

# OPTIMIZATIONS OF NETWORK LAYOUT AND TRANSPORT SERVICE FREQUENCIES IN VIEW OF INTERESTS OF TRANSIT LINE OPERATORS AND UTILIZERS

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## Abstract:

Layouts of bus networks in cities are always irrational currently, transport service frequencies also need to be optimized according to the real network layouts, operation conditions and travel experience of passengers, so it is essential to optimize bus transit network layouts and transport service frequencies systematically. Different stakeholders are involved in the optimization of urban bus transit network layouts like the government, operators and passengers, whose interests are always contradictory. In order to optimize transit network layout and service frequencies from the view point of operators and utilizers, this research constructs a multi-objective model and proposes a solution algorithm. The proposed multi-objective model is established from the perspective of operators with the goal of minimizing total operating costs for one day, and from the perspective of the utilizers to minimize the total travel time, respectively. Also with the application of electric bus in cities, buses in this research are electric buses all for green travel. Moreover, a solution algorithm is proposed in this research to solve the proposed multi-objective model with simulated annealing algorithm and genetic algorithm. Simulated annealing algorithm is used as the main framework of the solution algorithm from the perspective of operators to minimize operating costs, while genetic algorithm is used as the subroutine of simulated annealing algorithm to optimize total travel time. Verification of the proposed model and the solution algorithm is based on an intuitive network. The application results of a numerical experiment verified that the proposed optimization model and the solution algorithm are able to optimize the network layout and service frequencies at the same time.

**Keywords:** transit network layout design, transportation service frequency optimization, multi-objective optimization, simulated annealing algorithm, genetic algorithm

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## 1. Introduction

Transit planning process consists of five stages: transit network design, transit network frequency setting, transit network timetabling, bus scheduling, crew scheduling and rostering (López-Ramos et al., 2017) and transit network design is the first step in constructing an efficient and environmentally friendly urban public transportation. Moreover, different stakeholders involved in transit network design like operators, utilizers and the government with contradict interests, and the optimization of transit network layout are the process that the travel demand is continuously met and the interests of all stakeholders are continuously coordinated.

Research on transit network design began in the 1960s, and the researches took the interests of operators, the interests of utilizers, or both of them into account. Mandl (1979) established an optimization model to minimize the total time of utilizers, and optimized the transit network of 15 stations and 21 sections, having a great impact on the follow-up research. Moreover, the network structure proposed in this study had been widely used for testing algorithm design in the following studies. Beltran et al. (2009) considered the impact of environment and constructed a transit network optimization model with the allocation of green buses based on the weighted sum of operating costs, travel costs and external costs. Furthermore, total travel time and transfer times were highlighted in some studies to attach importance of utilizers. Nikolic and Teodorovic (2013) constructed an optimization model to minimize the total travel time of all utilizers with transfer times taken into consideration, and numerical experiment was taken on the network of Mandl's road network to validate the proposed solution algorithm. Feng et al. (2018) attached importance on transfer times and established a transit network optimization model with the goal of minimizing the total travel time of all utilizers. Owais and Osman (2018) set up the optimization model with the objective function of minimizing the weighted sum of the average travel time and the number of operating buses in the network of public transportation, and Mandl's road network was also used to verify the solution quality in this study. Network layout optimization and frequency setting have been combined to design transit network in a more comprehensive and rational way. Cipriani et al. (2012) established a model with the function of weighted sum of operation costs, travel costs and

penalty costs to optimize the transit network and determine the frequencies. Nikolic and Teodorovic (2014) optimized the transit network design and frequency setting, where the objective function is consist of the weighted values of the number of utilizers who transfer more than twice, the total travel time and the number of buses needed for operation, and the frequencies were decided by passenger flow in the most crowded section and busload. Arbex et al. (2015) considered transit network layout and frequency setting optimization with the goal of minimizing total travel time and the number of operating buses. Multi-LOGIT model was used to allocate passenger flow, and frequencies of buses were also set according to the passenger flow in the most crowded section and busload. In addition, Soto et al. (2017) researched the problem of network optimization and frequency setting considering the issues of bus capacity limitation and passenger flow allocation, and the lower limit of bus frequency is determined by the passenger flow in the most crowded section and busload.

This research establishes a multi-objective function to optimize transit network layout and service frequencies considering the interest of operators and utilizers, and the model is solved by the proposed nesting algorithm which is combined with simulated annealing algorithm (SAA) and genetic algorithm (GA). Moreover, numerical experiment is based on a small network to verify the proposed model and the solution algorithm.

The reminder of this paper is hold as follows. The model is presented in section 2, followed by the proposal of solution algorithm in section 3. Section 4 verifies the rationally of the proposed model and the solution algorithm based on a small network. And conclusions follow in section 5.

## 2. Model establishment

The transit network, which is abstracted with linear distance between stations, is symbolized as an undirected graph  $G = \{N, V\}$ , where  $G$  is the transit network,  $N$  is the point set in the undirected graph, referring to bus stations,  $V$  is the edge set in the undirected graph, referring to street segments. Any path used by transit utilizers is defined by a sequence of nodes and links.

Considering that travel demand between stations is fluctuant, behavior of bus utilizers are random, and

traffic conditions during driving are hard to determine, this study is carried out based on the following assumptions.

- (1) Travel demand of utilizers between any two stations on the transit network is unchanged,
- (2) Influence of traffic congestion on the average speed of buses and the allocation of transportation resources is not taken into account,
- (3) Operators use a single kind of electric bus with unlimited number of buses, and the capacity of charging stations is not considered,
- (4) The transit lines pass through the same station at the upward and downward transport directions, and there is no bus cross line operation,
- (5) Utilizers always choose the shortest path.

A multi-objective model is constructed from the perspective of operators and utilizers, to minimize the total operating costs in one day for one operator and to minimize total travel time of all utilizers respectively, and the headway is optimized by the number of buses in operating as follows.

Eq. 1 and Eq. 9 are the two objective function established from operators and utilizers, respectively. Eq. 2 to Eq. 4 concretely explain the objective function Eq. 1, while Eq. 5 to Eq. 8 work as the constraint to optimize network layout and service frequencies in the view point of the operator. Eq. 1 is the objective function from the perspective of operators, aiming to minimize total operating costs of the bus operator which is consist of total operating costs of all transit lines, and the operating costs of one transit line is composed of the maintenance costs of the buses in use and standby buses and expense related to operating.

$$\text{Min } C = \sum_i (M_i n_i + c^e g_i^w D n_i + M_i^b n_i^b) \quad (1)$$

where,

$C$ : Total operating costs of the operator in one day, nit: Yuan (Y),

$i$ : Transit line,

$M_i$ : Maintenance costs for operating buses on transit line  $i$  in one day, Unit: Y,

$n_i$ : Number of buses operated on transit line  $i$ ,

$c^e$ : Unit price of power consumed by one bus, Unit: Y,

$v_i$ : Average travel speed on transit line  $i$ ,

$g_i^w$ : The power that one bus on line  $i$  consumed by the unit distance at speed  $v$ ,

$D_i$ : Total operating distance of one bus on line  $i$  in one day, Unit: Meters (M),

$M_i^b$ : Maintenance costs for the standby buses on transit line  $i$ , Unit: Y,

$n_i^b$ : Number of standby buses on transit line  $i$ .

Eq. 2 means that charging times for one operating bus on the transit line in one day is related to the total operating time, round trip distance for one transit line, roundtrips for one bus when fully charged and charging time at stations, while the energy consumed at bus stops is not take into account. The value should be rounded up. Eq. 3 reveals that roundtrips for one bus when fully charged are decided by the energy that one bus can use after fully charged and round trip distance of transit line. This value should be rounded down. Eq. 4 represents that the total mileage of a bus traveling is related with the times of round trips in one day and the distance of the transit line.

$$w_i = \lceil T_i^o / (d a_i / v_i + t_i^p) \rceil \quad (2)$$

where,

$w_i$ : Charging times for one operating bus on transit line  $i$  in one day,

$T_i^o$ : Total operating time of the transit line  $i$  in one day, Unit: Hour (H),

$d_i$ : Round trip distance of transit line  $i$ , Unit: M,

$a_i$ : Roundtrips for one bus on transit line  $i$  when fully charged,

$t_i^p$ : Charging time of buses on transit line  $i$  at charging station.

$$a_i = \lfloor E \theta / d g_i^w \rfloor \quad (3)$$

where,

$E$ : The amount of electricity that one bus gets each time when fully charged once,

$\theta$ : Energy utilization.

$$D_i = w_i a_i d_i \quad (4)$$

Eq. 5 shows the total mileage of the bus on a line and the amount of electricity can be used after charged is related to the operating speed and requires that the energy after fully charged at least is able to finish one round trip transportation, which also limit the round trip distance of the transit line. Eq. 6 requires that the number of transport services on a transit line in one day must meet the minimum requirement of operating a transit line from the perspective of headway. Eq. 7 limits the total capacity on one line, requiring that it has to meet the maximum value of passenger flow in the upward and downward transport directions in any adjacent transportation section of all lines after the allocation of passage flow. Eq. 8 means that the operator provides transportation services based on certain headway, and frequency is the reciprocal of the headway. This equation is able to optimize the frequencies of transit lines by the transportation services that the operator can provide not just through the passenger flow in the most crowded section and busload, and the value should be rounded up.

$$d_i \leq E\theta / g_i^{vi} \quad (5)$$

$$n_w a_i \geq T_i^o / H_i^{Max} \quad (6)$$

where,  $H_i^{Max}$  means the maximum headway for operating buses on transit line  $i$ , Unit: H.

$$\text{Max} \left\{ \sum_i P_{mn}^{iup}, \sum_i P_{mn}^{idown} \right\} \leq U w a_i \quad mn \in i \quad (7)$$

where,

$U$  : Capacity of the electric bus,

$mn$  : Adjacent transportation section in line  $i$ ,

$P_{mn}^{iup}$  : Passenger flow in the upward transport direction of adjacent transportation section  $mn$  in line  $i$ ,

$P_{mn}^{idown}$  : Passenger flow in the downward transport direction of adjacent transportation section  $mn$  in line  $i$ .

$$H_i = \lceil T_i^o / n_w a_i \rceil \quad (8)$$

where,  $H_i$  means the headway on transit line  $i$ , Unit: H.

Eq. 9 constructs the objective function from the perspective of utilizers to minimize the total travel time of all utilizers consisting of the total waiting time and the travel time on travel sections, and transfer times are not taken into consideration. In addition, average waiting time for one utilizer at the bus stop is determined by the headway of the transit line.

$$\text{Min } T = \sum_{od} \left( \sum_i (H_i/2 + d_i^{od}/v_i) \right) q^{od} \quad (9)$$

where,

$T$  : Total travel time of all utilizers on the travel network, Unit: H,

$od$  : Travel demand pair,

$d_i^{od}$  : Travel distance of line  $i$  on demand pair  $od$  for one utilizer, Unit: M,

$q^{od}$  : Total travel demand on demand pair  $od$ .

### 3. Algorithm

The common practice of dealing with multi-objective optimization is linear weighted summation which is convenient but the determination of weight value is subjective. Lexicographic goal programming (López-Ramos et al., 2017) and  $\varepsilon$ -constraints (Gutiérrez-Jarpa et al., 2017) are also used in dealing the multi-objective optimization problem, but the two solutions have the disadvantage of complicated calculations and the difficulty in parameter restriction. Therefore, this research solves the multi-objective model from the perspective of metaheuristic algorithm design, inspired by Arbex et al. (2015), and the convergence condition is improved too.

Metaheuristic algorithm is widely used in transit network design with nonlinear mixed integer programming for convenience and efficiency, like SAA (Canca et al., 2017), GA (Pattnaik et al., 1998; Chakroborty, 2003; Arbex et al., 2015; Feng et al., 2018; Owais and Osman, 2018; Liu et al., 2018; Iliewicz and Harlecki, 2018), bee colony algorithm (Nikolic and Teodorovic, 2013; Zhao et al., 2018), and differential algorithm (Buba and Lee, 2018) et al. And this research combines SAA and GA to be the solution algorithm for the better fault tolerance ability and the better global search ability, respectively.

#### 3.1. Unit definition and bus equipment

A transit line is usually composed of several adjacent transportation segments, this research define

the unit as one or several transportation segments in lines, and define the unit coincidence as the number of lines passing through the unit. Fig. 1 shows how the unit is formed containing 5 stations and 2 lines, which are station 1, station 2, station 3, station 4, and station 5, as well as line 1 and line 2. Line 1 passes station 2, station 3, station 4, and station 5, and line 2 passes station 1, station 3, station 4, and station 5. Disperse the network according to the definition of the unit to break up lines and form three units, which are the link between station 1 and station 3, the link connects station 2 with station 3 and the transportation sections between the station 3, station 4, and station 5. And the coincidence of the 3 units are all 1.

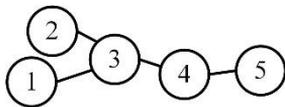


Fig. 1. Interpretation diagram of the unit

The principles for bus equipment on the network are as follows.

- (1) Break the lines in the transit network and form units. Find the unit, calculate the unit coincidence, and sort the units according to the order of unit coincidence from big to small.
- (2) Equip operating buses in lines. Calculate the necessary capacity one by one according to the travel demand of the upward and downward transport directions of each unit in decreasing order of the coincidence. Besides, for any line, the necessary capacity of the line is decided by the maximum value of the necessary capacity in the upward and downward transport directions of all units which it passes, and the number of operating buses of the line is determined accordingly.

Take the three units in Fig. 1 as an example. Firstly, according to the travel demand of each unit, the necessary capacity required to connect the unit composed by station 3, station 4 and station 5, the necessary capacity required to connect the unit between station 1 and station 3, and the necessary capacity required to connect the unit between station 2 and station 3 are able to be obtained one by one. Then, for one line, take the maximum value of necessary capacity of each unit included in the line as the necessary capacity required in this line. And according

to the necessary capacity of each line and the number of cyclic transport services that one bus can provide in operating time on lines, the number of buses for operating in Line 1 and Line 2 is able to be calculated.

### 3.2. Algorithm design

In this research, SAA and GA are nested to solve the proposed model from the perspective of the operator and utilizers. SAA is the frame algorithm to control convergence and ensures the network is optimized with the decrease of operating costs, whose acceptance probability is shown in Eq. 10, and the cooling rate is set to be fixed. While GA is used to optimize the network structure.

$$P = \exp((C_{new} - C_{current}) / T) \times 100\% \quad (10)$$

where,

- $P$  : Acceptance probability of the network layout obtained from a certain iteration,
- $C_{new}$  : Network operating costs obtained from an iteration,
- $C_{current}$  : The recorded smallest operating costs of network,
- $T$  : Value of current temperature.

Convergence criteria is improved based on the maximum number of iterations, which is commonly used in metaheuristic algorithm. Two termination conditions are proposed to ensure the convergence of the algorithm, which are the maximum number of loop iterations and termination temperature set by the SAA. Steps of solution algorithm are as follows, and the flow chat of the solution algorithm is shown in Fig. 2.

Step 1: Set relevant parameter values involved in the solution algorithm.

Step 2: Passenger flow allocation and network dispersion. Floyd algorithm is used to calculate the shortest travel path of bus utilizers to allocate passenger flow, then disperse the network into the units in lines and equip operating buses according to the principle of bus equipment. Additionally, it is worth mentioning that the unit formation and network dispersion provide a way for bus calculation, without changing the structure of the transit network.

Step 3: Objective function calculation and determine the direction of next iteration. According to the number of cyclic transportation one bus can provide in one day and the number of operating buses, the total number of transport services that one line can provide in the operation period is obtained, and the frequency of one line is determined by the total operation time and the total number of transport services. Then, the operating costs of the network can be calculated and the starting point of the next iteration can be determined by comparing it with the minimum operating costs retained. Holding the network layout in calculated costs when the calculated costs is less than the minimum operating costs retained, otherwise, accepting the network layout in calculated costs with certain probability using Eq. 10. Moreover, the network layout optimization is carried based on the layout of calculated costs when the calculated costs is accepted, otherwise, based on the layout in the previous step.

Step 4: Convergence judgement. If the termination temperature is less than or equal to the iteration termination temperature set by the SAA or the cumulative number of times of the algorithm is greater than or equal to the maximum number of loop iterations, stop the search of the algorithm and output the network with minimum operating costs. Otherwise, go to step 5.

Step 5: GA optimization. The retained network is used as the input network of GA to optimize the network design from the perspective of utilizers with

the goal of minimizing total travel time, and go to step 2.

In this study, the transit network is taken as an individual, the route is taken as the chromosome, and stations are taken as genes with binary coding. In the solution, the initial transit network is duplicated for several times to form the initial population. Furthermore, the fitness function of GA proposed in this work is constructed by the objective function to minimize total travel time.

Roulette selection is used to select the best individuals while the crossover operation and the mutation operation are based on random probability. The crossover operation proposed refers to the exchange of parental individuals with the same stations in each generation, and in the crossover process, parents will exchange part of the chromosome fragments with certain probability. To be specific, identify common stations in the parental individuals firstly, then randomly select the stations, and switch all stations on the right side of the selected stations in the line code. Moreover, the mutation operation proposed in this study is 0-1 string reverse based on random probability.

In each iteration, the proposed GA must satisfy the three constraints, which are network connectivity, line length limitation and the limits of cruising range of buses after one charge. Otherwise, the iteration of GA will be carried on the network before optimization. Flow chart of the proposed GA is shown in Fig. 3.

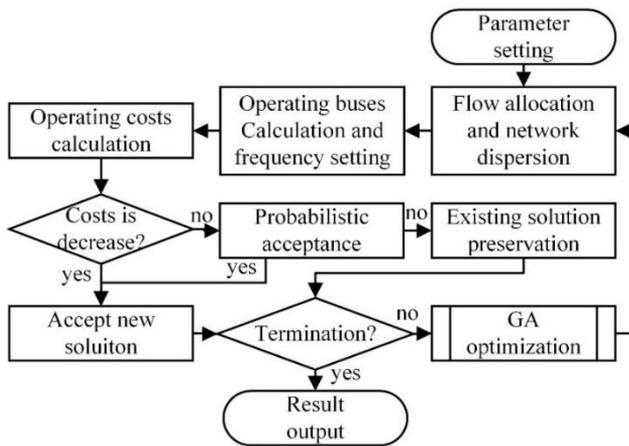


Fig. 2. Flow chart of the solution algorithm

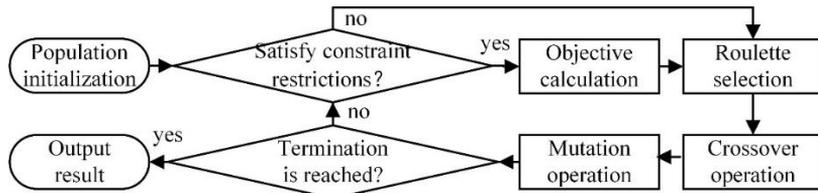


Fig. 3. Flow chart of the proposed GA

#### 4. Numerical experiment

A small network is used to verify the feasibility of the proposed model and the solution algorithm based on MATLAB R2016a. The initial network structure involved in the experiment is shown in Fig. 4. With 8 stations and 4 lines, which are station A, station B, station C, station D, station E, station F, station G and station H, as well as line 1, line 2, line 3 and line 4. And line 1 contains station D, station E and station F, line 2 contains station C, station D, station E, station F and station G, line 3 contains station D, station E, station F and station H, line 4 contains station A, station B, station D, station E and station F. Distance matrix between adjacent stations is shown in Table 1 and the travel demand matrix of stations is asymmetric shown in Table 2.

All the maximum headway in the network is equal, which is 0.50 hours, and the initial frequency of lines are three buses an hour. In addition, the electric power of the bus is 1 after each fully charged, and two standby buses are stored on each line. Moreover, the maintenance costs of the buses in operating is RMB 200 one day, while the maintenance costs of the standby buses is RMB 100 one day, and the price of energy that the electric bus consumed is assumed to be RMB 20 per meter. Value of partial parameters in the solution algorithm are set in Table 3.

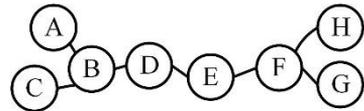


Fig. 4. Basic network structure of numerical test

Table 1. Distance matrix between adjacent stations

Distance (m)	A	B	C	D	E	F	G	H
A	0	1000	-	-	-	-	-	-
B	1000	0	-	800	-	-	-	-
C	-	-	0	1500	-	-	-	-
D	-	800	1500	0	600	-	-	-
E	-	-	-	600	0	900	-	-
F	-	-	-	-	900	0	1100	1300
G	-	-	-	-	-	1100	0	-
H	-	-	-	-	-	-	1300	0

Table 2. Table of asymmetric travel demand

Stop	A	B	C	D	E	F	G	H	Sum by Origin
A	0	473	705	222	340	522	240	404	2906
B	317	0	390	482	278	552	547	336	2902
C	695	330	0	250	692	286	426	325	3004
D	178	338	230	0	447	454	244	349	2240
E	260	242	568	333	0	381	278	514	2576
F	378	448	274	416	279	0	496	398	2689
G	200	413	414	216	262	344	0	654	2503
H	376	304	255	271	366	342	446	0	2360
Sum by Destination	2404	2548	2836	2190	2664	2881	2677	2980	21180

Table 3. Value of partial parameters in the solution algorithm

Parameter	Value
Rated passenger load of electric buses	40
Average speed	30 km/h
Percentage of electricity consumed per kilometer per bus	1%
Utilization of electricity of a bus after full charged	90%
Charging time	2.50 hours
Total operating time	15 hours
Maximum iteration number of SAA	200
Cooling rate	0.98
Maximum iteration number of GA	100
Initial temperature	100 °C
Termination temperature	0 °C
Population size	10
Crossover probability	0.20
Mutation probability	0.80

Changes of objective functions based on the numerical test are shown in Fig. 5, it can be seen that with the increase of iterations, the optimal costs decreases while the total travel time increases, and the change curves tend to be stable, suggesting that this research can obtain a balanced network layout, where the interests of operators and utilizers are contradictory. Moreover, the optimization results in Table 4 indicates that the proposed model and the solution algorithm are able to optimize transit network layout and service frequencies simultaneously, where the frequencies optimization is decided by the buses in operating and transportation services that the operator is able to provide based on travel demand, instead of just based on the travel demand in the most crowded section and busload.

Table 4. Results of network structure before and after optimization

	Lines	Stations	Frequencies (buses/h)
Initial network	1	D, E, F	3
	2	C, D, E, F, G	3
	3	D, E, F, H	3
	4	A, B, D, E, F	3
Optimized network	1	A, B, C	2
	2	C, B, D, E, F	4
	3	D, E, F, H	2
	4	G, F, H	3

**5. Conclusions**

This research focuses on transit network layout and service frequencies optimization from the perspective of operators and utilizers, and a multi-objective model, solved by the proposed algorithm with the nesting of SAA and GA, is proposed to obtain an optimized network layout and service frequencies of lines. In addition, the network dispersion as well as the bus equipment proposed in the solution algorithm are able to optimize transit network design in a new way, and service frequencies are able to be optimized by the number of buses in operating. Besides, imbalanced travel demand in the upward and downward transport directions of transit lines is considered by the proposed model, and the convergence criteria is also improved to two termination conditions.

More experiments are necessary to validate the proposed model and the solution algorithm in this research, and network devaluation indicators like non-linear coefficient, line repetition factor, full load rate, line network density, line coverage rate and so on, should be taken into account to be more practical. Furthermore, the service frequencies obtained in this work are the average departure frequencies, the headway during peak period should be optimized further.

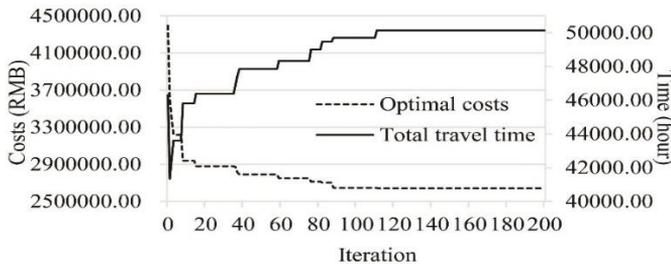


Fig. 5. Change diagram of two objective functions with the number of iterations

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