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A multi-criteria approach for evaluating the urban transport technologies by using SIMUS method

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Abstract. The study purpose a methodology based on Sequential Interactive Modelling for Urban Systems (SIMUS) method for ranking the urban transport technologies. The methodology of research includes three steps. The first step defines quantitative and qualitative criteria for the assessment of urban transport modes. Fourteen criteria of four groups, as ecological, economical, technological and social for evaluating the transport alternatives in urban environment have been defined. The second step includes a selection of alternatives of transportation by different transport means for a given route. In this research is investigated transportation by metro, buses and cars. The SIMUS method is applied in the third step for ranking the variants of transportation. The method solves successive scenarios formulated as linear programming. This step involves the ranking of alternatives and choice of optimal type of transportation. The methodology is approved for study the alternative mode of transportation for parallel routes from Sofia's transport network. It was found that the carriage by metro is the best transport technology for investigated route. The methodology and defined criteria could be applied to study the transport alternatives for different routes of Sofia's transport network, and also to assess the modes of transport in urban area of Sofia or other city.

1. Introduction

The urban transport system combines different modes of transport, which develop according to the city's territory, population size, socio-economic development and other factors. In major metropolis, the main types of public transport are metropolitan, bus, tram, trolleybus. The factors that are important for passengers to choose the type of transportation are the accessibility, time travel, freight rates, prices, etc. Undoubtedly, the electrified rail transport as metropolitan, light rail, tramway and trolleybus are environmental friendly. The bus transport and passenger car transport have a big part of urban transportations. They are the main source of air pollution. The metropolitan, as ecological and speed rail transport, occupies an important place in public transport to meet the needs of travel in major cities. The increase in environmental pollution due to exhaust from transport activities necessitate to seek efficient transport technologies that improve the quality of life in big cities in terms of air pollution.

The AHP method has been used in [1] to assess the importance of various parameters affecting the mode choice made by urban transport users e.g. time, fare, comfort, reliability and accessibility, etc. The research aims to understand the major influences on user behaviour in an environment where all modes are available for use. In [2] authors compared ANP method and AHP method to study the choice of different alternatives for urban transport. The capital cost, capacity, environmental benefit and socio-economic benefit was applied to rank the alternatives. The AHP method has been used in [3] for ranking light rail, a dual mode of tram and bus. The AHP method has been applied for selecting the best mode of transportation in Lagos State metropolis, [4]. The alternative modes of transportation were evaluated with nine decision criteria: transportation cost, environmental effect, capacity, safety, comfort, accessibility, reliability, number of interchanges required and journey time. In [5] is presented a model based on AHP method for public transport management. The following criteria have been defined: safety of the participants, ecology, availability, capacity of the network of traffic routes, and economic indicator. The ELECTRE III/IV and AHP methods taking into account two



models of decision maker preference: passenger and operator have been used in [6] to study six scenarios of transportation. A set of six criteria was proposed: waiting time; riding time; accessibility to the stop; comfort of travel; cost of rolling stock purchase; cost of building, maintenance and renewal of route. The ELECTRE III method has been applied in [7] to assess four variants of the mass transit system in Czestochowa. Two methods – TOPSIS and SAW were used and compared in [8] to determine the best transport development alternative based on traffic parameters. In [9] the authors investigated alternative-fuel buses for public transportation using multi-criteria analysis. The main criteria that were used are social, economic, technological, and transportation. Sub-criteria for each main group have been defined.

The both compensatory and non-compensatory approaches including lexicographic, SAW method, TOPSIS method and Concordance Analysis have been applied in [10] to assess the three urban public transport modes. In [11] the following criteria to assess transport alternatives for urban development have been studied: accessibility measurements, impact of each stop on the total travel time, catchment areas for population and jobs, existing urban functions in the surroundings of the stops, potential for urban development of housing, activities and equipment, potential for connection with other modes, and cost of construction.

An integrated multi-criteria approach is proposed in [12] for evaluation of public transportation systems based on Delphi method, group AHP method and ROMETHEE method. The criteria of selection of transport types that have been used are: travel cost, travel time, waiting time, suitability, accessibility and safety.

In [13] has been formulated ten clusters form the basis for the overall evaluation of the transport system - comfort, vehicles, customer service, information, reliability, security, payment, entertainment, accessibility, and terminals infrastructure. In [14] the relationships between attribute-based satisfaction, overall satisfaction and customer characteristics are studied by means of constructing three linear models. The 15 criteria have been studied. In [15] was elaborated model based on two statistical methods (factor analysis and ordered logit modelling) assessed the quality implications of the variability of the users' perceived satisfaction with respect to the public transit systems. The research conducted in [16] uses logit model to investigate the passenger flows by rail and buses in Sofia. Two types of factors are used: price and quality of service (travel time, frequency, comfort, etc.). In [17] is elaborated multi-criteria model based on rank-order centroid method. The groups of criteria that were used are: engineering designers and developers, economic and financial, environmental communities, service operators and users. In [18] two criteria have been introduced for assessment the different means of transportation: traffic performance index and weighted traffic performance indices.

It can be summarized that the transport costs, travel speed; frequency; prices of the tickets; safety, comfort are the main criteria for assessment of different alternative modes of transportation that have been studied. The main types of methods that have been used can be summarized as follow: different multi-criteria methods to determine the weights of defined criteria and rank the alternatives; statistical methods to investigate the clusters for evaluation of the transport system. The experts' assessment is used to determine the weights of criteria, which leads to the increase of subjectivism in decision making.

The SIMUS (Sequential Interactive Modelling for Urban Systems) is a hybrid method based on Linear programming, Weighed Sum Method (WSM) and Outranking and aid to solve decision-making problems with multiple objectives. SIMUS was developed by Nolberto Munier, and tested in many and diverse type of projects, [19]. The weights of criteria are not used to make decision. The application of SIMUS method does not use subjective assessments of weights of criteria by experts.

The aim of the study is to define the criteria and to develop a methodology for assessment the passenger transport modes in urban area by using SIMUS method for make decision, and taking into account of the both requirements of the carrier and the expectations of the passengers, and also environmental protection.

2. Methodology

The methodology for evaluating the effectiveness of urban transport includes the following steps:

- Step 1: Definition of the criteria to evaluate the transport technology of carriage. The choice of mode of transport depends on a set of criteria, as ecological, economical, technological, and social. In this study the following criteria have been defined: C1 - Carbon dioxide (CO₂), g/pass.km; C2 - Carbon monoxide (CO), g/pass.km; C3 - Nitrogen oxides (NO_x), g.passkm⁻¹; C4 - Non-methane hydrocarbons (NC), g.pass.km⁻¹; C5 - Particulate matter (PM), g.pass.km⁻¹; C6 - Transport costs for fuel (electric energy), BGN; C7 - Ticket price, BGN.pass.⁻¹; C8 - Direct operating costs, BGN.pass.⁻¹; C9 - Time travel, min.; C10 - Frequency of shipments, number of transport means.h⁻¹; C11 - Comfort. This means the possibility of a seating place during a trip, and a comfortable trip of the standing; C12 - Security. This means safety with regard to road accidents; C13 - Reliability. This means the accuracy performance of the timetable; C14 - Stability. This mean independence from meteorological conditions. The first five criteria are connected to the ecological impact of transport means. The criteria from C2 to C5 present the polluting emissions. The criteria from C6 to C8 are economic indices. C9 and C10 are technological criteria. The criteria from C11 to C14 are social indices. The values of criteria from C11 to C14 is set wit "1" if the answer for performance of criteria is "yes", and "0" if the answer for performance of criteria is "no".

- Step 2: Determination of the variants of transportation by different transport means for a given route. In this research is investigated urban transportation by metro, buses and cars.

- Step 3: Determination of the optimal variant of transportation. The study uses the SIMUS method as a tool for ranking the variants of transportation. The method is based on linear programming. It consists of following steps:

- Organization of the decision matrix of criteria and alternatives. The matrix consists two parts. The first Left Hand Side (LHS) presents the values of criteria for the alternatives. The second part Right Hand Side (RHS) establishes the limits to each criterion. The matrix consist also the type of optimization for each criterion, and the type of operator. The value of RHS could be set by decision maker or determined as equal of maximum normalized value of the row when the objective of criterion is of maximum. In the case of minimum of objective function the value of RHS is equal of minimum normalized value of the row.

- Determination the normalized values of LHS part of decision matrix. The normalization can be made by different method as total sum in row, maximum value in row, Euclidean formula and min-max. The choice of normalization system does not affect the results of ranking the alternatives.

- Determination the Efficient Results Matrix (ERM). This matrix is formed according the procedure of SIMUS method which uses simplex algorithm of linear programming. The number of linear optimization models is equal to the number of criteria. The first optimization model is compiled by using the first criterion as the objective function which is removed from decision matrix. The restrictive conditions of the model are the others rows of the matrix. The procedure is repeated with the other criteria. It is necessary the all criteria to be used as objective functions. The ERM matrix is formed based on results of all linear optimization models. The elements of ERM show the score of each alternative for each optimization model.

- Ranking the alternatives using ERM. The procedure consists the following steps: normalization of the ERM; determination the sum of all elements in each column (SC); determination the number of participation of each alternative in each column of normalized ERM named Participation Factor (PF); determination the normalized values of PF (NPF) by dividing each value of PF to the total number of criteria; determination the values of the criterion for ranking - the multiplication of the NPF by the SC for each alternative. The ranking of the alternatives is made according descending order of the criterion. The maximal values of criterion show the best alternative.

- Ranking the alternatives using Determination Project Dominance Matrix (PDM). The number of column and the rows in PDM has equal to the number of alternatives. The elements of PDM are determined successively starting from the highest value in the first row by calculating the differences between values in the same row of normalized ERM. The procedure is repeated with all the values.

The row sum and column sum of matrix PDM are determined. The ranking of the alternatives is made according criterion net dominance, which presents a difference between row and column values for the same alternative. The ranking is made according descending order of the criterion. The maximal values of criterion show the best alternative.

3. Results and discussion

The methodology is approved for study the alternative mode of transportation for parallel routes from Sofia's transport scheme. The section Sofia University St. Kliment Ohridski metro station - G.M. Dimitrov metro station has been investigated. The following alternatives of transportation have been studied: Alternative 1- metro; Alternative 2- bus; Alternative 3 - car.

This area is served by metro and on a parallel route runs bus 280. There are also cars that moved in this section.

The following conditions have been taken into account when determining the criteria's values:

- The morning peak period from 8.00 to 9.00 o'clock is examined. For a peak period, filling factor for metro trains and buses was adopted equal of 0.9. For carriage it is assumed that one or two passengers travel in one car.
- The European Environmental Protection Agency's model for estimating the emissions from a vehicle based on the total fuel consumption or engine power is used for determining the parameters of emissions from road transport. The Euro 5 standard is applied.
- The Carbon dioxide (CO₂) emissions for electricity generation have been accounted for metro transport. The CO₂ emissions are 0.460 t.MWh⁻¹ according data from National Statistical Institute of Bulgaria. The CO₂ emissions is assumed to be 130g.km⁻¹ for a car, and 170g.km⁻¹ for a bus. When determining the pollutants emissions, a power of 180 kW for an urban bus was adopted with an average power of 80% of the bus power.
- In the study, it is assumed that in the morning peak period the metro trains are 81-740/741 series (produced from 2005 to 2013). The relative power consumption for this series is 7.02kWh.km⁻¹. The electricity price is 282.46 BGN.MWh⁻¹.
- It is suggested the following: the number of cars with gasoline and diesel engines for the studied period is equal; the average fuel consumption for a car is 12 l.100km⁻¹; the average fuel consumption for a bus is 35 l.100km⁻¹ for urban carriage; the cost for average fuel consumption is 3.06 BGN.km⁻¹.
- When determining the direct operating costs for the metro, the costs of running trains (electricity) and wage costs of drivers are taken into account. These costs are 4.80 BGN.trainkm⁻¹ according data from Sofia metro. When determining the running costs of a car, it is assumed that the cost of oil, tires, maintenance, insurance, taxes, are 40% of the fuel costs, i.e. according to the above mentioned average fuel consumption for a car 12l.100km⁻¹, the operating costs are 0.34 BGN.km⁻¹.
- The number of metro trains and buses of line 280 for morning peak period is determined according the data given by Urban Mobility Centre. The cars' frequency is 10 minutes.
- The ticket price for the metro and bus transport is calculated according a discount for 10 trips and it is 1.20 BGN.ticket⁻¹. When traveling by car, the ticket price is equal to the fuel consumption per passenger.
- The operating costs and the value of harmful emissions for different mode of transport are compared by passenger-kilometer.

Table 1 presents the parameters of investigated alternatives. Table 2 shows the LHS data of decision matrix and contains the values of criteria. Table 3 show the normalized values of LHS data and thresholds. The sum in row of LHS data is applied for normalization. The part named "Thresholds" show the type of optimization for each criterion, the respective operator, and the value of RHS that establishes the limits to each criterion. The value of RHS column is determined according the normalized values of each row.

Table 1. Parameters of alternatives.

Parameters	metro	bus	car
Length, km	4.5	5.94	5.53
Number of seats (sitting and standing)	344	95	5
Number of passengers in a vehicle in peak period, pass.vehicle ⁻¹	310	85	2

Table 2. Decision matrix- LHS Data.

Criteria	LHS Data		
	Alternative		
	1	2	3
C 1	10.50	1.98	65.00
C 2	0.00	0.13	0.38
C 3	0.00	0.04	0.06
C 4	0.00	0.17	0.06
C 5	0.00	0.002	0.003
C 6	1.48	4.15	1.32
C 7	1.20	1.20	0.66
C 8	0.02	0.04	0.17
C 9	8.00	17.00	14.00
C 10	3.00	8.57	10.00
C 11	0.00	0.00	1.00
C 12	1.00	0.00	0.00
C 13	1.00	0.00	0.00
C 14	1.00	0.00	0.00

Table 3. Normalized LHS Matrix and RHS.

Criteria	Alternative			Thresholds		
	1	2	3	Action	Operator	RHS
C 1	0.14	0.03	0.84	min	≥	0.03
C 2	0.00	0.25	0.75	min	≥	0.00
C 3	0.00	0.39	0.61	min	≥	0.00
C 4	0.00	0.74	0.26	min	≥	0.00
C 5	0.00	0.40	0.60	min	≥	0.00
C 6	0.21	0.60	0.19	min	≥	0.19
C 7	0.39	0.39	0.22	min	≥	0.22
C 8	0.07	0.16	0.77	min	≥	0.07
C 9	0.21	0.44	0.36	min	≥	0.21
C 10	0.14	0.40	0.46	max	≤	0.46
C 11	0.00	0.00	1.00	max	≤	1.00
C 12	1.00	0.00	0.00	max	≤	1.00
C 13	1.00	0.00	0.00	max	≤	1.00
C 14	1.00	0.00	0.00	max	≤	1.00

Table 4 presents the linear optimization models with objective function and restrictive conditions based on SIMUS method for the first and for the second criterion. Initially, the first criterion has been used as the objective function. The restrictive conditions are presented by the others rows of normalized matrix. In table 4 x_j presents the score of each alternative; $j = 1, \dots, m$ are the number of variants.

Table 4. Linear models.

Liner model for first criterion		Liner model for second criterion	
Objective function:		Objective function:	
$0.14.x_1 + 0.03.x_2 + 0.84.x_3 \rightarrow min$	(1)	$0.25.x_2 + 0.75.x_3 \rightarrow min$	(13)
Restrictive conditions:		Restrictive conditions:	
$0.25.x_2 + 0.75.x_3 \geq 0$	(2)	$0.14.x_1 + 0.03.x_2 + 0.84.x_3 \geq 0.03$	(14)
$0.39.x_2 + 0.61.x_3 \geq 0$	(3)	$0.39.x_2 + 0.61.x_3 \geq 0$	(15)
$0.74.x_2 + 0.26.x_3 \geq 0$	(4)	$0.74.x_2 + 0.26.x_3 \geq 0$	(16)
$0.40.x_2 + 0.60.x_3 \geq 0$	(5)	$0.40.x_2 + 0.60.x_3 \geq 0$	(17)
$0.21.x_1 + 0.60.x_2 + 0.19.x_3 \geq 0.19$	(6)	$0.21.x_1 + 0.60.x_2 + 0.19.x_3 \geq 0.19$	(18)
$0.39.x_1 + 0.39.x_2 + 0.22.x_3 \geq 0.22$	(7)	$0.39.x_1 + 0.39.x_2 + 0.22.x_3 \geq 0.22$	(19)
$0.07.x_1 + 0.16.x_2 + 0.77.x_3 \geq 0.07$	(8)	$0.07.x_1 + 0.16.x_2 + 0.77.x_3 \geq 0.07$	(20)
$0.21.x_1 + 0.44.x_2 + 0.36.x_3 \geq 0.21$	(9)	$0.21.x_1 + 0.44.x_2 + 0.36.x_3 \geq 0.21$	(21)
$0.14.x_1 + 0.40.x_2 + 0.46.x_3 \leq 0.46$	(10)	$0.14.x_1 + 0.40.x_2 + 0.46.x_3 \leq 0.46$	(22)
$x_3 \leq 1$	(11)	$x_1 \leq 1$	(23)
$x_1 \leq 1$	(12)	$x_3 \leq 1$	(24)

The results for optimization by the first criterion are recorded in the first row of Efficient Results Matrix (ERM); the results for optimization by the second criterion are recorded in the second row of ERM matrix, Table 5. The procedure is applied consistently for all criteria. The Software SIMUS System which uses Simplex method of linear optimization has been used to make the research.

Figure 1 and Table 5 show the results of Efficient Results Matrix. The values of normalized ERM is presented in Table 6. The results presents that alternative 1 (transportation by metro) has the score "1" for eight of the criteria when they are applied as objective functions. This means that this alternative is the best according these criteria.

Table 5. ERM Matrix.

Criteria	Alternative			Objective function
	1	2	3	
C 1	0.00	0.55	0.00	0.01
C 2	1.00	0.00	0.00	0.00
C 3	1.00	0.00	0.00	0.00
C 4	1.00	0.00	0.00	0.00
C 5	1.00	0.00	0.00	0.00
C 6	0.34	0.00	0.38	0.14
C 7	0.00	0.22	0.30	0.15
C 8	1.00	0.00	0.00	0.07
C 9	0.35	0.19	0.02	0.16
C 10	0.00	0.00	0.00	0.00
C 11	0.00	0.00	1.00	1.00
C 12	1.00	0.00	0.00	1.00
C 13	1.00	0.00	0.00	1.00
C 14	1.00	0.00	0.00	1.00

Table 6. ERM Normalized.

Criteria	Alternative		
	1	2	3
C 1	0.00	1.00	0.00
C 2	1.00	0.00	0.00
C 3	1.00	0.00	0.00
C 4	1.00	0.00	0.00
C 5	1.00	0.00	0.00
C 6	0.48	0.00	0.52
C 7	0.00	0.42	0.58
C 8	1.00	0.00	0.00
C 9	0.63	0.33	0.03
C 10	0.00	0.00	0.00
C 11	0.00	0.00	1.00
C 12	1.00	0.00	0.00
C 13	1.00	0.00	0.00
C 14	1.00	0.00	0.00
Sum of Column (SC)	9.11	1.76	2.13
Participation Factor (PF)	10	3	4
Normalized PF (NPF)	0.71	0.21	0.29
Final Result (SC x NPF)	6.51	0.38	0.61
ERM Ranking			
Alternative 1 - Alternative 3 - Alternative 2			

The alternative 1 is the best also by criterion C9 (Time travel) when it are given as objective function. The results of optimization by criterion C11 (Comfort) and C12 (Security) shows that the alternative 1 and alternative 3 are the best. When the first criterion is applied as objective function, the alternative 2 have a highest score. The third alternative is the best when criterion C6 (Transport costs for fuel or electric energy) and criterion C7 (Time travel) are used separately as an objective function. The optimization by the criterion C10 (Frequency of shipments) shows that the scores alternatives are equal.

Table 7. Project Dominance Matrix (PDM).

Subordinated variants - alternatives - options	Row sum of			Net dominance	
	Dominant Alternative	1	2		3
1	0	8.8	8.6	17.4	14.3
2	1.4	0	1.3	2.7	-7.7
3	1.6	1.7	0	3.3	-6.6
Column Sum of subordinated Alternatives	3.0	10.5	9.9		
PDM Ranking				Alternative 1 - Alternative 3 - Alternative 2	

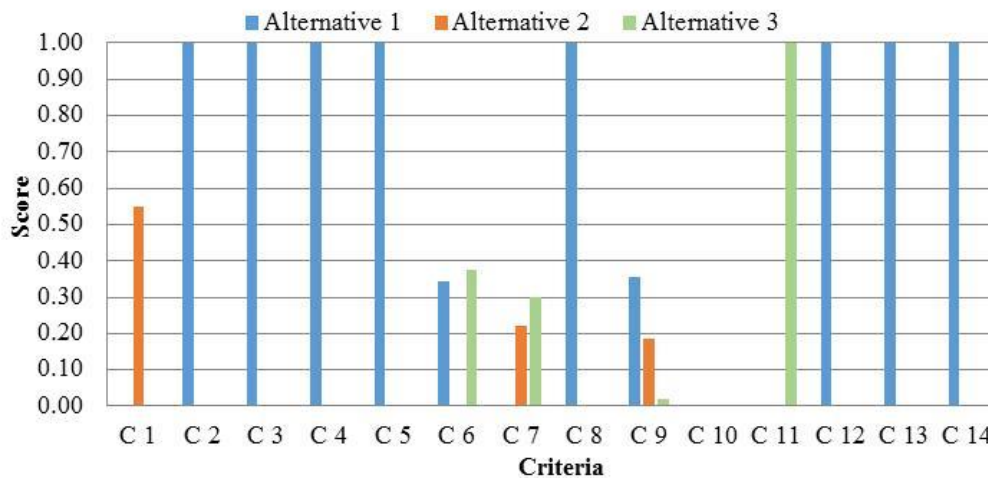


Figure 1. Score of the criteria by alternatives.

Table 6 presents the results of ERM Ranking. It can be seen in Fig. 1 that the alternative 1 is the best by ten criteria, alternative 2 is the best by three criteria, and alternative 4 satisfy four criteria. This is also given in Participation Factor (PF) in Table 6. The maximal score of Sum of Column (SC) has alternative 1 (transportation by metro). The Normalized Participation Factor (NPF) has maximal value also for alternative 1. The total number of criteria is 14. This number is taken into account in the calculation of NPF. The ERM ranking is as follow: Alternative 1 - Alternative 3 - Alternative 2.

Table 7 show the PDM Ranking. The criterion of ranking - net dominance is shown in the last column of the table. The first alternative has the big dominance value of 17.4. The second alternative has the big subordinate value of 10.5. The results show that the alternative 1 has greatest value of the Net dominance and it is a best. The last row of the table presents the PDM ranking. It can be seen that the both ranking by ERM and PDM are equal.

4. Conclusion

1. Fourteen criteria that are connected to four groups, as ecological, economical, technological and social for assessment the transport alternatives in urban environment have been defined.
2. In this study has been elaborated a methodology which uses linear optimization method and SIMUS procedure for assessment alternative transport mode in urban area. The solution for each criterion, as objective function of linear optimization model has been determined.
3. The model has been experimented for parallel routes of Sofia's transport network. It was found that the carriage by metro is the best transport technology for investigated route.
4. The alternative – transportation by metro is the best for nine criteria when they are given as objective function, i.e. this includes the following criteria: minimum of carbon monoxide (CO), nitrogen oxides (NO_x), non-methane hydrocarbons (NC), particulate matter (PM), direct operating costs, time travel, and maximum of security, reliability, and stability.
5. The methodology and defined criteria could be used for study the transport alternatives for different routes of Sofia's transport network, and also to assess the modes of transport in urban area of Sofia or other cities.

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