical Engineering* 9(6): 1–10. https://doi.org/10.1177/1687814017706433

Solomon, M.; Chalifour, A.; Desrosiers, J.; Boisvert, J. 1992. An application of vehicle-routing methodology to large-scale larvicide control programs, *Interfaces* 22(3): 88–99. https://doi.org/10.1287/inte.22.3.88

Sun, B.; Wei, M.; Yang, C.; Xu, Z.; Wang, H. 2018a. Personalised and coordinated demand-responsive feeder transit service design: a genetic algorithms approach, *Future Internet* 10(7): 61. https://doi.org/10.3390/fi10070061

Sun, B.; Wei, M.; Zhu, S. 2018b. Optimal design of demand-responsive feeder transit services with passengers' multiple time windows and satisfaction, *Future Internet* 10(3): 30. https://doi.org/10.3390/fi10030030

Tang, K.; Xiao, X; Wu, J.; Yang, J.; Luo, L. 2017. An improved multilevel thresholding approach based modified bacterial foraging optimization, *Applied Intelligence* 46(1): 214–226. https://doi.org/10.1007/s10489-016-0832-9

Wei, M; Chen, X.-W.; Sun, B. 2015. Model and algorithm of schedule coordination in regional bus transit with multiple transport modes, *Journal of Highway and Transportation Research and Development* (*English Edition*) 9(3): 78–84. https://doi.org/10.1061/JHTRCQ.0000460