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Multiple criteria evaluation of different redesign variants of the public tram system

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Abstract

The paper presents a multiple criteria evaluation of ten redesign variants of the public tram system in one of the medium sized cities in Poland. The variants have been constructed heuristically, based on "common sense", best practices and authors' expert knowledge in the field. Multiple criteria evaluation of the proposed variants has been performed with the application of a consistent family of criteria that includes social, economic, technical and environmental aspects. It also represents the interests of the Decision Maker and different stakeholders. The authors have defined different models of preferences. The decision problem, formulated as a multiple criteria ranking problem has been solved with the application of selected Multiple Criteria Decision Making/ Aiding MCDM/A methods, such as: AHP and ELECTRE III/IV. The authors have carried out a series of computational experiments and have compared their results with intuitive decision making process carried out in the local Town Hall. The proposed methodology can be viewed as a decision support tool for governmental officers and local administration.

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Keywords: Multiple Criteria Evaluation; Public Tram System; Redesign; AHP method; Electre III/IV method;

1. Introduction

The growing wealth of societies and consequently a greater access to passenger cars is responsible for the significant increase of the motorization index with a simultaneous fall in public transportation usage (Leea,

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Rivasplata, 2001). This observation indicates that concrete actions should be undertaken to change this trend and encourage people to use public transportation more frequently and with more trust and desire. Unfortunately, many public transportation systems, including Polish ones, are maladjusted to the needs of the customers and not properly managed (Witkowski, Kiba-Janiak, 2012; Żak, Fierek, 2007). Therefore, they require comprehensive redesign resulting in the improvement and enhancement of the service delivered. Redesign of the public transportation system is a complex process that consists in introducing substantial changes in several of its critical components. The redesign of the public transportation system may involve: route changes, relocation of stops, construction of integrated multi-modal transfer terminals, fleet reassignment, better coordination of schedules, and many others. As a result different variants – transportation solutions for the public transportation system can be constructed. The proposed variants should be evaluated and the best/most desired option should be selected. There are several approaches and methodologies which carry out such an evaluation, including: cost-benefit analysis (CBA) (Nickel et al, 2009), cost-effectiveness analysis (CEA), regional economic impact study (REIS), environmental impact assessment (EIA) (De Brucker et al, 2011) and Multiple Criteria Analysis (MCA) (Levine, Underwood, 1996; Żak et al, 2014).

It is very common that during the redesign process the analysts face the challenge to consider the interests of different stakeholders and find solutions that would balance these interests accordingly. In public transportation the major groups of stakeholders include (Żak, Fierek, 2007): local authorities, operators of public transportation system, passengers and local community. In many cases the expectations of these groups are in contrast and a comprise must be found to satisfy them to a certain extend. For these reasons MCA, often called MCDM/A, gains increasing popularity among the above mentioned methodologies as a tool of evaluation of transportation projects, solutions and system (Lee, 2000, Novak et al, 2012; Żak, Thiel, 2001).

In this paper the authors have presented the methodology of designing and evaluating alternative variants of the tram transportation system. They have focused their analysis on a comprehensive, multiple criteria evaluation of the generated variants and have shown how the evaluation of the tram public transportation system should be performed. The authors have developed a universal, consistent family of criteria that can be applied to evaluate different redesign variants of the public tram transportation system including different expectations of the Decision Maker (DM) - local authority and various stakeholders such as: passengers, operator and local community. They have also presented how to model the DM's and stakeholders' preferences and how to generate rankings of the designed variants. In the computational phase they have proven the applicability of two MCDM/A methods: AHP and ELECTRE III/IV to the evaluation of the public tram transportation systems.

The authors have made an attempt to answer the following research questions: Which of the two applied methods - AHP or Electre III/IV - is more useful for the evaluation of the redesign variants of the public tram system? What are the major similarities and differences between AHP and Electre III/IV methods in terms of: defining and scaling criteria, modeling preferences, generating final results? How the generated rankings compare to the intuitive decisions made by local authorities (government)?

The paper is organized as follows. The first section provides general background for the performed analysis. The second section introduces the readers into MCDM/A methodology, with particular emphasis on description of AHP and Electre III/IV methods. The following section presents the considered decision problem statement. Section four shows computational experiments and their results, which are compared results to the intuitive decision made by the local authorities. In the last section the authors formulate conclusions and the further directions of the research.

2. Multiple Criteria Decision Making/Aiding in Public Transportation

MCDM/A (Steuer, 1977; Vincke, 1992; Żak, 2005; Ehrgott, 2005; Belton, Steward, 2003) is a field of study that concentrates on solving the so called multiple criteria decision problem, i.e. a situation in which, having defined a set of actions/variants/solutions ***V*** and a consistent family of criteria ***F*** the DM tends to (Vincke, 1992):

- determine the best subset of actions/variants/solutions in ***V*** according to ***F*** (choice problem),
- divide ***V*** into subsets representing specific classes of actions/variants/solutions, according to concrete classification rules (sorting problem),
- rank actions/variants/solutions in ***V*** from the best to the worst, according to ***F*** (ranking problem).

The MCDM/A methodology distinguishes major stakeholders of a decision process: a DM, an analyst and interveners. In the multiple criteria based decision making process the interests of these stakeholders are considered and the interaction between them takes place. Due to the complex nature of a multiple criteria decision problems the decision process focused on solving the problem is strongly supported by different, mathematical and computer science methods, called MCDM/A methods. They can be divided into 3 major families: the methods of American inspiration based on the utility function, the outranking methods of the European origin, utilizing the concept of the outranking relation and the interactive methods (Roy, 1990a; Vincke, 1992; Figueira et al, 2005; Żak et al, 2014). The first group includes such methods as: Analitic Hierarchy Process – AHP (Saaty, 1980; Saaty, 2008) and UTilités Additives – UTA method (Jacquet-Lagrèze, Siskos, 1982). Among methods based on the European school one can distinguish: Electre I-IV (Benayoun et al, 1966; Roy, 1990b) and Promethee I and II (Brans, et al, 1986). The last group contains methods focused on the dialogue and interaction with the DM, including: STEM (Benayoun et al, 1971), GDF (Geoffrion et al, 1972), VIG (Korhonen, Laakso, 1986).

In this paper the authors apply and compare two MCDM/A methods: AHP and Electre III/IV. The AHP method is a mathematical algorithm supporting multiple criteria decision making and solving a complex multiple criteria, hierarchical decision problem (Saaty, 2008). The AHP method is based on pair-wise comparisons of analyzed elements of the hierarchy - criteria and variants (on particular criteria) with the application of a grading scale from 1 to 9 (Saaty, 2008). Each grading number – relative weight represents relative strength of the compared element against another and has a compensatory character, i.e.: the value characterizing the less important element (1/2, 1/5, 1/9) is the inverse of the value characterizing the more important element in the compared pair (2, 5, 9). The algorithm of the AHP method focuses on finding a solution for a, so called, eigenvalue problem (Saaty, 1980) on each level of the hierarchy and it can be divided into the following stages (Saaty, 2008):

- Identification of the decision problem. Development of it's hierarchy, including definition of the overall goal, criteria, sub-criteria and variants.
- Defining preferences (relative weights w_r) in the form of matrices of pairwise comparisons of all elements of the hierarchy (1 to 9 point scale) (Saaty, 1980).
- The investigation of the consistency level of the preferential information given by the DM at each level of hierarchy (matrices of relative weights w_r). Calculation of consistency indexes CI ($CI < 0.1$).
- Computation of a set of vectors containing normalized values of absolute weights $\boldsymbol{w_a}$ for criteria, sub-criteria and variants, summing up to 1 (100%).
- Aggregation of the absolute weights $\boldsymbol{w_a}$ by an additive utility function. Computation of the utility of each variant $\boldsymbol{i} – \boldsymbol{U_i}$ which defines its position in the final ranking.

The final result of the AHP method is a ranking of variants from the best to the worst constructed based on the computed values of the variants' utilities. More detailed description of the AHP method can be found in several publications (Chan et al, 2006; Vaidya, Kumar, 2006; Lei, Guanghe, 2010).

Electre III/IV method belongs to a larger family of Electre methods (Roy, 1990b) and focuses on solving a multiple criteria ranking problem, based on the application of the outranking relation. Electre III/IV method enables ordering a finite set of variants from the best to the worst. The ranking of variants is generated as a result of their evaluation on a family of criteria F, and with the application of preferential information submitted by the DM. The computational algorithm of the Electre III/IV method consists of three stages (Żak, 2005):

- Definition of a set of variants $\boldsymbol{V}$ and a consistent family of criteria $\boldsymbol{F}$ combined with construction of an evaluation matrix. This stage is also focused on definition of the DM's preference model. The preferential information is defined in the form of criteria weights - $\boldsymbol{w}$ and the indifference - $\boldsymbol{q}$, preference - $\boldsymbol{p}$ and veto - $\boldsymbol{v}$ thresholds.
- Determination of the outranking relation $\boldsymbol{S(a,b)}$, which indicates the extent to which "$\boldsymbol{a}$ outranks $\boldsymbol{b}$" overall. This relation is expressed by the degree of credibility $\boldsymbol{d(a,b)}$, being an equivalent of the global concordance indicator $\boldsymbol{C(a, b)}$ constructed in the concordance test weakened by the discordance indexes $\boldsymbol{D_j(a,b)}$ constructed in discordance test**.** The values of $\boldsymbol{d(a,b)}$ are from the interval [0,1].
- Exploitation of the outranking relation $\boldsymbol{S(a,b)}$. Based on the computation of $\boldsymbol{d(a,b)}$ the method establishes two preliminary rankings (complete preorders) using a classification algorithm (distillation procedure). During this procedure one can obtain a descending and an ascending preorder. The final ranking is generated in the form of the ranking matrix or the outranking graph as an intersection of the above mentioned complete preorders. The following situations can be distinguished there: indifference **(I)**, preference **(P)**, lack of preference **($\mathbf{P^-}$)** and incomparability **(R)**.

More information about the Electre method can be found in the works of Roy and others (Roy, 1998; Roy, 1996; Roy, 1982; Figueira, Roy , 2002; Vincke, 1992; Figueira et al, 2005).

3. The considered decision problem

3.1. Problem statement

The decision problem considered in this paper results from the comprehensive analysis of the public transportation system in a medium-sized metropolitan area (Gorzow city in Poland). The system is based on buses and trams. It is substantially imbalanced in terms of the modal split; the dominating component is bus transportation sub-system (85% of the vkm covered). As opposed to the bus sub-system (36 lines) the tram sub-system is underdeveloped and is composed of 3 lines, only. The bus sub-system covers the area of 80 km^2 and it connects major parts of the city, while the tram sub-system is very fragmented. The average age of the bus fleet is 14 years, while the average age of tram fleet equals 47 years. All buses are adapted for disabled, the elderly and parents with small children while no trams satisfy the needs of these kinds of passengers.

Due to its fragmentation, low accessibility and low reliability many passengers complain about the standard of travel by the tram transportation system. They claim that tram routes are located at some distance (more than 500 meters) from the major housing estates inhabited by about 40,000 people. A shortage of direct connections between major parts of the city and an inconvenient tariff system result in residents being reluctant to use the current network of trams in favor of bus or individual transportation. In addition, passengers complain about low availability of the tram cars combined with their low reliability and poor level of the comfort of travel. For the same reasons the operator is also concerned. It realizes that tram system generates substantial on-going expenditures for fleet and infrastructure repairs and maintenance. It is clear for the operator that tram fleet is underutilized and generates a high level of empty vehicle-kilometres. Local authorities are aware that leaving the tram system in its present form may result in a drastic reduction in demand for this type of transportation, substantial increase of the cost of maintenance of rolling stock and traction, and ultimately may contribute to the elimination of the tram transportation system in the city.

In these circumstances the City Board undertook a project of a comprehensive redesign of the tram transportation system and elaborated a set of alternative transportation solutions to support the transformation of the tram system. The proposed solutions have been designed heuristically by experts (Gromadzki, 2013). In order to develop the variants expectations of different stakeholders have been taken into account, including the interests of local government, operator, passengers and local residents (community). In addition the evaluation of variants have been carried out with emphasis on various aspects including technical, economic, social and environmental perspectives. Thus, all these elements have been included in the formulation of a consistent family of 11 criteria. In the decision making process local authorities play an important role of a DM. The main objective of the DM is to improve the quality of life in the city and provide an efficient and effective public transportation system.

3.2. Construction of variants

As presented in the *Problem Statement* (section 3.1) the 10 considered variants, denominated by V0 – V9 represent different concepts and scenarios of the redesign of the public tram system in a medium-sized metropolitan area (Gorzow city in Poland, Gromadzki, 2013).

Variant 0 (V0) represents the existing public transportation system. The system is based on trams and buses, and delivers service to approximately 125,000 inhabitants. It covers the area of 110 km^2, including: 85% of the area covered by buses and 15% of the area covered by trams. The bus sub-system is composed of 36 routes of the total length of 432 km, while the tram sub-system includes 3 routes with the total track length of 25 km. The bus and tram fleet is on average 16 and 28 years old, respectively. The number of vehicle-kilometres covered by the bus system is 5,002 vkm (84%) and 913 vkm (16%) by trams. The headways on main tram routes are 7.5 and 15 min. in peak and off-peak hours, respectively.

Variant 1 (V1) represents a concept of slight changes implemented in the existing public transportation system. The newly designed solutions focus on reaching one of the largest housing estates in the city. On the one hand this is a convenient solution for residents of this estate. On the other hand it may cause some difficulties related to the removal of the eastern belt of allotments. Moreover, the planned route extensions run in direct contact with residential buildings. Variant V1 covers the same area as Variant V0 but the share of area covered by trams increases in this variant to 18%. The bus sub-system is composed of 34 routes with a total length of 406 km, while the tram sub-system includes 4 routes whose total track length equals 34 km. There are 65 buses and 45 tram cars operating in the system. The bus and tram fleet is on average 15 and 22 years old, respectively. The number of vehicle-kilometres covered by the bus system is 4,603 vkm (73%) and 1,673 vkm (27%) by trams. The headways on main tram routes are 6.5 and 13 min. in peak and off-peak hours, respectively.

Variant 2 (V2) represents a similar to variant V1 concept of slight changes implemented in the existing public transportation system. The newly designed solutions focus on reaching the largest housing estates and the regional hospital. The introduction of the new tram route, connecting the city center with the hospital, generates certain difficulties in the neighborhood of the hospital where traction would be directly adjacent to the roadway. Variant V2 covers a similar area as variant V1, including bus sub-system and tram sub-system coverage. The bus sub-system is composed of 34 routes with the total length of 411 km, while the tram sub-system includes 4 routes whose total track length equals 32 km. There are 65 buses and 45 tram cars operating in the system. The fleet average age is as in V1. The number of vehicle-kilometres covered by the bus system is 4,645 vkm (75%) and 1,590 vkm (25%) by trams. The headways as in variant V1.

Variant 3 (V3) introduces radical changes in the public transportation system. This variant represents a combination of two previous propositions of variants V1 and V2. Therefore, the difficulties encountered in the previous two variants will be present, again in this variant. Variant V3 covers the same area as Variant V0 but the share of area covered by trams increases in this variant to 25%. The bus sub-system is composed of 33 routes with the total length of 393 km, while the tram sub-system includes 5 routes whose total track length equals 37 km. There are 63 buses and 50 tram cars operating in the system. The bus and tram fleet is on average 15 and 20 years old, respectively. The number of vehicle-kilometres covered by the bus system is 4,476 vkm (70%) and 1926 vkm (30%) by trams. The operating headways on the principal tram routes are: 7.5 minutes and 15 minutes during peak and off-peak hours, respectively.

Variant 4 (V4) represents moderate changes in the existing public transportation system, corresponding to slightly more extended concepts and transportation solutions as in variant V1. It is proposed in this variant to expand the tram transportation system in a similar way to variant V1 with an introduction of an additional route running from the eastern part of the largest housing estate to the city center. As a result the total number of tram routes in variant V4 increases to 5. However, the planned city centre revitalization may exclude this additional route from the utilization for a period of time. Variant V4 covers the same area as variant V0 but the tram sub-system coverage increases in this variant to 20%. The bus sub-system is composed of 33 routes with the total length of 406 km, while the tram sub-system includes 5 routes whose total track length equals 36 km. There are 65 buses and 46 tram cars operating in the system. The fleet average age is as in V1. The number of vehicle-kilometres covered by the bus system is 4,612 vkm (74%) and 1654 vkm (26%) by trams. The operating headways on the principal tram routes are 8 minutes and 16 minutes during peak and off-peak hours, respectively.

Variant 5 (V5) represents a similar to variant V4 moderate changes in the existing public transportation system. In variant V5 the extension of the tram sub-system to 5 routes is proposed. This envisages introduction of a new tram line running from the western part of the largest housing estate to the city centre is envisaged. Again, the planned city centre revitalization may exclude this additional route from the utilization for a period of time. Variant V5 similarly to variant V4 covers the same area of both the tram and bus systems. The latter is composed of 33 routes with the total length of 411 km, while the former includes 5 routes whose total track length equals 34 km. There are 66 buses and 45 tram cars operating in the system. The age of the fleet is at the same level as in variant V4. The number of vehicle-kilometres generated by buses and trams are 4,654 vkm (75%) and 1,571 vkm (25%), respectively. The operating headways on the principal tram routes are 8 minutes and 16 minutes during peak and off-peak hours, respectively.

Variant 6 (V6) being a combination of two previously proposed variants, V4 and V5, represents the most radical changes in the public transportation system. Therefore, in this variant the same difficulties as presented in variants V4 and V5 are anticipated. Variant V6 covers the same area as variant V0 but the tram sub-system coverage increases to 35%. The bus sub-system is composed of 31 routes with the total length of 389 km, while the tram sub-system includes 7 routes whose total track length amounts to 39 km. There are 62 buses and 50 tram cars operating in the system. The average age of the bus and tram fleet is 14 and 20 years, respectively. The number of vehicle-kilometres covered by the bus system is 4,432 vkm (69%) and 2015 vkm (31%) by trams. The operating headways

on the principal tram routes are: 7.5 minutes and 15 minutes during peak and off-peak hours, respectively.
Variant 7 (V7) represents a limited edition of variant V1, which is simple to implement, but not necessarily beneficial for the passengers. This variant introduces an extension of the existing tram transportation network to the east-southern part of the largest housing estate. Variant V7 covers the same area as variant V0, including the tram coverage that remains at this variant at the level of 15%. The bus sub-system is composed of 34 routes with the total length of 415 km, while the tram sub-system includes 4 routes whose total track length is 31 km. 66 buses and 43 tram cars operate in the public transportation system envisaged by variant V7. The average age of the bus fleet is 15 year, while the age of the tram cars is 23 years. The number of vehicle-kilometres covered by the bus system is 4,691 vkm (76%) and 1,497 vkm (24%) by trams. The operating headways on the principal tram routes are 7 minutes and 14 minutes during peak and off-peak hours, respectively.
Variant 8 (V8) represents a concept based on a reduced public tram transportation system. In this variant the tram routes through the city center are replaced by an eco-friendly bus transportation system. Therefore, the problem of movements within the city center during the revitalization period is avoided. At the same time citizens living in the largest housing estate do not have access to the tram transportation system. Variant V8 covers the same area as variant V0 but the tram coverage decreases in this variant to 5%. The bus sub-system is composed of 37 routes with the total length of 480 km, while the tram sub-system includes only 1 route whose total track length is 18 km. A total of 77 buses and 28 tram cars operate in the system. The bus fleet has an average age of 14 years. At the same time the tram cars are more than 23 years old. The number of vehicle-kilometres covered by the bus system is 5,451 vkm (91%) and 530 vkm (9%) by trams. The operating headways on the principal tram routes are 10 minutes and 20 minutes during peak and off-peak hours, respectively.
Variant 9 (V9) represents a combined concept of changes implemented in the existing public transportation system. This variant includes selected solutions presented in variants V1 and V8. Similarly to variant V8 the tram routes in the city center are replaced by the electric buses. At the same time a tram transportation network in the eastern part of the largest housing estate is introduced (as presented in variant V1). This variant is compatible with the city revitalization plans and the extension of the tram route allows the largest housing estates to be reached. Unfortunately, this option raises some difficulties as presented in variant V1. Variant V9 covers the same area as variant V0 but the tram coverage decreases in this variant to 7%. The bus sub-system is composed of 36 routes with the total length of 445 km, while the tram sub-system includes 4 routes whose total track length is 18 km. There are 72 buses and 38 tram cars operating in the system. The average age of the bus fleet is 15 years, while the age of the tram cars is over 26 years. The number of vehicle-kilometres covered by the bus system is 5,052 vkm (82%) and 1,119 vkm (18%) by trams. The operating headways on the principal tram routes are 8 minutes and 16 minutes during peak and off-peak hours, respectively.

3.3. Definition of the family of criteria

Based on a thorough literature review the authors constructed a consistent family of 11 criteria (C1 – C11) that allow the evaluation of the proposed redesign variants of the public tram system (Żak, Fierek, 2007; Lee, 2000; Masser et al, 1993; Novak et al, 2012). 6 criteria: C4, C5, C6, C7, C9, C11 are formulated as single, while the 5 remaining ones: C1, C2, C3, C8, C10 include 2-3 sub-criteria. Criterion C10 is a particular case, which consists of 2 sub-criteria and 4 sub-sub-criteria.
The proposed criteria represent the interests of various stakeholders. Criteria C1, C2, C3, C4 and C5 express passengers' expectations, while criteria C9, C10 and C11 correspond to the interests of the local community. The local authorities' and the operator's points of view are represented by criteria: C6, C7 and C8. All criteria are presented in table 1 and are computed based on forecasts for 2025.

Table 1. The evaluation matrix of ten different redesign variants of the public tram system

Criteria		Variants									
		V0	V1	V2	V3	V4	V5	V6	V7	V8	V9
C1. Accessibility of the tram transportation system	C1.1. The total length of the tram network to the area of the city [km/km^2], maximized	0,29	0,39	0,37	0,43	0,42	0,39	0,46	0,36	0,21	0,21
	C1.2. The share of tram cars and buses adapted for the disabled and the elderly, [%], maximized	79,8	80,9	80,9	81,4	80,9	81,1	81,3	80,7	86,7	80,9

	C1.3. Total average daily number of tram cars operating in the city per 1000 inhabitants, [-], maximized	0,11	0,17	0,17	0,20	0,17	0,17	0,20	0,15	0,07	0,13
C2. Reliability of the public transportation system [%]	C2.1. Share of rides carried out according to a timetable, [%], maximized	95	94	94	96	94	94	96	95	95	96
	C2.2. Share of rides carried out in a timely manner, [%], maximized	82	84	84	85	84	84	85	84	81	83
C3. Quality of the means of transport	C3.1. Brand new tram cars introduced to the system, [%], maximized	13,5	21,8	21,8	25,7	21,8	21,6	25,9	20,2	13,3	15,5
	C3.2. Modernized tram cars as percentage of the total rolling stock, [%], maximized	17,3	16,4	16,4	15,9	16,4	16,2	16,1	16,5	11,4	10,9
	C3.3. Average age of tram cars, [years], minimized	28	22	22	20	22	22	20	23	23	26
C4. Waiting time, [minutes], minimized		4	3	3	4	4	4	3,5	3,5	5	4
C5. Directness of connections, [-], maximized		8	11	11	13	13	13	17	11	3	5
C6. Investment costs, [mln zl], minimized		129	300	275	395	312	287	407	246	185	252
C7. Annual operating costs of the tram transportation system, [mln zl], minimized		41	43	43	44	43	43	45	43	41	42
C8. Efficiency	C8.1. Number of passengers per vehicle-kilometer in the tram transportation system, [-],maximized	8	5	4	4	7	6	9	3	8	8
	C8.2. Tram fleet utilization rate, [%], maximized	20	21	18	25	20	18	25	21	21	19
C9. Social sustainability of the considered tram transportation system, [points], maximized		2	5	5	7	6	6	8	3	2	4
C10. Environ-mental friendliness	C10.1. The impact of the public transporta-tion system on environment – C10.1.A. Average level of CO emission, [g/km], minimized	1,76	1,52	1,52	1,41	1,52	1,54	1,38	1,57	1,86	1,70
	C10.1.B. Average level of HC emission, [g/km], minimized	0,43	0,36	0,36	0,33	0,36	0,37	0,33	0,38	0,43	0,41
	C10.1.C. Average level of NOx emission, [g/km], minimized	2,71	2,29	2,29	2,11	2,29	2,33	2,06	2,38	2,72	2,58
	C10.1.D. Average level of PM emission [units/kWh], minimized	92	71	71	65	71	73	63	74	92	87
	C.10.2. Share of vehicle-kilometers covered by tram cars and electric buses in all vehicle-kilometers, [%], maximized	15	27	26	30	26	25	31	24	18	21
C11. Nuisance associated with the implementation of particular variants, [points], minimized		1	7	6	8	7	7	9	3	2	7

4. Computational experiments

Computational experiments have been conducted with the application of Electre III/IV and AHP methods (described in section 2). The experiment carried out with the application of the AHP method has been based on the source, raw data, presented in the evaluation matrix (table 1). The application of the Electre III/IV required that for all criteria containing sub-criteria the original data have been normalized and transformed into a 0-1 interval. In the next step the models of DM's preferences for the Electre III/IV and AHP methods have been developed. They are presented in tables 2 and 3, respectively. In the Electre III/IV method the importance of the individual criteria have been determined by weights – w on the linear scale (0-20 points), while in the AHP method it has been defined with the application of relative weights w_r (on the scale 1 to 9), through pairwise comparisons of criteria. Seven criteria are maximized (value +1 in table 2) while the remaining 4 are minimized (value -1 in table 2).

The sensitivity of the DM in the Electre III/IV method has been indicated by the values of thresholds: q, p, v, while in the AHP method by pairwise comparisons of variants on particular criteria on the 1 to 9 scale. In the latter case the variants V0 – V9 have been pair – wise compared for each criterion. As a result similar matrices to the one presented in table 3 have been constructed. Using the computational procedure of Electre III/IV and AHP methods (described in section 2) two final rankings, presented in figure 1, have been generated.

Table 2. The model of the DM's preferences characteristic for the Electre III/IV method

Criterion	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
Weight (w)	18	20	12	8	4	15	16	14	10	6	2
Preference direction	1	1	1	-1	1	-1	-1	1	1	1	-1
Indifference (q)	0,12	0,1	0,1	1	2	15	1	0,1	2	0,1	2
Preference (p)	0,3	0,3	0,3	3	5	50	4	0,4	6	0,4	6
Veto (v)	0,53	0,7	0,75	5	10	250	10	0,9	16	0,9	18

Table 3. The model of the DM's preferences characteristic for the AHP method. Pairwise comparisons of criteria

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	w_r (%)
C1	1	0.50	4.00	5.00	7.00	2.00	2.00	3.00	5.00	6.00	8.00	0,188
C2	2.00	1	5.00	7.00	8.00	3.00	3.00	4.00	6.00	7.00	9.00	0,266
C3	0.25	0.20	1	3.00	5.00	0.33	0.33	0.50	2.00	3.00	5.00	0,064
C4	0.20	0.14	0.33	1	2.00	0.25	0.25	0.33	0.50	2.00	3.00	0,033
C5	0.14	0.12	0.20	0.50	1	0.17	0.17	0.20	0.33	0.50	2.00	0,02
C6	0.50	0.33	3.00	4.00	6.00	1	1.00	2.00	4.00	5.00	7.00	0,128
C7	0.50	0.33	3.00	4.00	6.00	1.00	1	2.00	4.00	5.00	7.00	0,128
C8	0.33	0.25	2.00	3.00	5.00	0.50	0.50	1	3.00	4.00	6.00	0,087
C9	0.20	0.17	0.50	2.00	3.00	0.25	0.25	0.33	1	2.00	4.00	0,043
C10	0.17	0.14	0.33	0.50	2.00	0.20	0.20	0.25	0.50	1	3.00	0,027
C11	0.12	0.11	0.20	0.33	0.50	0.14	0.14	0.17	0.25	0.33	1	0,015

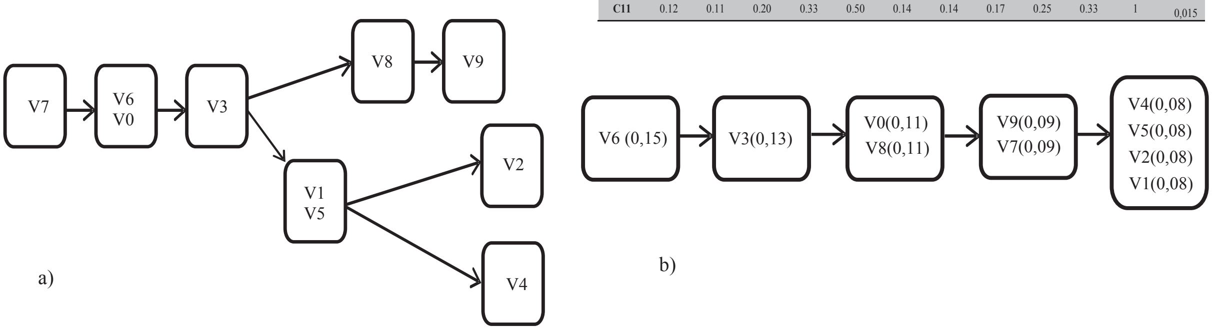

Fig. 1. Final ranking of the redesign variants of the public tram system generated by (a) Electre III/IV and (b) AHP methods

Looking at the results of computational experiments carried out with the application of both methods one may easily discover that they are not identical. Both rankings have different winners: V6 (AHP) and V7 (Electre III/IV). At the same time they both support the selection of three variants: V6, V0 and V3 (upper positions in both rankings). The most significant differences between the results of two computational experiments refer to variants V7 and V9. The former is the leader of the ranking generated by Electre III/IV method and it is placed in the middle – lower part of the ranking generated by the AHP method. The latter is located in the middle – lower part of the ranking generated by the AHP method and at the same time it is considered to be the weakest candidate in the ranking generated by the Electre III/IV method. As far as the reminder of variants is concerned (V1, V2, V4, V5 and V8) they can be found as similarly placed by both methods.

Some of the differences between the final rankings result from methodological assumptions of the two considered methods. The natural feature of Electre III/IV method is that in its final ranking one can distinguish the following relationships between variants: preference (P) – one variant is placed above another (e.g. V7 and V6 together with V0), indifference (I) – variants are placed in the same box (e.g. V1 and V5) and incomparability (R) – variants are not interconnected (e.g. V2 and V4 and V8). In the final ranking generated by the AHP method only two situations can be differentiated: preference (P), when the utility of the preferred variant is larger than the utility of the second variant – e.g. V6 against V3; indifference (I), when the utilities of compared variants (after rounding) are equal – e.g. V0 and V8.

Based on the generated results one may select a set of variants being placed at the upper positions in both rankings, including variants V6, V3 and V0. These variants are the strongest and highly recommended solutions. In this set, variant V6 seems to be the best option for the redesign of the public tram system. It comes out on top of the ranking generated by the AHP procedure and it is placed at the 2nd position in the ranking generated by Electre III/IV method. It represents the most radical transformation of the tram transportation system and features the most extensive development of the tram network. V6 receives the highest scores on 15 out of 21 criteria and sub-criteria. It can be considered as efficient and passenger – oriented variant that guarantees high transportation standards. It is surprising that two variants – V6 and V0, representing opposite approaches to the tram system transformation, have received similar overall assessments.

It is important to point out that variant V9, which has attained one of the lowest positions in this group of variants, has been selected for implementation by local authorities. It is surprising that local Town Hall has selected the variant that has been poorly assessed on many criteria, including: C1 - Accessibility, C3 - Quality of the means transport, C5 - Directness of connections or C10 - Environmental friendliness. This discrepancy clearly demonstrates the difference between intuitive, subjective decision making processes and their equivalents based on rigid reasoning and quantitative oriented, advanced decision making methodologies.

5. Conclusions

The paper presents the original methodology that has been developed to support DM-s in redesigning and evaluating a public tram system. In order to select the best/compromise solution the authors have applied MCDM/A methods: Electre III/IV and AHP. Ten considered variants (V0-V9) have been developed and evaluated according to 11 criteria. The family of criteria has represented different stakeholders' expectations, and has included various aspects of the considered decision problem, such as: technical, economic, social and environmental.

Both methods, AHP and Electre III/IV, are universal and generate rankings of the variants – alternative solutions of the public tram system. However, each method possesses certain advantages and disadvantages. The AHP method presents the decision problem in a hierarchical form, which provides its transparent structure with all considered components. It allows taking into account both criteria and sub-criteria in the evaluation of variants based on the original raw data. The AHP method concentrates on finding a solution based on the variants' utilities – U_i which constitute their numerical assessments in the final ranking. This characteristic enables the DM to recognize the distance between particular variants and estimate the level of advantage of one option against another. On the other hand, the AHP method is time-consuming and difficult to apply for complex decision problems with a large number of variants and criteria. The definition of the DM's preferences based on pair-wise comparisons of the elements of hierarchy is both labor – intensive and error prone procedure. The evaluation of variants on the 1 to 9 scale and the multiplicative formula of defining the DM's preferential judgments may cause certain inconsistencies, which may eventually give rise to the generation of certain inaccuracies in the final results The Electre III/IV method is less flexible in terms of handling the formulation of the decision problem. In addition if sub-criteria are required in the problem formulation they must be aggregated and expressed as normalized values. At the same time Electre III/IV method enriches possible options of distinguishing mutual relations between variants to include: preference (P), indifference (I) and incomparability (R). The presented research concerning public tram system has revealed its practical meaning and applicability. The final ranking generated by Electre III/IV method has a graphical form only and does not include numerical evaluations of variants. In such circumstances the DM can see what the position of a particular variant in the ranking is but cannot directly assess the distance between variants in quantitative terms. The strength of the Electre III/IV method is the proposed way of constructing the DM's preference model, based on weights of criteria w and thresholds q, p, v. Thanks to that the definition of the DM's preferences is less time-consuming and guarantees that the DM can model his / her preferences with more precision and in a more realistic way.

From a practical point of view the results of this paper have showed that the multiple criteria evaluation of the redesign variants of the public tram system has generated different results than the intuitive decision process which has been carried out in the local Town Hall. Variant V9, selected by local authorities for implementation, has obtained one of the lowest positions in both rankings. The authors support the radical transformation of the public tram system presented in variant V6. This variant has obtained the best overall evaluations, being placed at the top and second positions in both rankings, generated by the AHP and Electre III/IV method, respectively.

Further research should be conducted in the following areas: utilization of other MCDM/A methods to evaluation of a public tram system, extension of the analysis into the whole public transportation system and application of the combined MCDM/A and Group Decision Making (GDM) methodologies to the selection of the most rational variant of the public transportation system redesign.

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