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SELECTION OF POSSIBLE SCENARIOS FOR IMPROVING THE QUALITY OF PUBLIC TRANSPORT SERVICES THROUGH THE USE OF HYBRID FUZZY-MCDM MODELS

Summary. A unified calculating approach is needed for public passenger transportation. All public transport companies and other stakeholders would have additional opportunities to create a transport offer if the unified methodology was made available to them and if calculations and calculation criteria were harmonized. Thus, the main goal – improving citizen mobility – would be accomplished. For this reason, in the study, we suggested the hybrid fuzzy methods for evaluating and improving the quality of public transport service. Unreliable responses of survey participants often distort group decision-making regarding the problem of public services, negatively affecting the end of the calculation procedure. Fuzzy multicriteria decision-making approach has been used. The suggested technique has the advantage of taking into account the degree of fuzzification of respondents' judgments about the choice scenario, while also using two MCDM models to eliminate bias in the responses.

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1. INTRODUCTION

Sustainable development requires the implementation of activities in accordance with the existing needs [1], while being aware of the limited possibilities of natural resources [2]. This means the necessity to search for and develop new technologies that will enable the reduction of energy consumption. And the improvement should not include travel limitation [3] It should be remembered that in relation to transport, many guidelines indicate the implementation of shared journeys (public collective transport) as a solution that positively affects the transport system, but also the environment, through reducing the load on the transport network or reducing the emission of harmful substances [4], [5], [6], [7]. The increase in the number of public transport passengers requires a constant improvement in the quality of services in order to maintain the current mode of travel, as well as to convince other people. The quality of collective public transport is determined using a set of different parameters. Starowicz [8] distinguished such parameters as: frequency, punctuality, reliability, comfort, information, travel cost, contact with the customer, time availability and travel time. In the handbook [9] reliability and travel time are called the key parameters related to the perception of the public transport system by users. In other publications, attention was also paid to the safety aspect (among others [10], [11]). Redman et al. [12] also identified vehicle condition among the quality parameters. The quality of the fleet is also indicated in the reports of the collective transport assessment by BEST [13].

One of the decision-making problems is the assessment of the quality of public collective transport, and thus the possibility of indicating places that require improvement. The organization and implementation of efficiently functioning public transport should mainly result from the cooperation of three stakeholders - cities, carriers and public transport managers in a selected area (depending on the adopted management pattern). Based on the literature review, the article divides selected quality parameters of public collective transport, creating a hierarchical system from them, and then identifies a number of activities (scenarios) aimed at improving the functioning of this type of transport. In addition to the scenarios indicated below, the considerations also included, among others, construction of transfer stations and implementation of dynamic passenger information. However, due to the fact that the city of Katowice was selected for the case study, where both solutions have already been implemented, the list of scenarios has been reduced. Possible actions (scenarios) ultimately included: on the city side - separation of bus lanes and bus priority at intersections (to a greater extent than at present), and on the carrier's side - fleet replacement. Two scenarios were identified for the manager of public transport - changing (improving) timetables and introducing new lines and bus stops. Finally, for the selected set of parameters (criteria) and scenarios, a fuzzy multi-criteria decision-making approach (MCDM) was used. It is just an option for decision makers to support them with decision-making process.

2. METHOD

It is always problematic, which multi-criteria decision-making approach should be chosen. Sometimes a very general approach can be used like in [14] to support finding the best option to make travel by using all sharing modes and public transport services. Broniewicz and Ogrodnik [15] analysed a lot of scientific papers about the transport sector published between 2000 and 2021 and proofed that AHP is the most popular MCDM method, and the next one is TOPSIS. In multi-criteria approach, the relevant parameters or criteria often have different dimensions, which may result in difficulties in assessment. To prevent this problem, the Fuzzy approach is required [16]. Authors already used fuzzy MCDM to choose scenarios for the management of the railway transportation company [17]. In the current paper Fuzzy AHP for calculating weights is used, and it is mixed with Fuzzy Topsis for determining priority in scenarios.

The steps of the calculation procedure are described below:

Step 1: The Decision Maker evaluates the criteria or scenarios by comparing them using the linguistic concepts in Table 1. It includes comparison of the Saaty scale and fuzzy triangular scale (FTS). The FTS is used to represent the statement "Criterion 1 (C1) is Weakly Important than Criterion 2 (C2)" if the decision maker states "Criterion 1 (C1) is Weakly Important than Criterion 2 (C2)" (2, 3, 4). On the other side, the pairwise contribution matrix of the criteria will be compared using the FTS between C2 and C1.

Tab. 1

Linguistic terms and Saaty's scale for pairwise comparisons (based on [18], [19])

Linguistic terms	Saaty scale	Fuzzy triangular scale
Equally important (Eq. Imp.)	1	(1,1,1)
Weakly important (W. Imp.)	3	(2,3,4)
Fairly important (F. Imp.)	5	(4,5,6)
Strongly important (S. Imp.)	7	(6,7,8)
Absolutely important (A. Imp.)	9	(9,9,9)
The intermittent values between two adjacent scales	2	(1,2,3)
	4	(3,4,5)
	6	(5,6,7)
	8	(7,8,9)

The pairwise contribution matrices are shown in Eq. 1, where $\tilde{d}_{ij}^{k}$ denotes the preference of the k[th] decision maker for the i[th] criterion over j[th] criterion. The triangular number demonstration in this instance is denoted by "tilde," and the preference of the first decision maker for the first criterion over the second criterion is denoted by $\tilde{d}_{12}^{1}$, which equals $\tilde{d}_{12}^{1}$ = (2, 3, 4).

$$\tilde{A}^k = \begin{pmatrix} \tilde{d}_{12}^k & \cdots & \tilde{d}_{1n}^k \\ \vdots & \ddots & \vdots \\ \tilde{d}_{n1}^k & \cdots & \tilde{d}_{nn}^k \end{pmatrix} \qquad (1)$$

Step 2: When there are several decision-makers, the average of each person's preferences ($\tilde{d}_{ij}^{k}$) is used to calculate ($\tilde{d}_{ij}$) , which is then computed according to Eq. 2.

$$\tilde{d}\text{ij} = \frac{\sum_{k=1}^{K} \widetilde{d_{ij}^{k}}}{K} \tag{2}$$

Step 3: Based on averaged preferences, the pair-wise contribution matrix is updated as shown in Eq. 3.

$$\tilde{A} = \begin{pmatrix} \tilde{d}_{12} & \cdots & \tilde{d}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{d}_{n1} & \cdots & \tilde{d}_{nn} \end{pmatrix} \tag{3}$$

Step 4: As stated in Eq. 4, according to Buckley [20], the geometric mean of fuzzy comparison values for each criterion is produced. Represents triangular values in this situation.

$$\tilde{r}\text{i} = \left[\prod_{j=1}^{n} \tilde{d}_{ij}\right] \; 1/\text{n} \tag{4}$$

Step 5: Using Eq. 5, get the fuzzy weights of each criterion by integrating the next three substages.
Step 5a: Calculate the vector sum of each $\tilde{r}_i$.
Step 5b: Determine the summation vector's (-1) power.
Step 5c: Multiply each $\tilde{r}_i$ with this reverse vector to get the fuzzy weight of criteria i ($\widetilde{w}_i$).

$$\widetilde{w}\text{i} = \tilde{r}\text{i} \;\otimes \tilde{r}1 \oplus \tilde{r}2 \oplus \ldots \oplus \tilde{r}\text{n} \;)\text{-1} \;\; = (\text{lwi, mwi, uwi}) \tag{5}$$

To find the weights criterion, follow these five steps.

Step 6: The decision-maker is advised to quickly examine the ratings of scenarios on a number of subjective factors using the linguistic variables (given in Table.2). These linguistic variables could be described by the triangle-shaped fuzzy number $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$.

Tab. 2
Linguistic variables for the ratings

Very Poor (VP)	(0, 0, 1)
Poor (P)	(0, 1, 3)
Medium Poor (MP)	(1, 3, 5)
Fair (F)	(3, 5, 7)
Medium Good (MG)	(5, 7, 9)
Good (G)	(7, 9, 10)
Very Good (VG)	(9, 10, 10)

Let A_1, A_2,..., A_m be feasible scenarios, and C_1, C_2,..., C_n be the criteria used to compare scenario performances. A fuzzy multi-criteria decision-making method for choosing problems is represented as the following matrix:

$$\widetilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & . & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & . & \tilde{x}_{2n} \\ . & . & . & . \\ . & . & . & . \\ \tilde{x}_{m1} & . & . & \tilde{x}_{mn} \end{bmatrix} \tag{6}$$

$$\widetilde{w} = [\widetilde{w}_1, \widetilde{w}_2, \ldots, \widetilde{w}_3] \tag{7}$$

where $\tilde{x}_{ij}, \forall i,j$ is the fuzzy rating of scenario A_i (i = 1,2,…, m) with respect to criterion C_j and $\widetilde{w}_j$ (j = 1, 2,…, n) is the weight of criterion C_j.

Step 7: The transformation of the several criterion scales into a single scale using the linear scale method ensures consistency between language evaluations of subjective criteria and objective criteria evaluation. The normalized fuzzy decision matrix R may be represented as follows:

$$\tilde{R} = [\tilde{r}_{ij}]m*n$$
$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right),\ j \in B,\ \tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), j \in C \tag{8}$$
$$C_j^* = \max cij \quad \text{if } j \in B,$$
$$a_j^- = \min a_{ij} \quad \text{if } j \in C,$$

where B and C are the set of benefit criteria and cost criteria, respectively.

The normalizing procedure discussed above preserves the condition that the ranges of normalized fuzzy numbers correspond to [0,1].

Step 8: Calculate the weighted normalized fuzzy decision matrix:

$$\tilde{V} = (\tilde{v}_{ij}), \tilde{v}_{ij} = \tilde{r}_{ij} * wj \tag{9}$$

Step 9: Compute the Fuzzy Positive Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS). The FPIS and FNIS are calculated as follows:

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, \ldots, \tilde{v}_n^*), \quad \text{where } \tilde{v}_j^* = \max\{v_{ij}\} \tag{10}$$
$$A- = (\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^-), \quad \text{where } \tilde{v}_j^- = \min\{v_{ij}\} \tag{11}$$

Step 10: Compute the distance from each scenario to the FPIS and FNIS:

$$di^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^*), \ di- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-) \tag{12}$$

Step 11: Compute the closeness coefficient CCi for each scenario. For each scenario Ai, we calculate the closeness coefficient CCi as follows:

$$CCi = \frac{d_i^-}{d_i^- + d_i^*} \tag{13}$$

Step 12: Rank the scenarios. The scenario with the highest closeness coefficient represents the best scenario.

3. CASE STUDY

3.1. Determining weights of criteria

As a case study, Katowice city was selected. In the case, exactly three stakeholders exist – urban authorities (responsible for transport infrastructure), carriers (responsible for bus fleet) and public transport managers (responsible for the organization of public transport in the area). Figure 1 contains selected criteria with a hierarchical structure. Possible scenarios are also shown. The list of criteria and scenario is based on literature review (described in the Introduction section).

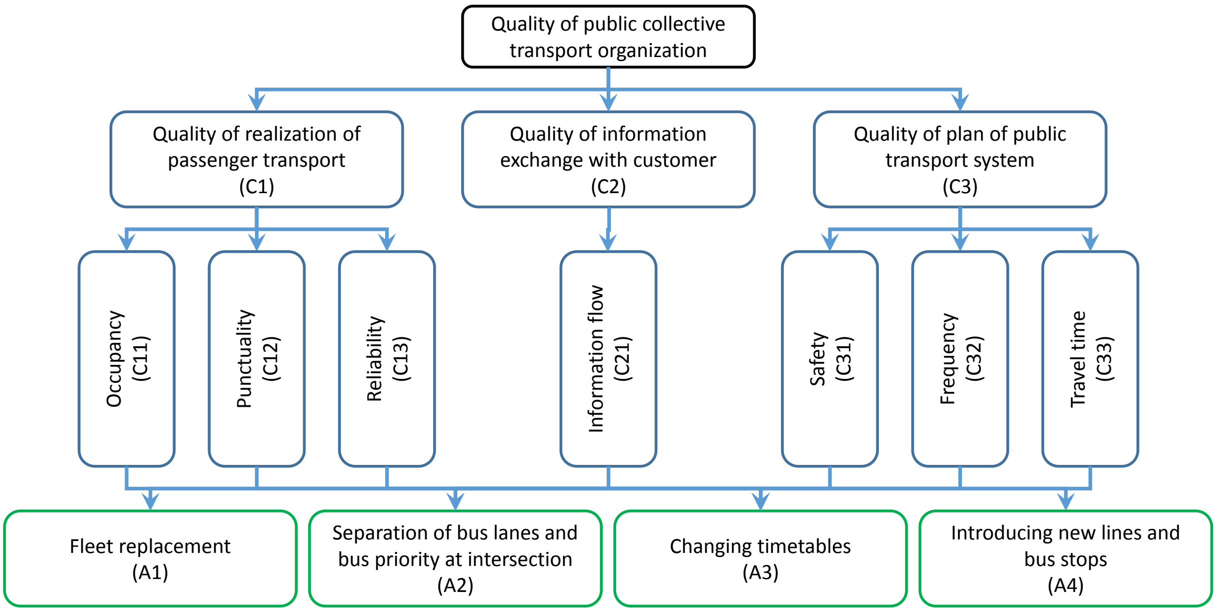

Fig. 1. Public transport quality as a hierarchical structure with criteria and scenarios

To determine the criteria and evaluate the scenarios, a meeting was arranged with a group who specializes in urban transportation. In order to determine the mean pair-wise comparison of the criterion and sub-criteria based on his preferences, questionnaires were employed.

Tab. 3

Comparison matrix for criteria

	Quality of realization of passenger transport	Quality of information exchange with customer	Quality of plan of public transport system
Quality of realization of passenger transport	(1,1,1)	(6,7,8)	(2,3,4)

Quality of information exchange with customer	(1/8,1/7,1/6)	(1,1,1)	(1/4,1/3,1/2)
Quality of plan of public transport system	(1/4,1/3,1/2)	(2,3,4)	(1,1,1)

Tab. 4

Comparison matrix for sub-criteria of C1

	Occupancy	Punctuality	Reliability
Occupancy	(1,1,1)	(1/4,1/3,1/2)	(2,3,4)
Punctuality	(2,3,4)	(1,1,1)	(1/6,1/5,1/4)
Reliability	(1/4,1/3,1/2)	(4,5,6)	(1,1,1)

Tab. 5

Comparison matrix for sub-criteria of C3

	Safety	Frequency	Travel time
Safety	(1,1,1)	(2,3,4)	(1/4,1/3,1/2)
Frequency	(1/4,1/3,1/2)	(1,1,1)	(1/4,1/3,1/2)
Travel time	(2,3,4)	(2,3,4)	(1,1,1)

After the first three stages of the procedure have been finished, Eq. 4 is used to obtain the geometric mean of the fuzzy comparison values for each criterion and sub-criterion. For the "Quality of realization of passenger transport" criteria, for instance, Eq. 14 produces the - geometric mean of fuzzy comparison values.

$$\tilde{r}\text{i} = \quad \prod_{j=1}^{n} \tilde{d}_{ij} \quad 1/n = (1*6*2)\text{^}(1/3),\ (1*7*3)\text{^}(1/3),\ (1*8*4)\text{^}(1/3) \qquad (14)$$

For all criteria and sub-criteria, Table 6 displays the geometric means of fuzzy comparison values. The total values and the reversal values are also displayed.

Tab. 6

Geometric means of fuzzy comparison values

Criteria and Sub-Criteria	$\tilde{r}_\text{i}$		
Quality of realization of passenger transport	2.28	2.75	3.17
Quality of information exchange with customer	0.31	0.36	0.43
Quality of plan of public transport system	0.79	1	1.25
Total	3.39	4.12	4.87
Reverse	0.29	0.24	0.2
Occupancy	0.79	1	1.25
Punctuality	2	2.46	2.88
Reliability	1.07	1.18	1.44
Total	3.87	4.65	5.58
Reverse	0.25	0.21	0.17
Safety	0.79	1	1.25
Frequency	0.39	0.48	0.62

Travel time	1.58	2.08	2.51
Total	2.77	3.56	4.4
Reverse	0.35	0.28	0.22

The fuzzy weight of the sub-criteria in the step 5 is determined using Eq. 5. In Table 7, the final weights are presented.

Tab. 7

The fuzzy weight of each computed criteria

Sub-Criteria	W_i		
Occupancy	0.13	0.14	0.14
Punctuality	0.34	0.35	0.33
Reliability	0.18	0.17	0.16
Information flow	0.09	0.08	0.08
Safety	0.06	0.06	0.07
Frequency	0.03	0.03	0.03
Travel time	0.13	0.14	0.14

4.2. Determining scenarios

The decision-maker evaluates the rating of scenarios in regard to each criterion by using the linguistic rating variables (given in Table 2).

Tab. 8

Linguistic variables for the ratings

	C11	**C12**	**C13**	**C21**	**C31**	**C32**	**C33**
A1	MP	F	VG	F	VG	G	VG
A2	G	VG	F	F	VP	G	P
A3	VG	VG	G	G	MP	MG	MP
A4	VG	VG	G	G	P	G	MP

The Fuzzy Positive Ideal Solution (FPIS) and the Fuzzy Negative Ideal Solution (FNIS) are computed in accordance with step 9 after steps 6, 7, and 8 have been completed to produce the fuzzy weighted matrix. As a consequence, Table 9's distance between each scenario and the FPIS and FNIS.

Tab. 9

The distance from each scenario to the FPIS and FNIS

A1	**A2**	**A3**	**A4**
0.63	0.67	0.35	0.36
0.57	0.53	0.86	0.85

Table 10 displays the closeness coefficient CC_i for each option after determining the separation between each scenario and the FPIS and FNIS.

Tab. 10
The closeness coefficient CCi for each scenario

A1	A2	A3	A4
0.47	0.44	0.7	0.69

A3 > A4 > A1 > A2

5. CONCLUSIONS

The constant increase in the quality of public collective transport is one of the foundations of the city's transport system. In this approach, the presented analysis may support decision makers. Of course, it is only an example of how the fuzzy-MCDM approach can be used in relation to collective public transport problems.

The use of the above method allowed for the evaluation of the public transport system. In the case, four scenarios (A1-A4) were taken into account. Changing in timetables (A3) is the best choice, according to table 10, which is the outcome of picking scenarios. Introducing new lines and bus stops (A4), fleet replacement (A1), and separation of bus lanes (A2) are rated lower.

The approach presented in the article relates only to one of the pillars of the transport system elements organized by the city. The aim of further research will be to build a model for assessing the functioning of the city's transport system in a broader sense (taking into account other municipal services and individual transport as a whole).

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