Multiobjective modelling in choice of route and vehicle for public city transportation for minimum travel time, low cost and energy consumption

Velizara Pencheva, Asen Asenov
[1]Department Transport
University of Ruse "Angel Kanchev"
Ruse, Bulgaria
{vpencheva, asasenov}@uni-ruse.bg

Ivan Georgiev
[2]Department Applied Mathematics and Statistics
University of Ruse "Angel Kanchev"
Ruse, Bulgaria
irgeorgiev@uni-ruse.bg

***Abstract*— There are more than 1.5 million trips in the Republic of Bulgaria using urban passenger transport per day, with 1 688 230 trips recorded in 2017. On these trips, passengers are often faced with the choice for route and vehicle. This is especially true for multimodal travel. A number of factors influences this choice. On the one hand, it is the result of technical, time, financial and environmental constraints, the quality of the transport service and the socio-economic characteristics of the passenger. On the other hand, the different perspectives of individual travelers who try to satisfy their individual preferences must be considered. In recent times, this has been often linked to the public interest in sustainable development, including sustainable transport. In this paper is shown a multi-criteria optimization for the choice of passenger journeys according to three criteria (minimum travel time, low cost and energy consumption) with options for choosing number (n) types of vehicles. As a result, the options for passenger journey (Pareto optimal decisions) are obtained and therefore are given opportunities to the person who takes decisions (passenger) to choose one of these solutions.**

***Keywords*— multicriteria optimization, sustainable transport, Pareto optimal solutions, urban passenger transport**

I. INTRODUCTION

Public urban transport provides basic travel in urban areas and has a significant impact on population mobility. In cities with over 100 000 inhabitants, and especially in large metropolitan areas, urban passenger transport is numerous. For example, in Beijing, China, there are about 11.29 million daily commutes [1]. The average travel time and distance is 54 minutes and 19.4 km [2].

Although much smaller in Bulgaria, the issues related to urban passenger transport are identical. Buses are used for urban passenger transportation in all Bulgarian cities and trolleybuses are used only in 10 cities [3]. In the capital, in addition to bus and trolleybus transport, tram and metro services were developed. The total number of bus routes in the cities of the country for 2017 is 565 with the length of the routes 6.4 thousand km, for which 346 550 000 passengers were transported on the same year and transport work done approximately 131 131 mil. pkm, with an average distance of 9 km. Trolleybus transport has a route length of 400 km, passengers carried 77 682 000, transport work done 342 mil. pkm at an average transport distance 4.44 km. Including the metro and tram transport of the capital, the total number of passengers transported by urban transport in the country for 2017 is 616 204 000 and transport work done was 4 543 mil. pkm.

One of the contemporary aspects of urban passenger transport is the choice of route and vehicle. A number of factors influences this choice. On the one hand, it is the result of technical, time, financial and environmental constraints, the quality of the transport service and the socio-economic characteristics of the passenger. On the other hand, the different perspectives of individual passengers trying to increase their individual advantage must be considered. In recent times, this has too often been linked to the public interest in sustainable development, including sustainable transport. Many of the models offered in the literature make single-criterion optimization, usually from the path or time elapsed, assuming that the other quantities are proportionally dependent, which simplifies the models but does not produce good results, especially in multimodal trips. Research shows the need to implement multi-criteria decision-making models. These models allow for a number of conflicting views to be considered and lead to the definition of the 'best compromise'. Route selection problems typically involve a set of route alternatives and vehicles to choose from, considering a number of criteria. This publication optimizes the choice of passenger movement on three criteria, with options for choosing n types of vehicles.

II. EXPOSITION

A. *Criteria for the choice of route by the passenger in a multimodal network.*

While studies of fixed-route and fixed-vehicle travel have been extensively reviewed in the literature, the study of preferences for route and vehicle preference for multimodal travel is less frequently considered. The multimodal route should provide the user with options for choosing the optimal route with the appropriate vehicle. Generally speaking, the attribute set must be complete to cover all relevant aspects of the solution problem [4].

Given that minimum travel time is one of the most widely used optimization criteria in multimodal route planning, this is often an important optimization criterion [5]. Another important criterion for the passenger is to minimize the cost of travel. Given the need for sustainable development in multimodal travel, to be considered the criterion is the improved energy efficiency of the vehicle, which is associated with the lowest energy consumption.

The choice of a vehicle to move on a single segment is closely linked to the third criterion, although the first two also influence it. Each mode of transport has different energy efficiency and different characteristics in respect of the different vehicles in one mode of transport. For example, bus transport has a variety of characteristics, age-related, technical parameters and more. The variety has also been supplemented by electric buses and hydrogen-powered buses that have emerged in recent years.

From a mathematical point to solve the multicriteria problem, the objective functions can be written as:

$\min(x)[F_1(x), F_2(x), \ldots, F_n(x)]$, where $F_i(x)$, $(i=1,2,\ldots,n)$ is ***i*** target function.

B. Formulation of the task

From one bus stop of urban passenger transport in a populated area, you have to get to another bus stop within the same area, generally passing through intermediate bus stops. The route from a given starting bus stop to a given bus terminal can be made on different routes and with different vehicles between two adjacent stops (between them, there is no other stop along the given route). Various criteria are set by which to move. Such problems are well described by the graph theory, and very often modelled as linear /nonlinear multicriteria optimization. In present case will be examined task including three basic criteria: minimizing travel time, minimizing the cost of travel and minimizing harmful emissions (ie, selecting such a route and vehicles between two stops on the route to minimize travel time, cost and energy consumption from vehicles on the route). To a large extent, all three criteria are correlated, but this is not always the case, so they need to be considered separately.

The routing scheme of the settlement is considered as an oriented graph, at which each stop is assigned a node in the graph and at each time connecting a stop № i, with anther stop № j, matching the oriented weighted edge (i, j) in the graph. This weight c_{ij} of the edge is directly related to the criterion set. In the case of three criteria, three weights will be initiated for each vehicle with number k passing along the edge: travel time c_{ij}^{k1}, the cost of traveling on a given edge c_{ij}^{k2} and energy consumption c_{ij}^{k3} by edge (i,j). If between two stops, are passing k vehicles, all three criteria are initiated by k weights - $c_{ij}^{11}, c_{ij}^{21}, \ldots, c_{ij}^{k1}; c_{ij}^{12}, c_{ij}^{22}, \ldots, c_{ij}^{k2}; c_{ij}^{13}, c_{ij}^{23}, \ldots, c_{ij}^{k3}$. Clearly, all three criteria have weights $c_{ij}^{k_1 1}$, $c_{ij}^{k_2 2}$ and $c_{ij}^{k_3 3}$, which will be the smallest by the relevant criterion - $c_{ij}^{k_1 1} \le c_{ij}^{1l}, c_{ij}^{k_2 2} \le c_{ij}^{2r}, c_{ij}^{k_3 3} \le c_{ij}^{3m}\ \forall\, l, r, m = \overline{1,\ldots,k}$. The vehicle that has the smallest consumption between two stops on a given criterion will be called dominant on the given criterion between the specific two peaks. When one criterion is set, it is appropriate to consider only the dominant vehicles between two stops and the carriage can only be carried out with them. For simplicity, it will be assumed that a maximum of two vehicles are moving on each edge. So for every edge (i,j), it will be initiated with weights $c_{ij}^{11}, c_{ij}^{12}, c_{ij}^{13}$ c_{ij}^{21}, c_{ij}^{22}, c_{ij}^{23}. Thus, there are two choices for a vehicle between two stops (two vertices in the graph), with at least one of the criteria dominating each of these two choices (it is possible for the same vehicle to be dominant, two of the three, as and on three of the three criteria simultaneously). If only one criterion is followed, then the problem is reduced to the classical problem of finding the shortest path in a graph for which various algorithms are known - Dijkstra algorithm, Ford-Bellman algorithm and others. In the presence of two or more criteria, the task should be related to multicriteria optimization. In the presence of two or more criteria, it is common practice to initially solve the problem as single criteria for each individual (private) criterion. The formulation and mathematical model (single-criterion) of the shortest path in an oriented graph can be described as follows:

An oriented weighted graph with n nodes and an adjacency matrix C with weight (cost by one given criterion) c_{ij} is given along the oriented edge (i,j). If there is no directed edge connecting the node i with the node j, that menas there is no vehicle performing the transport by the given criterion, it is set as $c_{ij} = L$, where L is a very large number - $L \gg 1$. The shortest path (within the meaning of the criterion) is sought between 1^{-st} node and n^{-th} (node) (it can always numerate the starting node as № 1, the terminal node as № n).

The linear optimization model of the task for the shortest path is presented as follows:

$$minZ = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} x_{ij} \qquad (1)$$

$$\sum_{i=1}^{n} x_{ik} - \sum_{i=1}^{n} x_{ki} = 0 \;\; for\; k = 2 \ldots n-1 \qquad (2)$$

$$\sum_{i=2}^{n} x_{1i} = 1 \qquad (3)$$

$$\sum_{i=1}^{n-1} x_{in} = 1 \qquad (4)$$

$$x_{ij}\ is\ binary. \qquad (5)$$

The variable x_{ij} (5) is binary. If the path passes through an edge (i,j) from node i to node j, it takes the value 1, and 0 if it does not pass. Condition (1) expresses a set criterion for minimizing the total cost from the beginning of the road to its end. Constraints (3) and (4), respectively, state that exactly one node must be selected from the starting node to be travelled and from one node to reach the end node. For all other nodes, a Restriction (2) is adopted which requires equality between vehicles entering and exiting in each single intermediate node.

Different matrices $C^{k1}, C^{k2}, \ldots, C^{km}$ describing a given cost with k^{th} vehicle along the corresponding edges may be assigned as adjacent matrices. Neighborhood matrices are set according to what criterion is set - criterion for minimality of total travel time, criterion for minimality of total cost of travel, criterion for minimality of the total amount of energy consumption allocated to travel, etc. In the case of three criteria and two vehicles with Z_1, Z_2, Z_3, the costs according to the first, second and third criteria are indicated. Respectively with $c_{ij}^{11}, c_{ij}^{12}, c_{ij}^{13}$ is denoted the cost of the first vehicle according to the first, second and third criteria on edge (i,j). Similar is with $c_{ij}^{21}, c_{ij}^{22}, c_{ij}^{23}$ - the cost of the second vehicle according to the relevant criteria. Then the costs of the three criteria are determined by

$$Z_k = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij}^{1k} x_{ij}^{1} + c_{ij}^{2k} x_{ij}^{2}, k = 1, 2, 3 \qquad (6)$$

C. Mathematical model solution

The problem is to minimize the vector criterion

$$Z = [Z_1(x^k),\ Z_2(x^k),\ Z_3(x^k)] \quad (7)$$

$$x^k = (x_{11}^k, x_{12}^k, \dots, x_{nn}^k)$$

under restrictions

$$\sum_{k=1}^{2}\left(\sum_{i=1}^{n} x_{ir}^k - \sum_{i=1}^{n} x_{ri}^k\right) = 0 \ \ \forall\, r = \overline{2,..,n-1}, \quad (8)$$

$$\sum_{k=1}^{2}\sum_{i=2}^{n} x_{1i}^k = 1 \quad (9)$$

$$\sum_{k=1}^{2}\sum_{i=1}^{n-1} x_{in}^k = 1 \quad (10)$$

$$\sum_{k=1}^{2} x_{ij}^k \le 1\ \forall\, i,j = \overline{2,..,n-1}, \quad (11)$$

$$x_{ij}^k \in \{0,1\}, \forall\, k = \overline{1,2} \quad (12)$$

Here, the unknown variable x_{ij}^k (12) assumes a value of 1 in case of the path passes through an edge (i,j) in the direction node i - node j with k^{th} vehicle or 0. Constraints (9) and (10) respectively indicate that one starting point and one vehicle must be selected from the starting node and starting at the final node from exactly one node and one vehicle. Restriction (8) has the same meaning as restriction (2). Condition (11) reflects the fact that no more than one vehicle can be selected per direction in one direction. The problem (7)-(12) thus posed is a problem of multicriteria integer linear optimization. The problem formulated in this way has the following two features: integerness of the solution (in this case the variables are binary) and the second set criteria are three.

Specific for multicriteria optimization is the presence of many optimal solutions. This set is considered by Pareto [6]. In this set there is no solution that dominates over all the others by the given criteria. Therefore, it is rational to find a larger number of solutions than the Pareto set. Unambiguous selection of a solution for many criteria, some of which contradict each other, requires expert opinion and is often subjective. In this case of multicriteria optimization there are two:

• the decisions obtained by using numerical methods to be close to the real decisions of the Pareto front;

• certain decisions differ substantially from one another and possibly choose one of them.

In general, existing multicriteria optimization methods are:

1. Optimization of a generalized criterion constructed according to a given compromise scheme [7, 8, 9].

2. Determining the Pareto set and selecting a solution from this set [10, 11, 12, 13].

Some of these methods are: The weight method proposed by L. Zadeh, [9, 14], the ε -constraint method proposed by Haimes, Lasdon, Wismer, the method of achieving the goal [14], minimax method [15], global criterion method [16], nonlinear trade-off method proposed by A.N Voronin [7], Parametric Space Investigation method (PSI) [10, 17] and other.

Problem (7) - (12) is revisited. The aim is to find a sufficient number of optimal Pareto solutions. The constraints (8) - (11) as well as the vector criterion (7) are linear. This implies a convex allowable area. The integerness of the variables is imposed by condition (12). This condition makes it difficult to solve the problem. Such tasks are known as NP-complexity. Under these conditions, the solution is integer or partially integer and in the general case does not coincide with the Pareto-optimal solutions for continuous variables. From the fact that the allowable area is convex, a generalized weighting method can be constructed to find the optimal Pareto solutions. The generalized criterion is constructed by the individual partial criteria, as their linear combination with weights λ ^ k, k = 1, 2, 3. Weights must perform:

$$\sum_{k=1}^{3}\lambda^k = 1,\ \lambda^k \ge 0, k = 1,2,3. \quad (13)$$

A set of different random numbers given as values of the weights λ^k solves a one-criteria integer problem:

$$\min Z = \lambda^1 Z_1 + \lambda^2 Z_2 + \lambda^3 Z_3 = \sum_{k=1}^{3}\lambda^k Z_k = \lambda^1 \sum_{i=1}^{n}\sum_{j=1}^{n}(c_{ij}^{11}x_{ij}^1 + c_{ij}^{21}x_{ij}^2) + \lambda^2 \sum_{i=1}^{n}\sum_{j=1}^{n}(c_{ij}^{12}x_{ij}^1 + c_{ij}^{22}x_{ij}^2) + \lambda^3 \sum_{i=1}^{n}\sum_{j=1}^{n}(c_{ij}^{13}x_{ij}^1 + c_{ij}^{23}x_{ij}^2), \quad (14)$$

under conditions (8) - (12). The different selection of these solutions forms the Pareto optimal front when the integer of the variables or part of them is required.

As the dimension of the task (14) increases, the time and memory resources needed to solve it increase rapidly. The problem is solved repeatedly with randomly generated vector weights. It is advisable to select random generation in a specific way, with the aim of less attempts to achieve greater efficiency in finding Pareto optimal solutions. For this purpose, a systematic quasi-uniform probing is applied - deterministic points of the so-called '$LP\tau$ – row' (Sobol test points) [18, 19].

A software implementation of the Matlab product has been made. The program inputs are the number of vehicles and three adjacent matrices (respectively, according to the three criteria) for each vehicle (by default, the optimal path is sought between the first and last node, if necessary, the units are renumbered). Output data are vectors describing the sequence of nodes visited, which vehicle passes through each edge, and the totals according to the three criteria.

According to the three criteria and with two vehicles passing through each rib, a specific example is considered. In Table I is weights c_{ij}^{11} between the different peaks by the first criterion for the first vehicle.

TABLE I. NEIGHBORS MATRIX OF WEIGHTS c_{ij}^{11} BETWEEN THE DIFFERENT PEAKS BY THE FIRST CRITERION FOR THE FIRST VEHICLE

№	1	2	3	4	5	6	7
1	L	0.679	0.310	0.949	L	L	L
2	0.758	L	L	L	0.341	L	L
3	0.797	L	L	0.001	L	0.508	L
4	0.106	L	0.498	L	0.926	0.857	L
5	L	0.856	L	0.088	L	0.384	0.280
6	L	L	0.843	0.251	0.338	L	0.444
7	L	L	L	L	0.870	0.627	L

In table form, not shown in the report, are recorded the weights of: for first vehicle: c_{ij}^{12} between the peaks by the second criterion; c_{ij}^{13} between the different peaks by the third criterion; for the second vehicle: c_{ij}^{21} between the individual peaks according to the first criterion; c_{ij}^{22} between the different peaks by the second criterion; c_{ij}^{23} between the individual peaks by the third criterion.

For all specific data like these in Table I the admissible area is probed with N = 100 Sobolev points. Pareto solutions according to three criteria are given in Table II.

TABLE II. RESULTS FROM PARETO OPTIMISATION

Results	***Path in column (by nodes)***	***Edges passed with first vehicle***	***Edges with 2nd vehicle***	***Criteri-on Z_1 value***	***Crite-rion Z_2 value***	***Crite-rion Z_3 value***
1	(1.4.5.7)	(1.4)	(4.5). (5.7)	2.147	2.1411	0.2902
2	(1.2.5.7)	-	(1.2).(2.5).(5.7)	0.9064	1.3806	0.8626
3	(1.3.6.7)	(3.6)	(1.3). (6.7)	1.8868	1.2302	0.7437
4	(1.3.6.7)	(1.3).(6.7)	(3.6)	1.2823	1.2694	0.2909

On table 2 are shown four different possibilities for moving from the first to the seventh peak. Neither solution is not dominated by any of the other solutions simultaneously on three criteria. This confirms the fact that these are Pareto optimal discrete solutions. There are different techniques for choosing one of all Pareto optimal solutions [20]. For the specific example the opportunity is given to the person who takes decisions to choose one of these decisions.

III. Conclusion

The results of the work show that for multimodal urban passenger transport. multicriteria optimization makes possible to find a compromise solution according to a specified criterion. Sustainable urban development is closely linked to the energy efficiency of vehicles and the optimization of moving at the lowest energy consumption. Adding this criterion to criteria for the minimum travel time at the lowest cost makes possible to better consider the needs of the passenger. combined with the needs of the public. This is directly related to the selected type of vehicle. The obtained variants of moving the passenger through Pareto optimal discrete solutions give the person who takes decisions (the passenger) the opportunity to choose one of these solutions.

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