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Multi-objective transport network design with a reversible simulated annealing algorithm

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A B S T R A C T

In order to rationally coordinate inconsistent objectives in transport network design, this research newly develops a multi-objective network layout optimisation model solved by an improved Simulated Annealing Algorithm (SAA). Two temperature control variables and one cost difference control variable are defined in the proposed SAA. They work in cooperation to restart the optimum search from the latest temporary optimal solution if the search is made excessively in any searching direction as well as expand the searching area for the globally optimal network layout with the minimum operation cost. The genetic algorithm is embedded into the reversible SAA to iteratively provide a network configuration with the minimum total time expense of all the transports for the minimisation of the network operation cost. It is confirmed that the new optimisation model solved by the reversible SAA integrating the genetic algorithm is able to effectively minimise both the total transport time expense and the network operation cost with searching for the best fits between these two basically inconsistent objectives from different perspectives. The proposed approach can be utilised to optimise configurations of not only urban transit lines for passenger mobility organisation but also logistics transportation routes for manufacturing production management.

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A R T I C L E I N F O

Keywords:
Transport network design;
Multi-objective optimisation modelling;
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1. Introduction

Transport network design has been a focused research issue for a long time since the heuristic algorithm proposed by Lampkin and Saalmans [1]. Valuable research achievements have been made from the perspectives of transport efficiency [2, 3], network operation cost [4-6], transport service coverage [4, 7], environment protection [8], etc. Many studies attach importance to the simultaneous minimisations of network operation cost and total transport time expenditure by optimising the layout of transport lines [9-11]. However, because minimising the operation cost of a transport network is, on the whole, inconsistent with saving the time expense of its utilisers the most [10], the optimal solutions are difficult to be satisfyingly found in consideration of different interests of network operator(s) and utilisers [10, 12]. In order to solve this problem, continuous efforts have been made on different aspects.

The most common way to solve the inconsistency of different optimisations is transforming the multi-objective optimisation problem into a mixed-integer programming issue with a linear integration of distinct objectives. For example, the weighted sum of the costs of the operator(s), the users and the unsatisfied travel demands are minimised in the work of Fan *et al*. [13] by optimising the bus routes for zonal demand aggregation and variable transit demands. From the perspective of multimodal trips, Cipriani *et al*. [9] try to optimise the configuration of a bus network with elastic travel demands for the minimisation of the linear combination of the operator expense, the user expenditure and the external cost. Similarly taking into account the interests of the operator(s), the users and the external environment, Pternea *et al*. [8] develop an efficient model linearly integrating different objectives to propose a sustainable solution to the transport network design problem. In the research of Chu [11], the weighted sum of the cost for the operations of the bus lines, the generalised expense of all the passengers and the penalty for the unsatisfied travel demands are minimised by simultaneously optimising the bus route network layout and the bus timetables for the network operation.

It is obvious that the weights of various objective functions in the mixed-integer programming studies are difficult to be convincingly determined in a completely rational way. As a result, non-weighted strategies such as alternating, hierarchical and phased optimisation approaches are developed for the multi-objective network configuration optimisation. For instance, in order to minimise both the total time expense of passengers and the amount of necessary vehicles for the operation of a transit network, Arbex and da Cunha [10] develop a new Genetic Algorithm (GA) which is totally different to the conventional one [14, 15]. These two optimisation objectives are cyclically alternated along the generations of the individuals in the newly developed GA. Moreover, in view of the interactions between flows of buses and cars, a bi-level model is proposed by Yu *et al*. [16] to minimise not only the average time cost of travellers taking various travel modes but also the ride comfort difference of passengers on different bus routes in a multi-modal traffic environment for the optimal distribution of bus lanes. From a phased optimising viewpoint, López-Ramos *et al*. [6] develop a lexicographic goal programming model which integrates railway network design phase and train frequency setting phase to minimise the travel time of the passengers as well as the costs for construction and operation of the railway network.

Though effectively applied in some cases, the existing approaches are still not fully able to satisfactorily coordinate the inconsistent objectives in a transport network layout optimisation work, because of various interests of different groups [17]. Inspired by the network topology optimisation studies of Karsten *et al*. [18] and Saad *et al*. [19] in shipping and communication fields, this research focuses on the transport network layout optimisation with a new way of thinking for the optimal coordination of these two inconsistent objectives. Applicable to optimising configurations of both passenger transit lines for mobility organisation and logistics transportation routes for manufacturing production, a multi-objective transport network layout optimisation model is newly developed in this study and solved by an improved Simulated Annealing Algorithm (SAA). The proposed SAA is able to restart the search for the optimum network layout with the minimum operation cost from the latest temporary optimum solution in its iterative executions. Moreover, the GA newly developed by Feng *et al*. [20] is embedded into the reversible SAA to iteratively provide a transport network configuration with the minimal total time cost of all the utilisers to be optimised for the minimisation of the network operation cost.

The remaining parts of this paper are organised as follows. Section 2 first develops the new optimisation model. Thereafter, the SAA proposed in this research is explained in Section 2. Section 3 makes computational experiments and discusses the results to validate the newly developed multi-objective optimisation model solved by the reversible SAA. Finally, Section 4 makes the conclusions of this study and proposes some future research issues.

2. Materials and methods

2.1 Model definition

The stops on the transport network are, in this research, regarded as the points of transport generations and attractions and have sufficient service capacities. In other words, the distance of a transport on the network from the departure place to the starting stop and the distance from the final stop to the destination place are beyond the considerations in this work. Moreover, the spatial distribution of the transport demands is unchanged. Furthermore, if a stop is passed through by the operating vehicles of a transport line, every vehicle operating on this line provides transport services at this stop. The influences of the dwell time of a vehicle at a stop and the traffic conditions on the network upon the transport time are ignored. That is, the transport time is mainly determined by the transport distance and the average technical Operation Speed (OS) of vehicles in this research. In addition, there are no limitations to the numbers of the operating vehicles of different types for every transport line and all the vehicles operating on a line have the same technical OS in this study.

Furthermore, a transport line is unable to use the vehicles of other lines to meet with its transport demands in this work. A transport line has all of its operating vehicles cyclically start from one of its terminal stops to the other by passing through all the intermediate stops on this line and return by following the same route reversely. One way roads are not considered here. In other words, every two neighbouring stops on a line are connected bi-directionally with two inter-stop transport links consisting of the same successive road links in opposite transport directions. It is also assumed that the preparations of all the vehicles providing transport services on a transport line are completed at one fixed terminal stop of this line.

It is explained by Eq. 1 that one objective of the optimisation model developed in this study is the minimisation of the total operation cost of all the transport lines for a certain time period (e.g., one day) when the transport services are provided. As interpreted by Eq. 2, the operation cost of a transport line is simultaneously decided by multi-factors. The operators need to take into account the cost for operating vehicle maintenance, transport line operation and backup vehicle maintenance. As a result, it is necessary for each line to consider the maintenance cost of each vehicle of every type for operation or backup, the amounts of the vehicles of different types for various purposes and the energy consumption (i.e., usually fuel or electricity cost) of a vehicle of each type for a distance of the transport with some technical OS. The maintenance expense and Energy Cost (EC) intensity of one vehicle of a certain type for some utilisation purpose and the number of the vehicles for backup are all relatively fixed for a transport line. The unit price of the EC for transport operation is also stable in a certain time period. Therefore, determined by the layout of the transport network, both the number of the vehicles operating on each transport line and the transport distance of each operating vehicle mainly decide the operation cost of the network for a transport service time period.

$$Min\ C = Min \sum_{ij} C_{ij} \tag{1}$$

Symbol C represents the operation cost of a transport network, and C_{ij} indicates the operation cost of transport line ij (which provides the circling transport services between the terminal stop i and the terminal stop j) on the network.

$$C_{ij} = \sum_k f_{ij}^k n_{ij}^k + \sum_k c^e g_{ij}^{k,v_{ij}} D_{ij}^k n_{ij}^k + \sum_k f_{ij}^{k,B} n_{ij}^{k,B} \tag{2}$$

The f_{ij}^k is the maintenance cost of one operating vehicle of type k for line ij, n_{ij}^k denotes the number of the operating vehicles of type k for line ij, c^e stands for the unit price of the EC for transport operation, v_{ij} indicates the required technical OS of the vehicles operating on line ij, $g_{ij}^{k,v_{ij}}$ is the EC per unit transport distance (i.e., EC intensity) of one operating vehicle of type k at the technical OS of v_{ij} on line ij, D_{ij}^k denotes the transport distance of an operating vehicle of type k on line ij, $f_{ij}^{k,B}$ represents the maintenance cost of one backup vehicle of type k for line ij, and $n_{ij}^{k,B}$ is the number of the backup vehicle(s) of type k for line ij.

As explained by Eq. 3, the transport distance of an operating vehicle on a transport line is determined by the distance of one entire circle of the transport on the line, the complete circles of the transports provided by the vehicle once it is prepared for its operation and the complete operation times of the vehicle within the operation time period of the transport line. It is interpreted by Eq. 4 that the complete circles of the transports made by a vehicle after its preparation is decided by its Energy Storage Capacity (ESC), EC intensity, Energy Utilisation Rate (EUR) and the distance of one entire circle of the transport on the line. If a vehicle is ready for its operation, it is able to complete at least one entire circle of the transport on the line where it provides transport services, as explained by Eq. 5.

$$D_{ij}^k = d_{ij}c_{ij}^k \left[T_{ij}^O / \left(\frac{d_{ij}c_{ij}^k}{v_{ij}} + t_{ij}^{k,p}\right)\right] \tag{3}$$

In Eq. 3, d_{ij} represents the distance of one entire circle of the transport on line ij, c_{ij}^k is the complete circles of the transports provided on line ij by one vehicle of type k once it is prepared for its operation, T_{ij}^O stands for the operation time of line ij, and $t_{ij}^{k,p}$ denotes the necessary preparation time of one vehicle of type k for its operation on line ij.

$$c_{ij}^k = \left[\left(\left(E^k/g_{ij}^{k,v_{ij}}\right)\theta_{ij}^{k,v_{ij}}\right)/d_{ij}\right] \tag{4}$$

In Eq. 4, E^k is the ESC one vehicle of type k, and $\theta_{ij}^{k,v_{ij}}$ is the EUR of one vehicle of type k at the technical OS of v_{ij} on line ij.

$$d_{ij} \le \left(E^k/g_{ij}^{k,v_{ij}}\right)\theta_{ij}^{k,v_{ij}} \tag{5}$$

It is indicated by Eq. 6 that the time cost of an entire transport is composed of the time expensed in vehicles operating on different lines and the time consumed in waiting for vehicles. The time used for awaiting a vehicle operating on a transport line is represented here by the maximum headway of all the vehicles operating on this line. Eq. 7 explains the lower limit to the vehicle-kilometers provided by all the vehicles operating on a line. Moreover, the operating vehicles allocated to a transport line should offer the adequate transport capacity for the maximum accumulated transport demand between every two neighbouring stops on this line, as interpreted by Eq. 8. In addition, the upper limit to the time cost of a transport is explained by Eq. 9. The other objective of the optimisation model developed in this research is the minimisation of the total time expense of all the transports, as interpreted by Eq. 10, under the constraints explained by Eq. 5 and Eq. 9.

$$T^{od} = \sum_{ij\in TL^{od}}\left(H_{ij}^{Max} + \left(d_{ij}^{od}/v_{ij}\right)\right) \tag{6}$$

In Eq. 6, T^{od} represents the time expense of a transport from stop o to stop d, TL^{od} denotes all the lines serving the transport from stop o to stop d, H_{ij}^{Max} is the upper limit to the headways of all the vehicles operating on line ij, and d_{ij}^{od} stands for the distance of the transport from stop o to stop d on line ij.

$$d_{ij}\left(T_{ij}^O/H_{ij}^{Max}\right) < \sum_k D_{ij}^k n_{ij}^k \tag{7}$$

$$Max\left\{Max\left\{\sum_{od} V^{od}\lambda_{pq,Up}^{od}, \sum_{od} V^{od}\lambda_{pq,Down}^{od}\right\}_{pq\in ij}\right\} \le \sum_k U^k c_{ij}^k \left[T_{ij}^O / \left(\frac{d_{ij}c_{ij}^k}{v_{ij}} + t_{ij}^{k,p}\right)\right] n_{ij}^k \tag{8}$$

Symbol V^{od} denotes the transport demand from stop o to stop d, pq represents the transport section between stop o and stop d which are neighbouring to each other on line ij, $\lambda_{pq,Up}^{od}$ is the 0-1 variable denoting if transport section pq serves the transports on the time-shortest path from stop o to stop d in the upward transport direction (i.e., by taking the value of 1) or not (i.e., by taking the value of 0), $\lambda_{pq,Down}^{od}$ is the 0-1 variable representing if transport section pq serves the time-shortest transports from stop o to stop d in the downward transport direction (i.e., by taking the value of 1) or not (i.e., by taking the value of 0), and U^k indicates the carrying capacity of one vehicle of type k.

$$Min\, T^{od} \le T^{Max} \tag{9}$$

where T^{Max} is the maximum time cost of a transport on the network.

$$Min\, T = Min\, \sum_{od} T^{od}\, V^{od} \tag{10}$$

where T denotes total transport time cost under constraints interpreted by Eq. 5 and Eq. 9.

2.2 Algorithm design

From the perspective of reducing the operation cost of a transport network the most, transport lines providing circling transport services are built on the shortest paths between every two neighbouring stops and necessary vehicles are allocated to each line, given all the sites of stops. The vehicle allocations need to consider the carrying capacity, OS, ESC, EC intensity, preparation time before operation, etc. of each vehicle, the length of every transport route, the accumulated transport demands between neighbouring stops, etc. However, the transport efficiency in such a case will be very low due to the frequent transfers between every two neighbouring stops. On the contrary, if there is always at least one transport route completely coinciding with the shortest path between any pair of all the stops and adequate vehicles operating on each route do not stop at the intermediate stops they passed through, the total time cost of all the transports will be minimised. Nevertheless, the operation cost of the network at this time will be extremely high because too many vehicles are needed.

It is impossible to construct transport networks in either of these two extreme ways to decrease the network operation cost or increase the transport efficiency. However, the main objective of the network design in one of the extreme cases can be actually transformed into endeavoring to make different lines have no common transport sections but connected with each other through some stops, as shown in Fig. 1. At the same time, from the perspective of minimising the network operation cost, the accumulated transport demands in different transport sections between neighbouring stops of a line need to be similar to each other for avoiding the transport capacity wastes in the transport sections with relatively few accumulations of the transports. In contrast, the objective of building the network in another extreme case can be changed in reality into reducing the time expenses of transports as much as possible in not only riding vehicles but also transfers between transport lines by optimising the layout of the lines for the minimal total time expenditure of all the transports. The network built at this time may be illustrated by Fig. 2. The common transport sections are indispensable in such a case. For instance, the transport section between D and F is commonly used by the line between A and F, the line between B and H, and the line between C and G, as shown in Fig. 2.

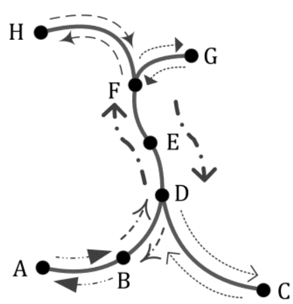

Fig. 1 Example of network layout for relatively low operation cost

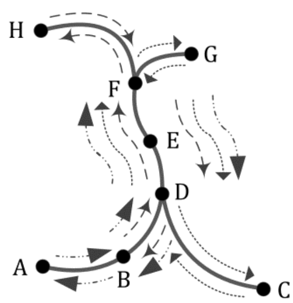

Fig. 2 Example of network layout for less transport time expense

With these two revised objectives, a new SAA explained in Fig. 3 is designed to solve the newly developed multi-objective optimisation model by iteratively searching for the proper network configuration satisfying both of the objectives the most from different viewpoints. Besides the total time cost of all the transports, the expense of the operating vehicles on their transport services is also analysed in this work. The initial network layout can be obtained on the basis of the Greedy algorithm [21] or by taking an existing transport network layout directly. Totally different to the ordinary SAA [22], the new SAA proposed in this research defines double temperature control variables (i.e., the iteration temperature control variable and the search temperature control variable). The iteration temperature control variable monitors the reduction of the optimum network operation cost with the iterative computations in the proposed SAA and, at the same time, judges whether the iterative calculations should stop or not. The search temperature control variable takes effect on the probability of adopting an obtained network configuration with a relatively high operation cost as the studied network layout in the iterative execution process of the SAA to explore the optimum solution in various searching directions.

Moreover, the cost difference control variable is also defined to decide the upper limit to the increase of the operation cost of the studied network layout in the executions of the proposed SAA from that of the latest temporally optimal network configuration obtained in a previous iteration of the SAA. If the increase of the network operation cost is no less than the upper limit, the search for the optimum network layout will return to the latest temporally optimal solution, from which, a new search starts. Meanwhile, in view of the relatively strong global optimisation ability [14, 15], the GA proposed by Feng *et al.* [20] is embedded into the reversible SAA to iteratively determine a network configuration with the minimum total time expense of all the transports to be optimised for the minimal operation cost. In this way, the minimisation of the network operation cost and the maximisation of the transport efficiency have the hierarchically alternating coordination to seek their optimal conjunction points.

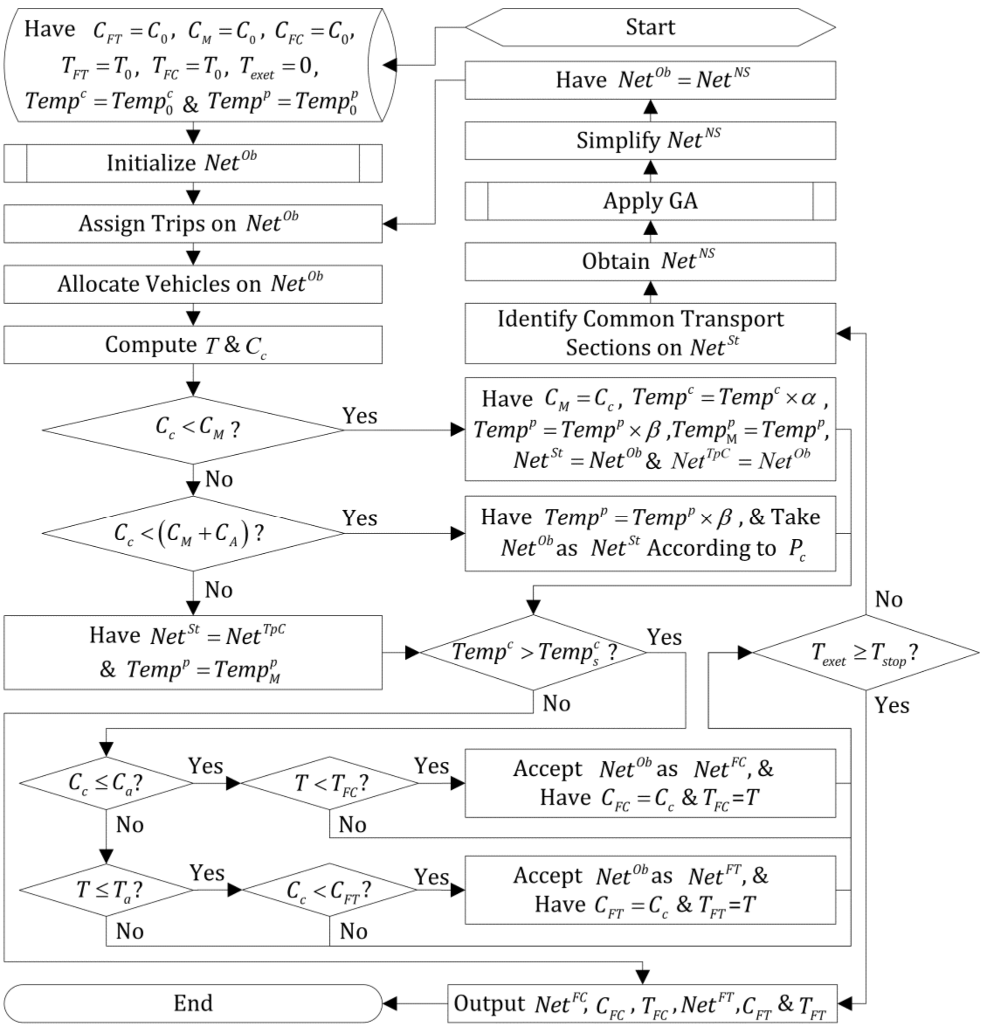

Fig. 3 Optimisation procedure of the proposed SAA

In the optimisation procedure of the proposed SAA, Net^{Ob} and Net^{St} represent the obtained network layout and the studied network layout, respectively. Net^{TpC} is the latest temporally optimal network layout. Net^{FC} denotes the final network layout with the least total transport time in comparison under the constraint of the upper limit to the network operation cost. Net^{FT} is the final network layout with relatively the minimum total operation cost of all the transport lines on the premise of the acceptably low total time expense of all the transports. C_c and C_M are defined as the operation costs of Net^{Ob} and Net^{TpC}, respectively. C_A is the cost difference control variable limiting the maximum value of $(C_c - C_M)$. C_{FC} and C_{FT} are the operation costs of Net^{FC} and Net^{FT}, respectively. C_0 is a very big positive number predetermined as the original value of C_M, C_{FC} and C_{FT}. C_a represents the acceptable maximum network operation cost determined according to transport capacities of all operating vehicles.

Furthermore, T_{FC} and T_{FT} denote the total time costs of all the transports on Net^{FC} and Net^{FT}, respectively. T_0 is another very big positive number predetermined as the original value of both T_{FC} and T_{FT}. T_a indicates the acceptable maximum total transport time. $Temp^c$ denotes the iteration temperature control variable whose original value is $Temp_0^c$. $Temp^p$ is the search temperature control variable whose original value is also $Temp_0^p$. $Temp_S^c$ represents the preset value of $Temp^c$ for stopping the iterative executions of the algorithm. $Temp_M^p$ denotes the specific value of $Temp^p$ at which Net^{TpC} is obtained. The values of $\alpha \in (0,1)$ and $\beta \in (0,1)$ are predetermined to control the decreasing speeds of $Temp^c$ and $Temp^p$, respectively. P_c represents the probability of adopting Net^{Ob} as Net^{St} when the operation cost of Net^{Ob} is more than that of Net^{TpC}. T_{exet} is the time spent on the iterative executions of the proposed SAA, and T_{stop} indicates the upper limit to the accumulated time for executing the reversible SAA designed in this research. The detailed steps of the optimisation process of the proposed SAA are as follows:

Step 1: Have $T_{exet} = 0$, $C_M = C_0$, $C_{FC} = C_0$, $C_{FT} = C_0$, $T_{FC} = T_0$, $T_{FT} = T_0$, $Temp^c = Temp_0^c$ and $Temp^p = Temp_0^p$, and initialise Net^{Ob}.

Step 2: Assign all the transport demands to each of their time-shortest transport routes on Net^{Ob}, according to Eq. 6. If two or more time-shortest transport routes from one stop to another are found, the corresponding transport demand is equally split to each of the shortest routes.

Step 3: Allocate necessary vehicles to each transport line on Net^{Ob} to satisfy not only Eq. 7 but also Eq. 8. Compute the total time cost of all the transport demands on Net^{Ob} (i.e., T) and C_c.

Step 4: If $C_c < C_M$, have $C_M = C_c$, $Temp^c = Temp^c \times \alpha$, $Temp^p = Temp^p \times \beta$ and $Temp_M^p = Temp^p$, and adopt Net^{Ob} as not only Net^{St} but also Net^{TpC}.

If $C_M \leq C_c < (C_M + C_A)$, keep $Temp^c$, Net^{TpC}, $Temp_M^p$ and C_M unchanged, have $Temp^p = Temp^p \times \beta$, and decide whether or not to take Net^{Ob} as Net^{St}, according to P_c calculated by Eq. 11.

$$P_c = exp((C_M - C_c)/Temp^p) \times 100\ \% \tag{11}$$

If $(C_M + C_A) \leq C_c$, have $Net^{St} = Net^{TpC}$ and $Temp^p = Temp_M^p$.

Step 5: If $Temp^c > Temp_S^c$, $C_c \leq C_a$ and $T < T_{FC}$, accept Net^{Ob} as Net^{FC}, and have $C_{FC} = C_c$ and $T_{FC} = T$.

If $Temp^c > Temp_S^c$, $T \leq T_a$ and $C_c < C_{FT}$, accept Net^{Ob} as Net^{FT}, and have $C_{FT} = C_c$ and $T_{FT} = T$.

Step 6: If $Temp^c \leq Temp_S^c$ or $T_{exet} \geq T_{stop}$, stop the executions of this algorithm, and output Net^{FC}, C_{FC}, T_{FC}, Net^{FT}, C_{FT} and T_{FT}.

Step 7: Identify each common transport section on Net^{St} for every aggregation of the transport lines with two common sets of the successive inter-stop road links in reverse transport directions. The identifications follow the decreasing order of the quantities of the transport lines aggregated by each of the common transport sections. Moreover, every two of the identified common transport sections have not any same part.

Step 8: Build transport lines based on each of the identified common transport sections on Net^{St} to obtain a new network layout (i.e., Net^{NS}).

Step 9: Apply the GA to update the layout of the lines on Net^{NS} for the minimisation of the total transport time expenditure on satisfying all the transport demands, as explained by Eq. 10, under the constraints interpreted by both Eq. 5 and Eq. 9.

Step 10: Delete each line coinciding completely with (a part of) another one to simplify the updated Net^{NS}. Take Net^{NS} as Net^{Ob}, and return to Step 2.

In the applied GA, the scale of the population is fixed and the chromosome amount of an individual is unchanged. Each individual (i.e., the transport network layout) is initialised with all the chromosomes (i.e., the transport lines) which are sequenced in the same order in different individuals. Every chromosome sequences its genes (i.e., the stops), according to the order of each stop on a transport line. Each gene can be found in at least one chromosome of every individual. Mutation is implemented to a certain ratio (e.g., Q %) of all the individuals. After mutating every randomly chosen chromosome of each individual belonging to the Q % of the population by probabilistically changing the configuration of the transport network on different aspects, the transport demands between each pair of the stops are assigned on every network layout to the time-shortest transport paths, according to Eq. 6. If there are two or more time-shortest paths from one stop to another, the corresponding transport demand is split equally to each of them. (100.00 % – Q %) of all the individuals with relatively small T are reserved in selection. The rest individuals (i.e., Q % of the population) are randomly paired to carry out the crossovers swapping probabilistically chromosomes at the same positions. Thereafter, the mutation is implemented again. Such iterative executions of the GA do not stop until a network configuration which is able to satisfy all the transport demands with the minimal T is obtained for the network operation cost minimisation in the proposed SAA.

3. Results and discussion

Fig. 2 provides the road network, illustrates the stops (i.e., A, B, C, D, E, F, G and H) and presents the initial layout of the transport network. The transport distances between neighbouring stops are explained in Table 1. The initial network layout consists of the lines with transports between each pair of A, B, D, E and F, every two of B, D, E, F and H, and all the pairs of C, D, E, F and G, respectively. Two computational experiments are made for the symmetrical and non-symmetrical distributions of the same total transport demand, which are correspondingly explained in Table 2 and Table 3. In order to simply the experimental computations, all the transport lines are supposed to have the same operation time period and use the same electric operating vehicles whose carrying capacity, ESC, EC intensity, EUR, preparation time before operation, etc. are determined in advance. Moreover, vehicles operating on different lines are supposed to have not only the same headway but also the same technical OS. Furthermore, it is also assumed that there is no upper limit to the time expense of a transport in the computational experiments. Values of some key parameters and variables are shown in Table 4 for the computational experiments. If $(C_c - C_M)$ in last iteration of executing the proposed SAA is negative, C_A in current execution of the SAA has a very big positive value. If $(C_c - C_M)$ in not only last and but also current execution of the proposed SAA is positive or zero, C_A in current iteration of executing the reversible SAA takes $\lambda(C_c - C_M)$ of last iterative execution of the SAA. The value of λ is $1/3$ here.

Table 1 Transport distances between neighbouring stops

Stop	A	B	C	D	E	F	G	H
A	-	10.00	-	-	-	-	-	-
B	10.00	-	-	8.00	-	-	-	-
C	-	-	-	15.00	-	-	-	-
D	-	8.00	15.00	-	6.00	-	-	-
E	-	-	-	6.00	-	9.00	-	-
F	-	-	-	-	9.00	-	11.00	13.00
G	-	-	-	-	-	11.00	-	-
H	-	-	-	-	-	13.00	-	-

Table 2 Symmetrical transport demand matrix

Stop	A	B	C	D	E	F	G	H	Sum by Origin
A	0	400	700	200	300	450	220	390	2660
B	400	0	360	410	260	500	480	320	2730
C	700	360	0	240	630	280	420	290	2920
D	200	410	240	0	390	430	230	310	2210
E	300	260	630	390	0	330	270	440	2620
F	450	500	280	430	330	0	420	370	2780
G	220	480	420	230	270	420	0	550	2590
H	390	320	290	310	440	370	550	0	2670
Sum by Destination	2660	2730	2920	2210	2620	2780	2590	2670	21180

Table 3 Non-symmetrical transport demand matrix

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 4 Values of parameters and variables

Parameters and Variables	Values
Carrying Capacity	40 passengers per vehicle
Technical OS	30.00 kilometers per hour
EC Intensity	1.00% of ESC per kilometer
EUR	90.00% of ESC
Preparation Time	2.50 hours
Upper Limit to Headways	0.50 hours
Transport Line Operation Time	10.00 hours
α	0.97
β	0.94
C_A	$+\infty$ or 1/3 of last $(C_c - C_M)$

As to the symmetrical transport demands explained in Table 2, it is shown in Fig. 4 that the decreasing trends of both the iteration temperature (i.e., $Temp^c$) and the optimum network operation cost (i.e., C_M) with the iterative executions of the proposed SAA are completely the same with each other. When the iteration temperature keeps invariant, the decrease of the search temperature (i.e., $Temp^p$) and the corresponding increase of the studied network operation cost (i.e., C_c) are reversible in different optimisation searching directions within a certain limit determined by the cost difference control variable. Moreover, as shown in Fig. 5 and Fig. 6, with the overall decrease of C_c, the total time expense of all the transports (i.e., T) generally keeps increasing, and a decrease of T is usually accompanied by a corresponding increase of C_c, because of their inconsistency. On the premise that the network operation cost (i.e., C_{FC}) is no more than the acceptable maximum value (i.e., C_a), the network layout (i.e., Net^{FC}) with the least total time expense (i.e., T_{FC}) is indicated to be one solution for the symmetrical transport demands, as illustrated in Fig. 6. In contrast, under the constraint of the upper limit (i.e., T_a) to the total time expense (i.e., T_{FT}), another solution is the network configuration (i.e., Net^{FT}) with the least operation cost (i.e., C_{FT}). It is also clarified in Fig. 6 that, only at the beginning of executing the proposed SAA, reducing C_c and saving T are consistent with each other. Represented by Net^C in Fig. 6, the network layout with both C_c and T minimised at such time can be specified by the executive iterations of the proposed SAA as the solution for the consistent minimisations of C_c and T, if C_c or/and T of Net^C is/are correspondingly no more than C_a or/and T_a.

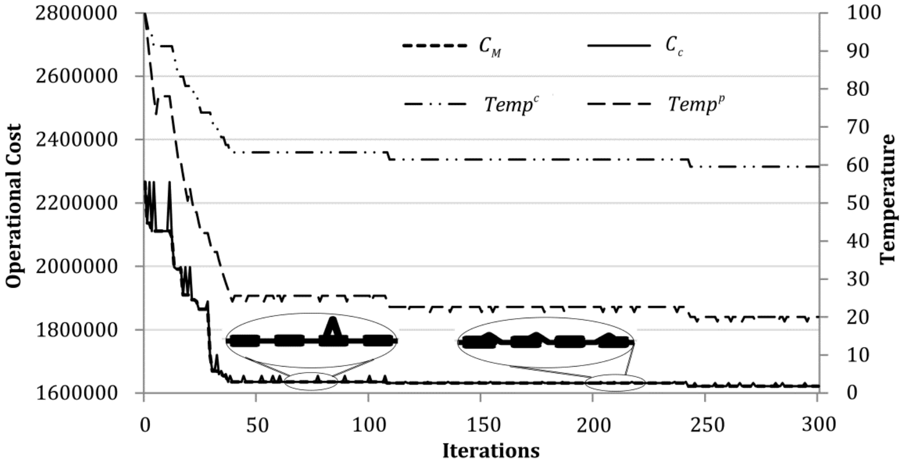

Fig. 4 Changes of C_M, C_c, $Temp^c$ and $Temp^p$ for the symmetrical transport demands

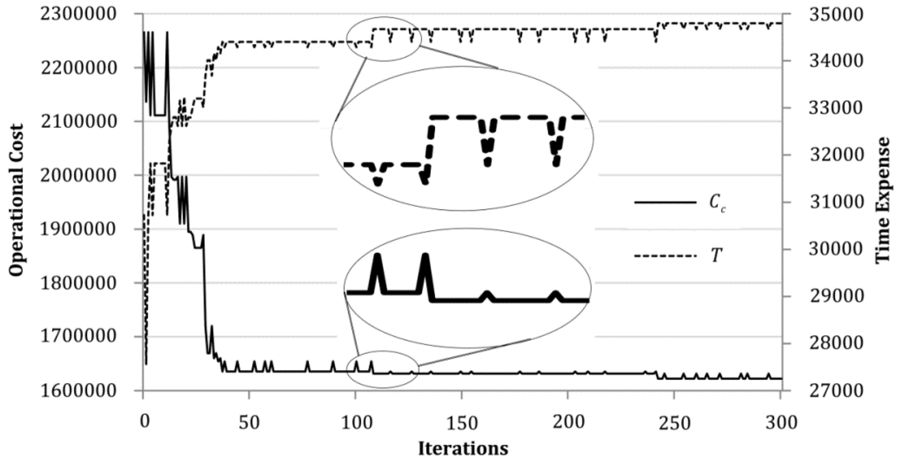

Fig. 5 Changes of C_c and T for the symmetrical transport demands

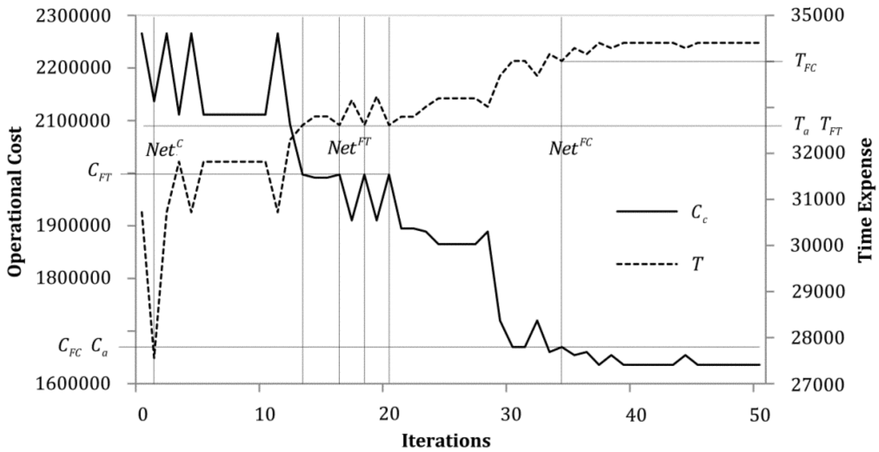

Fig. 6 Examples of the solutions for the symmetrical transport demands

In terms of the non-symmetrical transport demand distribution interpreted in Table 3, the changes of C_M, C_c, $Temp^c$, $Temp^p$ and T with the iterative executions of the reversible SAA are completely similar to their variations for the symmetrical demands, as explained in Fig. 7, Fig. 8 and Fig. 9. Due to the relative complexity of minimising both C_c and T for the non-symmetrical demands, C_M and $Temp^p$ decrease slower in comparison to their decreases with the iterations of executing the proposed SAA for the symmetrical demands. It is apparent that both minimising the operation cost of all the transport lines and maximising the efficiency of all the transports can still be effectively achieved in coordination from different viewpoints.

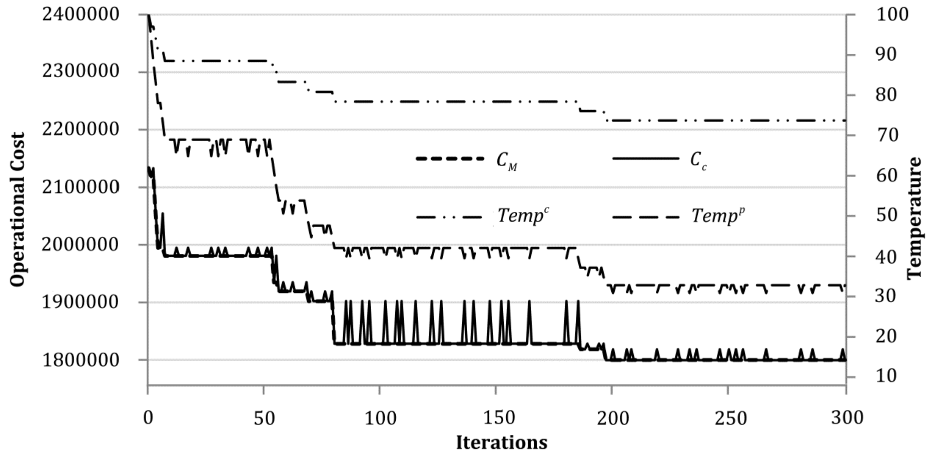

Fig. 7 Changes of C_M, C_c, $Temp^c$ and $Temp^p$ for the non-symmetrical transport demands

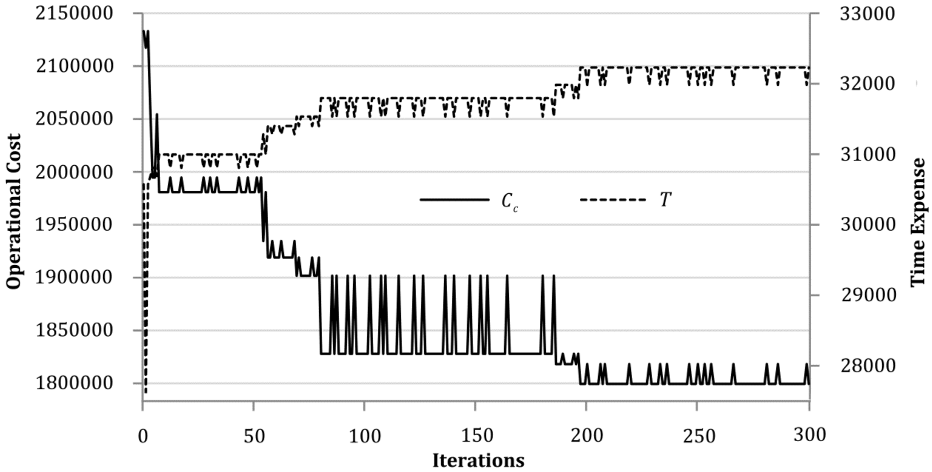

Fig. 8 Changes of C_c and T for the non-symmetrical transport demands

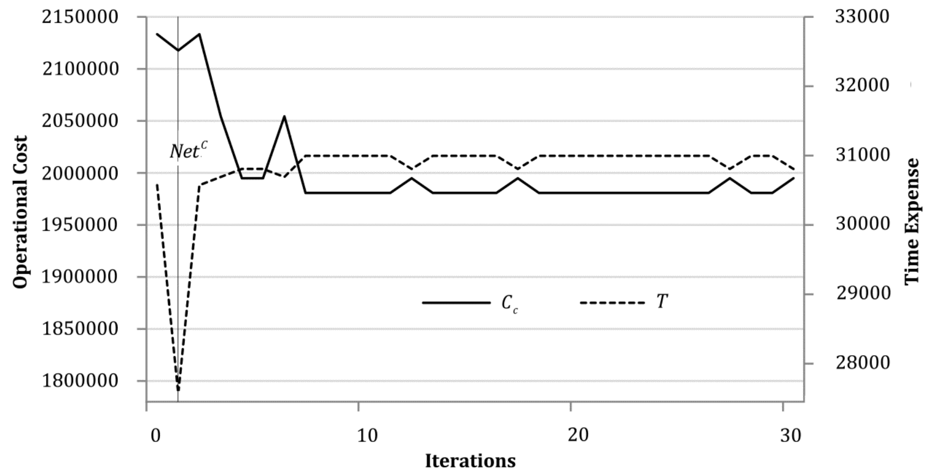

Fig. 9 Possible solution for the non-symmetrical transport demands

4. Conclusion

This research develops a new multi-objective transport network layout optimisation model solved by a newly proposed reversible SAA with the GA embedded. The area of searching for the optimum solution in iteratively executing the proposed SAA is rationally expanded by double temperature control variables. Moreover, the cost difference control variable makes the network layout optimisation able to restart from the latest temporally optimal solution by stopping an excessive search in any searching direction to avoid getting trapped in a local optimum. These three control variables work together to improve the capacity of the new SAA for the search of the globally optimal solution. The GA integrated into the reversible SAA iteratively decides a basic transport network configuration with the minimum total transport time to be optimised for the minimisation of the network operation cost. It is confirmed that the proposed model solved by the reversible SAA with the GA embedded is able to effectively optimise the layout of a passenger transit network or configurations of logistics transportation routes for both improving the transport efficiency and reducing the operation cost with the best fits between them.

In future research, the newly developed optimisation model solved by the proposed SAA ought to have more values of its different parameters and variables tested for different networks with various topologies to further validate the achievements of this study. Moreover, the dynamic designs of the transport services should be made in consideration of real-time traffic condition, changeable transport demand distribution, sharing vehicles between different transport lines, vehicle maintenance, etc. in future work. Furthermore, instead of controlling the minimisation of the network operation cost, the best fits between the maximisation of the transport efficiency and the minimisation of the network operation cost might also be achieved coordinately by controlling the search for the optimum total time expense of all the transports. This is worthy of further analyses in detail. In addition, as proposed by Kılıç and Gök [17] and Cheng *et al*. [23], respectively, both rationally initializing the configuration of a transport network with a relatively high efficiency and hierarchically optimising the network layout from environmental protection perspective are another two important tasks in the future.

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