

# COMBINED OPTIMISATION AND MCDA BASED SOLUTION OF THE TRAM DEPOT LOCATION PROBLEM

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## Abstract:

*This paper deals with an issue of technical facilities location in a public transport system. The decision problem is formulated as a selection of the most advantageous alternative, i.e. the location of a new tram depot among the already existing facilities of this type. The selection is preceded by the evaluation of the alternatives. The assessment is not a trivial task, because there are many groups of interest with usually contradictory points of view. Therefore, the evaluation of the new tram depot locations should represent different aspects, e.g., economical, technical, environmental, and organizational. To handle such a complex decision problem the authors propose a methodology, which is a composition of the optimisation and multiple criteria evaluation techniques. The developed methodology is experimentally applied to the selection of one out of five tram depot locations in the public transport system of the city of Poznan, Poland. All the computational experiments are performed by means of optimization and multiple criteria decision aiding (MCDA) methods and tools, i.e. a linear optimization engine Solver Premium Platform and AHP method with its application AHORNsimple. The calculations are the basis for recommending the location of a new depot in the central part of the transport system network, which is a reasonable solution taking into account, e.g. the proximity of the main railway line, the possibility of triple distribution of the transport means from depot. The proposed methodology of the decision problem solution gives also an opportunity to create the hierarchy of considered tram depot locations as well as to compare the position in the ranking of the best solution with the existing one. Since the proposed methodology assumes the selection of the most suitable MCDA method to the problem under consideration and the decision maker's preferences, it guarantees that the result of analysis becomes reliable and the decision aiding process is credible.*

**Keywords:** tram depot location problem, multiple criteria decision aid (MCDA), combinatorial optimisation, AHP method, AHORNsimple application

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## 1. Introduction

Public passenger transport in urban areas is carried out either with buses, trams, the underground, and trains. Their operation and availability for efficient performance of transportation tasks needs an extra space for the location of technical facilities such as vehicle depots. The main task of such depots is to park the fleet and ensure all the facilities necessary to perform the maintenance and repair of the vehicles. Therefore, a sufficient space for storage, manoeuvring and dispatching of the vehicles to the transportation lines has to be assigned. Moreover, an impact of such a depot and a transportation system itself on the environment, society, operational and safety factors is also crucial (see e.g. Jacyna *et al.*, 2018; Rudyk, Szczepański & Jacyna, 2019; Laport, Nickel & Saldanha da Gama, 2015). Thus, a determination of a location, size, and scale of the technical facilities in the depot becomes a very complex issue.

On the one hand, due to the nature and structure of the transport lines passing through central parts of urbanized areas, it would be most advantageous to locate such depots in the vicinity of city centres. This would ensure high availability of the depot to most transport lines and, at the same time, minimize the distance with empty runs of vehicles at the beginning and at the end of the day. This aspect can be discussed on the basis of systems theory and modelled using graph theory (e.g. Żochowska & Soczówka, 2018). On the other hand, due to financial considerations finding a suitable plot of land on densely urbanised areas is either impossible or it could generate extraordinary investment costs (e.g. Musso & Sciomachen, 1997). The issue is thus to reach a compromise between the needs and possibilities of making the location decision.

The authors of this article deal with the problem of depot location that could serve the fleet of trams in the urban area. The decision problem is to find the best location of a new depot, which will replace the existing one. This case is characterized by several significant limitations. Firstly, a current track structure has a huge influence on the location decision, i.e. the new depot should be as close as possible to the existing infrastructure. Secondly, the availability of potential plots of land next to the track structure is highly limited. Moreover, the selection of the tram depot should be preceded by the evaluation of potential locations, including different aspects, such as:

economical, technical, environmental, and organizational. They can represent contradictory points of view, thus a compromise solution should be found. Combining an optimal allocation of transport means or transport lines to individual depots and a multiple criteria evaluation of such solutions becomes a crucial part of the research. Based on the literature review presented in the next section this approach has not been discussed. Therefore, it constitutes the gap to be fulfilled by the proposal of a tram depot location methodology verified on the real-world example. This is also the aim of the presented research.

## 2. State-of-the-art of technical facilities location in public transport systems

In the literature, the problem of depot location is highly explored with respect to freight transport and distribution systems (see e.g. Drezner & Hamacher, 2004; Melo, Nickel & Saldanha da Gama, 2009; Szczepański *et al.*, 2019). There are numerous papers dealing with passenger transport, mostly concentrated on the fleet dispatching problem, e.g. Hamdouni, Desaulniers & Soumis (2007); Hamdouni, Soumis & Desaulniers (2007). Such a problem is related to the location of the depot, however, the key issue is to find the best solution in dispatching the fleet.

There is also a considerable number of research papers concentrated on optimisation of a bus depot location or so the called a garage location in urban areas. The function of such garages is to minimise empty bus runs, also called dead mileage, between the depots in the potential locations and the bus stops on the operated lines, e.g. Musso & Sciomachen (1997), Al Ali & Hassan (2018), He, Wang & Zhang (2019).

The extended version of a considered bus depot location problem can also assume the allocation of busses to the existing depots, e.g. Kontou *et al.* (2014), Mahadikar, Mulangi & Sitharam (2015). Since the general concept of the bus depot location problem is similar to the tram depot location issue, principally, some differences exist in the problem formalisation, its solution procedure and area of application. Musso & Sciomachen (1997) express their formulation with mixed integer-linear programming (MILP), constrained by the number of available depots and the number of lines possibly allocated to a single depot. The problem is solved by Lindo solver for Genoa, Italy. A similar formulation is also ap-

plied by He, Wang & Zhang (2019) and it is validated in Xi'an, China. In the research of Al Ali & Hassan (2018), the depot location problem is the subject of considerations concentrated on the availability of maintenance resources in the depot. The problem is formulated with MILP and validated on the transport system in Vancouver, Canada. There are also several studies on the issue of depot location whose objective function is the combination of the cost of empty runs and fixed costs of the depot over time (e.g. Haase *et al.*, 2020).

A group of papers on the so called garage location problem was initiated in 1984 by the research of Ball *et al.* (1984). The solution aims at minimizing the sum of fixed location costs, variable vehicles and crew costs. The optimization model is constructed and solved by an iterative heuristic procedure and a network flow-based algorithm. The last but not least, Chen *et al.* (2021) formulated the problem as a non-linear queuing-location-allocation model with the Lagrangian relaxation algorithm and solved it as a linear one.

In three studies by Sawicki & Fierek, the issue of bus depot location and public transport line construction (2017, 2018a) and the variation of long-term demands (2018b) is considered. The authors proposed a cost-oriented MILP formulation mixed with a macrosimulation four-stage procedure for defining the transportation tasks. The methodology was verified on a medium size public transport system and all computations have been performed with LP Solver and PTV Visum software.

Since the nature of bus depot location problem is similar to different types of mass transit systems, there is a very limited number of studies devoted to the problem of operations management of the tram or rail fleet (e.g. Carrese & Ottone, 2006) and the depot location problem. In the paper presented by Canca & Barrera (2018), a rapid rail transit system is considered, the rolling stock circulation plans are designed and the number and location of the depots is discussed. The problem is iteratively solved using a genetic algorithm. Kim & Kim (2021) in their research determine the optimal location of infrastructure maintenance depot (IMD) for storing special vehicles and to support the inspection and maintenance tasks for urban rail network. In other research, Kupka & Sawicki (2015) deal with the optimisation of tram assignment to the depots with alternative depot configurations. The minimised objective function

is formulated as a cost of everyday empty runs between set of depots and stops within the line. In another publication by Sawicki & Kupka (2016) the problem of tram depot location is discussed. The authors formulate the problem as a multiple criteria ranking of variants. Considering several variants of tram depot locations, the authors evaluate them by the set of five criteria and three sub-criteria.

Based on the literature review carried out, the following conclusions are drawn:

- Depot location in public transport systems is an extensively discussed decision problem, especially regarding the issue of bus transport system, with fewer studies dealing with tram transportation network.
- The depot location is a multiple criteria problem as it does not only consider the cost, but several other important criteria. Therefore, to handle such a complex decision problem, the multiple criteria decision aiding procedure is recommended.
- The problem of depot location using an optimal allocation of transport means or transport lines to individual depots in combination with a heuristic evaluation of such solutions has so far not been applied in the literature. This represents a potential manner of solving the depot location problem, and significantly expands the possibilities for conducting such evaluations.

### 3. Problem formulation

According to many researchers, a comprehensive analysis of a multidimensional decision problem should not only involve quantitative but qualitative criteria, as well. In order to select the best option, it is often necessary to compromise among possibly conflicting tangible and intangible factors. Different optimization models can be proposed to solve a decision problem. Their main advantages include a precise definition of the problem, using exact data in the mathematical model and obtaining a precise solution of the problem. However, optimization techniques have a weak point as the mathematically expressed formulas may ignore both qualitative and subjective considerations while solving decision problems (Xi *et al.*, 2010; Cheng, Chan & Huang, 2003). Another weakness of an optimization, single- or multiple criteria, is that after the result is generated, further analysis may still be required. Usually, to eliminate these disadvantages and to solve complex problems a multiple criteria decision analysis (MCDA)

is proposed. Its main strengths include the ability to cope with many conflicting criteria, the ability to structure the problem and support decision makers in gaining knowledge regarding the problem situation, and finally recommend the compromise solution (Belton & Stewart, 2002). Nevertheless, the formal structure of MCDA methods is ill-defined due to the problem's nature because it is not possible to find the optimal solution, i.e., the best one that takes into account all the considered criteria (Belton & Stewart, 2002; Vincke, 1992). Another important issue that must not be disregarded is subjectivity that is inherent in all decision making (Belton & Stewart, 2002), and may pertain to defining the set of variants, selecting the criteria, and expressing the preferences. Bearing in mind the above advantages and disadvantages, the authors believe that the mathematical programming should be integrated with the MCDA in order to deal with the selection of the tram depot location problem. First, a single objective combinatorial programming model is applied to determine the optimal location of the tram depot at the lowest operational costs. At this stage, several optimal alternatives are generated. Next, the optimal values of decision variables are applied to generate further results with respect to the consistent family of criteria. Finally, all the results are taken into account in the MCDA model in order to select the most satisfactory location of the tram depot.

The proposed methodology is experimentally verified on the real-world transportation network. It is applied to the selection of a new tram depot location in the public transport system in Poznan, Poland. The computational results based on this methodology are finally compared with the decision taken by the city authorities and the investor of a new tram depot.

#### **4. The proposed methodology of solving tram depot location problem**

##### **4.1. The assumptions and key phases of the methodology**

During the operational day, trams circulate on a defined set of transport lines between termini. Each tram that does not perform the transport task is parked at the depot, and the other maintenance activities can also be performed there. This means that every working day each tram rides the route between the depot and the transport line at least twice, i.e., during the morning dispatch from the depot to the line and during evening return from the line to the depot. In addition,

the number of trams on the line during the day may also fluctuate, so the excessive trams have to be returned to the depot and dispatched again when a demand increases. In the proposed research two obligatory rides of each tram during the day, i.e., morning dispatch to the line and return to the depot are considered exclusively. The construction of the transport lines and the location of termini in the transport network are not the subject of the consideration in this research.

According to the definition of a decision problem presented in the previous section, the issue of the technical facility location for the fleet of trams is a primary area of consideration. The location of the tram depot is treated as a problem of ranking alternatives, assuming that the suggested solution is at the top of the order. The alternative is a solution with a defined location of all tram depots in the transportation system to be analysed. All the required infrastructural adjustments performed in the transport system should also be included in each alternative.

The authors propose a methodology to solve the tram depot location problem. It is based on the results of previous research in this area concentrated on exclusive application of single-objective programming (Kupka & Sawicki, 2015) and MCDA (Sawicki & Kupka, 2016).

The proposed methodology consists of 5 key phases, see the structure in Fig. 1, including identification of the key constraints in the depot location problem - Phase 1, designing alternative solutions - a strategy of alternatives' configuration - Phase 2.1, defining the set of evaluation criteria - Phase 2.2, optimising the tram depots' structure - Phase 3.1, evaluating the alternatives with respect to the proposed family of criteria - Phase 3.2, selecting the most suitable decision aiding method - Phase 4, computational experiments and recommendation of the compromise solution, i.e. tram depot location - Phase 5.

##### **4.2. Phase 1 – Identification of key constraints**

The first phase of the procedure is devoted to identification of all crucial restrictions while selecting potential locations of tram depots in the area or in the neighbourhood of the existing transport system. In this phase a specific parcel where a tram depot is located or could be located alternatively is considered. The following constraints are taken into account:

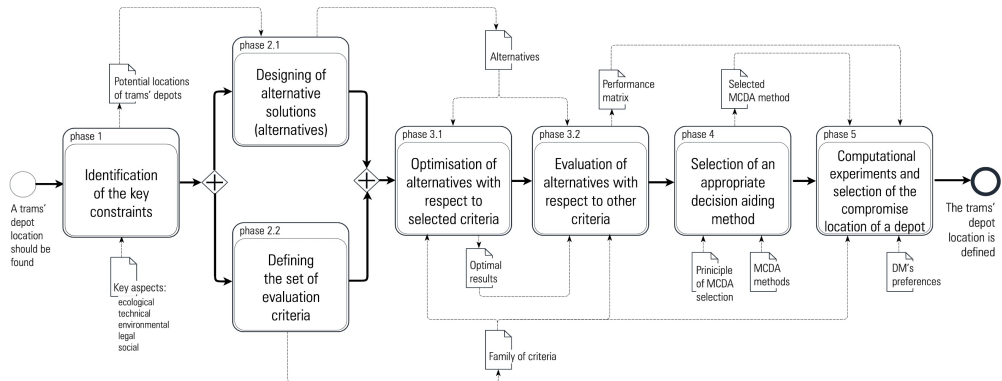


Fig. 1. Key phases of the proposed combined optimisation and MCDA methodology

- economic and finance restrictions, i.e. a budget limitation for the investment program;
- technical issues, i.e. all the required parameters resulting from the available and requested fleet;
- environmental aspects, including noise and vibration impact;
- legal considerations, i.e. legal status of the plots;
- social aspects, i.e. land use, course of the tram lines to meet the demand for travel, etc.

The result of Phase 1 involves a set of potential locations of tram depots in the considered transport network.

#### 4.3. Phase 2.1 – Designing alternative solutions (alternatives)

In the considered problem a set of depot's locations  $i$  ( $i = 1, \dots, I$ ) is considered. By  $i$ -location a specific plot on which the depot is located or could be located is defined. This means that term  $i$ -depot and  $i$ -location can be used interchangeably.

All the available locations are combinatorial configured into the unique solutions, called alternatives. Searching for the most appropriate locations of tram depots in the transport system calls for designing detailed alternatives that can help to determine their impact on all aspects of the decision process to be carried out.

Formally, based on Jacyna (2001), a set of  $r$  ( $r = 1, \dots, R$ ) considered alternatives  $A$  in the decision problem is expressed as:

$$A = \{A_1, \dots, A_r, \dots, A_R\} \quad (1)$$

#### 4.4. Phase 2.2 – Defining a set of evaluation criteria

An assessment of each alternative from  $A$  should be performed using  $F$ , which is a set of  $n$  ( $n = 1, \dots, N$ ) evaluation criteria, called a family of criteria, and formally is expressed by (2).

$$F = \{f_1(A), \dots, f_n(A), \dots, f_N(A)\} \quad (2)$$

The family of criteria covers a wide spectrum of evaluation aspects, mentioned in the previous section. In the tram depot location problem, the meaning of each criterion is as follows:

- $n = 1$ : energy waste  $WE(A_r)$  due to the tram movement between the allocated depot and the operated line in  $r$ -alternative; the criterion is minimised, expressed in [PLN/mth];
  - $n = 2$ : investment cost  $IC(A_r)$  for an additional track construction between the network and the new depot location in  $r$ -alternative; the criterion is minimised, expressed in [PLN];
  - $n = 3$ : operational reliability  $OR(A_r)$  of the whole system in  $r$ -alternative; the criterion is maximised, it is dimensionless [-];
  - $n = 4$ : troublesome location  $TL(A_r)$  of the depot for the environment in  $r$ -alternative; the criterion is minimised, it is dimensionless [-];
  - $n = 5$ : land use  $LU(A_r)$  aspect in  $r$ -alternative; the criterion is minimised, it is dimensionless [-].
- Formally, the family of criteria is expressed by (3).

$$F = \{WE(A_r), IC(A_r), OR(A_r), TL(A_r), LU(A_r)\} \quad (3)$$

The family of criteria  $F$  is composed of two complementary subsets of criteria. The first subset  $F^o$  consists of a single optimization criterion  $WE(A_r)$  with adequate constraints. This criterion is used to determine the best tram allocation among the available depot locations, for each alternative from  $A$ . The optimal allocation of trams with the minimum cost of wasted energy is expected with respect to the following constraints: fleet size, depot capacity and number of depots. The optimal values generated by  $WE(A_r)$  are directly applied to Phase 4 of the methodology, where one of the MCDA methods is applied to select the final solution, and where experiments are carried out. The values of decision variables from the optimal results on  $A$  are the inputs to express the criteria from the second subset  $F^a$  i.e.  $IC(A_r)$ ,  $OR(A_r)$ ,  $TL(A_r)$ , and  $LU(A_r)$ .

Finally, the family of criteria  $F$  is expressed by (4), as:

$$F = F^o \cup F^a \quad (4)$$

where:

$$F^o = \{WE(A_r)\}, \quad (5)$$

$$F^a = \{IC(A_r), OR(A_r), TL(A_r), LU(A_r)\}. \quad (6)$$

The optimisation criterion  $WE(A_r)$  is controlled by two binary decision variables  $y_{ir}$  and  $x_{ijk_r}$ . A variable  $y_{ir}$  in the  $r$ -alternative equals 1 if a depot is in  $i$ -location and 0 otherwise. A variable  $x_{ijk_r}$  equals 1 if in the  $r$ -alternative  $k$ -vehicle operated on a  $j$ -line is assigned to depot's  $i$ -location. This criterion is formulated as a minimised function of energy consumption related to the empty tram movement between the depot and the operated line. Criterion is expressed as (7):

$$WE(A_r) = \min \left( dc \sum_{i=1}^I y_{ir} \sum_{j=1}^J (l_{ij}^s + l_{ij}^l) \sum_{k=1}^K \rho_k x_{ijk_r} \right), \quad (7)$$

$$\forall r = 1, \dots, R$$

subject to:

$$\sum_{i=1}^I \sum_{k=1}^K \sum_{j=1}^J x_{ijk_r} = N, \quad (8)$$

$$\sum_{j=1}^J \sum_{k=1}^K x_{ijk_r} \leq Q_i + \Delta q_i; \quad \forall i = 1, \dots, I, \quad (9)$$

$$\sum_{i=1}^I y_{ir} \leq S, \quad (10)$$

each of (8)-(10) also  $\forall r = 1, \dots, R$ .

where:

- $i$  – index of tram depot location,  $i \in I$ ;
- $j$  – index of transportation line,  $j \in J$ ;
- $k$  – index of the tram operated on a transportation network,  $k \in K$ ;
- $\rho_k$  – energy consumption of  $k$ -tram per unit;
- $c$  – cost of energy consumption per unit;
- $d$  – number of days in the planning horizon;
- $l_{ij}^s$  – distance between gate of  $i$ -depot location and the first stop on  $j$ -line;
- $l_{ij}^l$  – distance between gate of  $i$ -depot location and the last stop on a  $j$ -line;
- $N$  – number of operated trams  $N \subset \mathbb{C}$ ;
- $Q_i$  – total tram depot capacity in  $i$ -location;
- $\Delta q_i$  – a buffer of  $i$ -depot capacity;
- $S$  – maximum number of depots in a transportation system.

The constraint (8) controls the assignment of the fleet of trams operating in the transportation system to the alternatively configured depots' structure. Constraint (9) defines the capacity of  $i$ -depot, that cannot be exceeded. The last constraint (10) determines the maximum number of depots in the transport system, considering the existing and alternative locations.

All the criteria from  $F^a$  are expressed as follows:

$$IC(A_r) = \min \left( \sum_{i=1}^I y_{ir} C_i \sum_{j=1}^J \sum_{k=1}^K x_{ijk_r} \right), \quad (11)$$

$$OR(A_r) = \max \left( P_r \left( \sum_{i=1}^I y_{ir} \sum_{j=1}^J \sum_{k=1}^K x_{ijk_r} \right) \right), \quad (12)$$

$$TL(A_r) = \min \left( E_r \left( \sum_{i=1}^I y_{ir} \sum_{j=1}^J \sum_{k=1}^K x_{ijk_r} \right) \right), \quad (13)$$

$$LU(A_r) = \min \left( U_r \left( \sum_{i=1}^I y_{ir} \sum_{j=1}^J \sum_{k=1}^K x_{ijk_r} \right) \right), \quad (14)$$

each of (11)-(14)  $\forall r = 1, \dots, R$ .

where:

- $C_i$  – investment cost connected with the additional track construction between  $i$ -depot and the transportation network in  $r$ -alternative;
- $P_r$  – reliable aspects of tram depot structure in  $r$ -alternative;
- $E_r$  – environmental aspects of tram depot structure in  $r$ -alternative;
- $U_r$  – land use aspects of tram depot structure in  $i$ -location and  $r$ -alternative.

Criterion  $IC(A_r)$  reflects the cost of all engineering works necessary to join the depot to the existing network, i.e., to build required tracks between the border of  $i$ -depot and the first node in the network. A parameter  $C_i$  is an expert-based calculated cost of required works and materials attached to each  $i$ -location. Three other criteria, i.e.,  $OR(A_r)$ ,  $TL(A_r)$ , and  $LU(A_r)$  help in holistic evaluation of each  $r$ -alternative. Their values are calculated for  $r$ -alternative as optimal decision variables resulted from solving the model upon  $WE(A_r)$  and the applied parameters. The parameters  $P_r$ ,  $E_r$ , and  $U_r$  are expert-based rates to express the following context:

- $P_r$  evaluates the level of the tram depots' configuration within  $r$ -alternative, which allows minimizing the risk for the tram's fleet not to be dispatched on the tracks between the depots and the transport network due to technical problems; the parameter is expressed on an integer scale and its range of variation varies from 1 to 5 pts, where the lowest and the highest values represent the worst and the best solutions, respectively.
- $E_r$  concerns the risk of noise and vibration generated by depots of  $r$ -alternative and assigned trams referred to the nearest neighbourhood; it is expressed on an integer scale and its range of variation varies from 1 to 5 pts, with the highest grade related to the highest impact on the neighbourhood.
- $U_r$  represents the impact of the  $r$ -alternative on the existing urban layout of the territory; it is a measure of coherency between the depots' locations and the type of area development, i.e., the location of the depot in an industrial, residential, and other areas. It is expressed on an integer scale and its range of variation varies from 1 to 5 pts, with the lowest grade related to the lowest impact on the current urban development.

#### 4.5. Phase 3.1 and 3.2 – Optimisation and evaluation of the alternatives with respect to the considered criteria

In Phase 3 (3.1 and 3.2), a quantitative measures for the evaluation of each alternative with respect to the considered set of criteria are collected. The results of both phases finally constitute the matrix of the alternatives' evaluations with respect to each criterion. They are directly applied in Phase 4, and finally for further selection of the compromise solution (Phase 5).

#### 4.6. Phase 4 – Selection of the appropriate decision aiding method

While selecting the most suitable decision aiding method, the convergence between the nature of the method and the decision problem, including the decision maker's preferences, has to be considered carefully. The process of method selection cannot be accidental or based on its popularity in the field of study. Guitouni & Martel (1998) suggest that despite the development of a large number of MCDA methods, none can be considered as the one appropriate to all decision situations. The problem of selecting the most suitable MCDA method to a given decision problem type is considered in the literature (see, Roy & Słowiński, 2013; Sawicka, 2012; Sawicka, 2020). Based on Sawicka (2020), a 4-step procedure has been applied by the authors of this paper, including:

- Step 1: comparative analysis of MCDA methods, including method classification, axiomatic analysis, practical applicability analysis;
- Step 2: recognition of the decision problem, including decision problematics, the structure of decision problem, the availability of information, types and character of information and time horizon of the decision;
- Step 3: identification of the decision maker's preferences, including the level of strategic decision, precision of preference information, preference structure and its expression, the moment of preference expression, the relation between the variants in the final result;
- Step 4: comparison of results and selection of the most suitable MCDA method.

The result of this phase includes the selected MCDA method with the highest coherence with the tram depot location problem, as well as the expression of decision maker's preferences. Based on the analysis,

the suggested MCDA method is Analytic Hierarchy Process - AHP (Saaty, 1980). It is worth to emphasize that since this phase resulted in the selection of the most suitable MCDA method to the presented problem, it might not be the best method while the similar decision problem is considered. Due to the steps 2 and 3 of Phase 4, the availability and type of the information in a new problem can be different, as well as DM's preferences characterized by subjective nature, including the way of their articulation and the expected result, i.e., the relation between variants. As a result, the Phase 4 and the following Phase 5 should not be omitted while a new decision aiding problem is considered.

#### 4.7. Phase 5 – Computational experiments and selection of the compromise tram depot location

In the last phase of the methodology, a compromise location of the tram depot is selected. It is based on the results of the previous phases, including the family of criteria (Phase 2.2), the matrix of performances (Phase 3.2) and the selected MCDA method (Phase 4). Phase 5 starts with calculations carried out with an Excel-based application of the AHP method AHORNsimple (Sawicki & Sawicka, 2020). They are preceded by the construction of the decision maker's (DM) preferences model. It is highly dependent on the characteristics of the method selected in Phase 4. It generally consists of two issues, including the expression of the relative weights between criteria and grading preferences between all the alternatives with respect to each criterion. The result is suggested having completed the computations with the application of the selected MCDA method.

### 5. Practical application – a new tram depot in Poznan

#### 5.1. General overview

The tram transport system in Poznan, Poland, involves almost 215 km of tracks, 14 tram loops  $\{L1, L2, \dots, L14\}$  and 3 tram depots, i.e.  $\{S_1, S_2, S_3\}$ . In the network, the transportation tasks are performed on 19 tram lines  $\{1, 2, \dots, 17, 18, 26\}$ , using 174 trains of 6 different types. A structure of the transport network is shown in Fig. 2.

The operator of the public transportation system - *Miejskie Przedsiębiorstwo Komunikacyjne* (MPK) faced the problem of eliminating one of its three tram depots, i.e.  $\{S_3\}$ . Due to the small size of the

depot, its poor condition, and the lack of expandability the operator decided to replace depot  $\{S_2\}$  while leaving two other locations, i.e.  $\{S_1, S_3\}$ .

#### 5.2. Phase 1 – Identification of the key constraints

One of the crucial constraints in this analysis was the availability of the plot to locate the new depot. Following a detailed analysis and discussion with the representatives of the authorities of the city, one possible location was suggested -  $\{S_6\}$ . Besides this, another four alternative locations were also suggested, including  $\{S_4, S_5, S_7, S_8\}$  (see work of Kupka & Sawicki, 2015). All the alternative locations are visualized on the scheme of the transportation network (see Fig. 2) and briefly characterized in the following Tab. 1.

#### 5.3. Phase 2.1 – Designing alternative solutions

Five possible locations  $\{S_4, \dots, S_8\}$  were considered for location of the new tram depot. At this phase, each potential location was translated into several alternatives  $\{A_1, \dots, A_5\}$ .

Due to the identified restrictions each alternative was a combination of three depots and represented a complex solution to be further evaluated in detail. A common and constant aspect of each alternative was the location of two tram depots  $\{S_1, S_3\}$ . The element, which characterized each alternative was a unique location of the third depot selected from the set  $\{S_4, \dots, S_8\}$ . Finally, the alternatives were as follows:  $A_1 = \{S_1, S_3, S_4\}$ ,  $A_2 = \{S_1, S_3, S_5\}$ ,  $A_3 = \{S_1, S_3, S_6\}$ ,  $A_4 = \{S_1, S_3, S_7\}$ , and  $A_5 = \{S_1, S_3, S_8\}$ .

#### 5.4. Phase 2.2 – Defining the set of the evaluation criteria

Using the proposed methodology to select the best location of the tram depot in Poznan, the family of criteria discussed in section 4.4, see phase 2.2, was adopted. The nature of all evaluation criteria is expressed by formulas (7)-(14).

#### 5.5. Phase 3.1 – Optimisation of alternatives with respect to selected criteria

In the family of criteria only one is formulated as an optimization criterion  $F^0$ , i.e. energy waste of empty runs  $WE(A_r)$ . The corresponding formulation is given in section 4.4, by formulas (7)-(10).



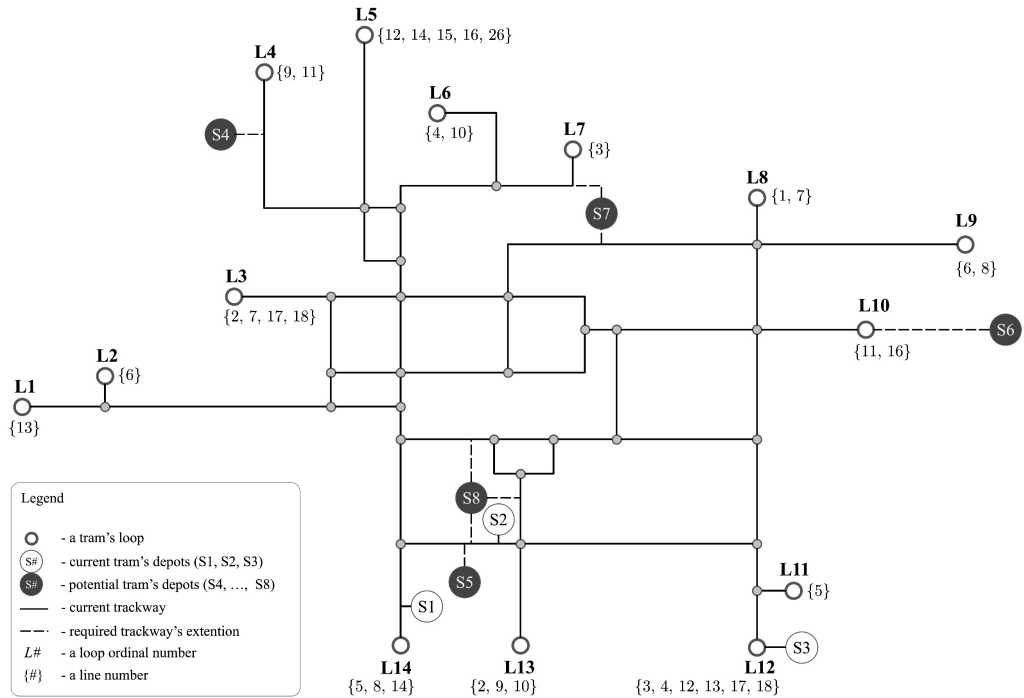


Fig. 2. The simplified scheme of the tram transportation network and the location of the depots in Poznan  
Source: based on Kupka & Sawicki (2015), Sawicki & Kupka (2016)

Tab. 1. Key characteristics of each potential tram depot location

Characteristic	Alternative tram depot locations				
	$S_4$	$S_5$	$S_6$	$S_7$	$S_8$
Area of the plot	[ha] 7.5	6.5	29.0	6.2	25.0
Length of required track extension	[m] 700	300	2000	1500*	2150*
Distribution of trams into alternative directions	[-] single	single	single	double	Triple
Access track location area	[-] outside the dense built-up area	outside the dense built-up area	across residential, dense urban area	outside the dense built-up area	along the railways (main lines) and across dense urban area
Surrounding area	[-] estate of single-family houses	industrial site, along the railways and solid fuel storage	industrial area, near railways and commercial center	residential, dense urban area, along the railways	industrial area
Potential risk	[-] R1**	R1	R1	-	-

\* a sum of the length of all 3 access tracks; \*\*R1 - possible lack of access to the depot due to a train failure on an access track

For the considered decision situation, the following list of parameters has been applied to the model:

- number of trams in use:  $N = 176$  [veh.],
- length of analytical period:  $d = 30$  [days],
- cost of energy:  $c = 0,5$  [PLN/kWh] per unit,
- energy consumption unit:  $\rho_k = 3,36$  [kWh/km],
- capacity of each depot:  $Q_1 \leq 56$  [veh.],  $Q_2 = 0$  [veh.],  $Q_3 \leq 49$  [veh.],  $Q_4 \leq 100$  [veh.],  $Q_5 \leq 100$  [veh.],  $Q_6 \leq 100$  [veh.],  $Q_7 \leq 100$  [veh.],  $Q_8 \leq 100$  [veh.],
- maximum number of depots:  $S = 3$  [-],
- distances between the first stop on a line and the depot, as well as between the last stop on a line and the depot are equal, i.e.  $l_{ij}^s = l_{ij}^t$ ; distance values are presented in Tab. 2.

Tab. 2. Distance between  $i$ -depot and the first stop on the  $j$ -line, in [m]

Line ( $j$ )	Depot $S_i$							
	$S_1$	$S_2$	$S_3$	$S_4$	$S_5$	$S_6$	$S_7$	$S_8$
1	380	1455	6390	910	2190	4822	1450	
2	1785	3520	4770	1100	6295	2405	500	
3	3100	10	2925	3155	5000	1500	2075	
4	3100	10	2925	3155	5000	1500	2075	
5	110	1010	4770	1400	2190	2405	1780	
6	2725	3250	5599	3255	4200	3070	1000	
7	380	1630	4660	910	2190	4475	1450	
8	110	5445	3535	1400	5925	1750	1595	
9	1785	3520	560	1100	6295	1500	500	
10	1785	3520	2925	1100	6860	1500	500	
11	3100	3250	560	3180	10	1500	1000	
12	3100	10	3535	3155	4600	2865	1000	
13	2725	10	3535	3155	4600	2865	1630	
14	110	5550	3535	1400	7205	2865	1595	
15	2725	6595	3535	3255	7465	2865	1630	
16	3100	7080	2925	3630	10	2865	2070	
17	3100	10	3535	3630	2190	1750	2070	
18	380	10	3535	910	5000	2865	1450	
26	2720	7080	3535	3630	7140	2865	2070	

The result of an optimal distribution of trams among the depots in alternatives  $A_3$  and  $A_5$  is presented in Tab. 3. The resulted value of criterion  $WE(A_r)$  for each of the alternative  $\{A_1, \dots, A_5\}$  is presented in Tab. 4.

### 5.6. Phase 3.2 – Evaluation of alternatives with respect to other criteria

The value of decision variables in the optimal solution of  $r$ -alternative ( $r = 1, \dots, 5$ ), i.e.  $y_{ir}$  and  $x_{ijkr}$  was next adopted for valuation of other criteria from  $F^a$ . The

formulas (11)-(14) presented in section 4.4 were applied to assess the alternatives taking into consideration the other criteria. The value of parameter  $C_i$  in criterion  $IC(A_r)$  was calculated as a result of the cost of all engineering works to join the depot to the existing transport infrastructure. The experts expressed comprehensive and holistic evaluation using a rating system with respect to the configuration of three tram depots in each alternative while considering three last criteria, i.e.,  $OR(A_r)$ ,  $TL(A_r)$  and  $LU(A_r)$ . Thus, the aspects of reliability  $P_r$ , environmental impact  $E_r$  and land use  $U_r$  were assessed. The result of the calculations is presented in Tab. 4.

Tab. 3. An assignment of trams to the depots in alternatives  $A_3$  and  $A_5$

Line ( $j$ )	Assignment $x_{ijkr}$ [veh.]						Trams on $j$ -line $N_j$ [veh.]
	$A_3$ (*)			$A_5$ (**)			
	$S_1$	$S_2$	$S_6$	$S_1$	$S_2$	$S_8$	
1	0	0	14	14	0	0	14
2	10	0	0	0	0	10	10
3	0	5	0	0	5	0	5
4	0	6	0	0	6	0	6
5	0	0	11	11	0	0	11
6	0	0	11	0	0	11	11
7	0	0	10	10	0	0	10
8	10	0	0	10	0	0	10
9	11	0	0	0	0	11	11
10	1	8	0	0	0	9	9
11	0	0	6	0	0	6	6
12	0	10	0	0	10	0	10
13	0	12	0	0	12	0	12
14	8	0	0	8	0	0	8
15	8	0	0	0	0	8	8
16	0	0	8	0	0	8	8
17	0	3	9	0	12	0	12
18	0	5	0	0	5	0	5
26	8	0	0	0	0	8	8

\*  $x_{ijkr}$  for other depots, i.e.  $\{S_4, S_5, S_7, S_8\}$  equals 0,

\*\*  $x_{ijkr}$  for other depots, i.e.  $\{S_4, S_5, S_6, S_7\}$  equals 0.

### 5.7. Phase 4 – Selection of the decision aiding method

Based on the practical applicability in the transport systems the following MCDA ranking methods were considered: ELECTRE III (Roy, 1985; Vincke, 1992), PROMETHEE (Brans, Vincke & Mareschal, 1986), AHP (Saaty, 1980) and UTA (Jacquet-Lagrez & Siskos, 1982). Taking into account the motivation of the most suitable MCDA method selection, see section 2.6, three methods were rejected, i.e.:

- UTA method, which is very useful only for a large

number of alternatives. Moreover, its algorithm requires the reference ranking, which should be created by the DM. In the considered tram depot location problem, it was hard to define it from the list of only five alternatives.

- ELECTRE III and PROMETHEE methods do not meet the DM’s way of preferences articulation, i.e. indifference, weak and strong preference and incomparability.

Finally, the AHP method was analyzed. The number of alternatives and evaluation criteria was appropriate to create the model of DM’s preferences. Moreover, these preferences can be expressed as the comparison between criteria, as well as between alternatives with respect to each criterion, which is highly appreciated by the DM. As a result, the AHP method was selected and AHORNsimple application (Sawicki & Sawicka, 2020) was used within a decision support process (Phase 5).

### 5.8. Phase 5 – The computational experiments and selection of the compromise tram depot location

As mentioned in section 5.7, the AHP method was chosen to support final selection of the most advantageous tram depot location. In the analyzed problem, all the computations in this phase have been performed with an Excel-based implementation of AHP, called AHORNsimple (Sawicki & Sawicka, 2020), i.e. Application of Excel-Based AHP method to solve multiple criteria Ranking problems – simple version. This decision aiding tool helps to solve the problems limited to 9 criteria and 9 alternatives. It is composed of 14 sheets. The first one “Decision process” presents the scheme of decision support process with an application of AHORNsimple, including the most important steps of the calculation procedure. In the following two sheets, i.e. “Criteria” and “Alternatives” the data are filled in

with names of criteria and alternatives, respectively. The fourth sheet “Rank criteria” allows the DM to put information about his/her preferences between each pair of criteria using a five-point scale presented below, while the following sheets from “R\_C1” to “R\_C9” should be filled in by the DM with information about the preferences between each pair of alternatives with respect to each criterion considered in the decision making process. These preferences are also expressed with an application of five-point scale. Finally, the last sheet “Result” shows in a numerical and graphical form the results of the calculations, including percentage shares of criteria and alternatives in the final ranking, ranking of alternatives according to considered criteria and relative importance of the considered criteria. In accordance to the procedural guidelines of the AHP, the preference information was collected, i.e. between the criteria and then between the alternatives with respect to each criterion. The DM in this case was the carrier (MPK Poznan), as a direct user of the planned new tram depot. In fact, institutional preferences have been defined by the representative of the carrier.

When setting preferences in the AHP method, a typical five-point grading scale of importance was applied (Saaty, 1980), where:

- 1: equal importance,
- 3: weak importance of one over another,
- 5: essential (strong) importance,
- 7: demonstrated (very strong) importance,
- 9: absolute importance.

Using this scale, a model of preferences between criteria was constructed by pairwise comparisons expressed directly by the DM (see Tab. 5). Next, pairwise comparisons between alternatives have been carried out. The procedure of their collection was the same as between criteria.

Tab. 4. Matrix of performances in the considered tram depot location problem

Criteria (F)			Alternatives (A)				
name	Direction of preferences	unit	$A_1$	$A_2$	$A_3$	$A_4$	$A_5$
$WE(A_r)$	min	[PLN/mth]	25,318	19,776	27,966	19,383	9,975
$IC(A_r)$	min	x1,000 [PLN]	52.5	22.5	269.3	116.7	176.7
$OR(A_r)$	max	[pts]	4	3	5	2	1
$TL(A_r)$	min	[pts]	4	1	5	2	2
$LU(A_r)$	min	[pts]	5	2	2	2	1

Five separate matrices of preferences between the alternatives with respect to each criterion were constructed. The results are presented in Tab. 5 - Tab. 10. Taking into consideration the comparisons between the criteria and between the alternatives (Tab. 5 - Tab. 10), it is worth noticing that on the diagonal there is grade 1, which means that pairwise comparisons between the same criteria and the same alternatives result in the equal importance relation between them.

Based on the information presented in Tab. 5, the absolute importance relation (grade 9 on Saaty scale) occurs only between the land use criterion  $LU(A_r)$ , see row  $LU(A_r)$  in Tab. 5, and the operational reliability criterion  $OR(A_r)$ , see column  $OR(A_r)$  in Tab. 5.

Tab. 5. The model of DM's preferences – the pairwise comparisons on considered family of criteria  $F$

$F$	$F$				
	$WE(A_r)$	$IC(A_r)$	$OR(A_r)$	$TL(A_r)$	$LU(A_r)$
$WE(A_r)$	1	1/3	3	1/3	1/7
$IC(A_r)$	3	1	5	1	1/5
$OR(A_r)$	1/3	1/5	1	1/5	1/9
$TL(A_r)$	3	1	5	1	1/5
$LU(A_r)$	7	5	9	5	1

Tab. 6. The model of DM's preferences – the pairwise comparisons of  $A_r$  with respect to  $WE(A_r)$

$A_r$	$A_r$				
	$A_1$	$A_2$	$A_3$	$A_4$	$A_5$
$A_1$	1	1/3	3	1/3	1/7
$A_2$	3	1	5	1	1/5
$A_3$	1/3	1/5	1	1/5	1/9
$A_4$	3	1	5	1	1/5
$A_5$	7	5	9	5	1

Tab. 7. The model of DM's preferences – the pairwise comparisons of alternatives  $A_r$  with respect to criterion  $IC(A_r)$

$A_r$	$A_r$				
	$A_1$	$A_2$	$A_3$	$A_4$	$A_5$
$A_1$	1	1/3	9	5	7
$A_2$	3	1	9	7	7
$A_3$	1/9	1/9	1	1/5	1/3
$A_4$	1/5	1/7	5	1	3
$A_5$	1/7	1/7	3	1/3	1

Tab. 8. The model of DM's preferences – the pairwise comparisons of alternatives  $A_r$  with respect to criterion  $OR(A_r)$

$A_r$	$A_r$				
	$A_1$	$A_2$	$A_3$	$A_4$	$A_5$
$A_1$	1	1/3	5	1/5	1/7
$A_2$	3	1	7	1/3	1/5
$A_3$	1/5	1/7	1	1/9	1/9
$A_4$	5	3	9	1	1/3
$A_5$	7	5	9	3	1

Tab. 9. The model of DM's preferences – the pairwise comparisons of alternatives  $A_r$  with respect to criterion  $TL(A_r)$

$A_r$	$A_r$				
	$A_1$	$A_2$	$A_3$	$A_4$	$A_5$
$A_1$	1	1/5	3	1/3	1/3
$A_2$	5	1	7	3	3
$A_3$	1/3	1/7	1	1/5	1/5
$A_4$	3	1/3	5	1	1
$A_5$	3	1/3	5	1	1

Tab. 10. The model of DM's preferences – the pairwise comparisons of alternatives  $A_r$  with respect to criterion  $LU(A_r)$

$A_r$	$A_r$				
	$A_1$	$A_2$	$A_3$	$A_4$	$A_5$
$A_1$	1	1/3	1/3	1/3	1/5
$A_2$	3	1	1	1	1/3
$A_3$	3	1	1	1	1/3
$A_4$	3	1	1	1	1/3
$A_5$	5	3	3	3	1

Moreover, the land use criterion  $LU(A_r)$  is rated higher than the other criteria, e.g. grade 7, compared to the energy waste  $WE(A_r)$  criterion, grade 5 compared to the investment cost criterion  $IC(A_r)$  and the troublesome location criterion  $TL(A_r)$ , as well.

The operational reliability criterion  $OR(A_r)$  occupies the worst position. The evaluation values compared to the other criteria are lower than one. It means that all the other criteria outrank the operational reliability one.

The analysis of the results presented in Tab. 6 - Tab. 10 leads to the following general conclusions:

- alternative  $A_5$  outranks all alternatives on criterion  $WE(A_r)$  reaching the highest grade 9;
- alternatives  $A_1$  and  $A_2$  reach the highest grade 9 outranking alternative  $A_3$  on criterion  $IC(A_r)$ ;

- alternatives  $A_4$  and  $A_5$  reach the highest grade 9 outranking alternative  $A_3$  on criterion  $OR(A_r)$ ;
- alternative  $A_2$  outranks all alternatives on criterion  $TL(A_r)$  reaching the highest grade 5;
- alternative  $A_5$  outranks all alternatives on criterion  $LU(A_r)$  reaching the highest grade 5.

The above makes it difficult to indicate the compromise solution, i.e. the tram depot location. Thus, solving the problem calls for the application of the AHP method.

Another important aspect of the analysis is that the designed model of the decision-maker's preferences is found to be consistent in nature. The consistency ratio  $CR$  applicable in AHP does not exceed the maximum acceptable threshold 0.1. The summary of the  $CR$  for criteria comparisons and alternatives is presented in Tab. 11.

Tab. 11. Consistency ratio  $CR$

Component of DM's preference model						
$F(A_r)$	$A_r(WE)$	$A_r(IC)$	$A_r(OR)$	$A_r(TL)$	$A_r(LU)$	
0.04	0.04	0.09	0.08	0.03	0.01	

The application of the preference model in the AHORNsimple method results in the determination

of relative importance of the considered criteria, and ultimately allows for the construction of a ranking of the alternatives considering such criteria (see Fig. 3). Based on the obtained results, the conclusion is that the most important criterion on a global scale is  $LU(A_r)$ , see C5 in Fig. 3 (a bottom part, pie chart), and it generates roughly 58% of the impact on the final decision among all five criteria. Two other criteria, i.e.  $IC(A_r)$  and  $TL(A_r)$ , see C2 and C4 in Fig. 3, are equally important reaching the level of around 16% each. The less important criterion in the experiment is  $OR(A_r)$ , see C3 in Fig. 3, whose impact on the final ranking of alternatives is below 4%.

The hierarchy of scenario configurations, which is also presented in Fig. 3 (upper right corner, a bar chart), indicates that  $A_5$  is the best alternative, assuming the location of the tram depot in the central part of the transport network structure -  $S_8$ . The highest position of alternative  $A_5$  (final score is 35.5%, see Fig. 3, upper left corner) results mainly from the highest scores obtained in relation to the criteria of land use  $LU(A_r)$ , see C5 (25.5%), and energy waste  $WE(A_r)$ , see C1 (4.1%), and its relatively high rating in the operational reliability criterion  $OR(A_r)$ , see C3 (1.8%).



Fig. 3. The partial and final results generated in AHORNsimple

Within the criterion of investment cost  $IC(A_r)$ , this alternative obtained one of the worst results, see C2 (0.9%), while in relation to the troublesome location of the depot, see C4 (3.2%), it was the same as  $A_4$ . Considering both  $IC(A_r)$  and  $TL(A_r)$ , see C2 and C4 in Fig. 3 respectively, the most advantageous solution is  $A_2$ , assuming the location of the new depot  $S_5$  in the close neighbourhood of the existing depot  $S_1$ .

As a result, the alternative  $A_5$  with the new depot location in  $S_8$  was ranked first, with the global rating of 35.5%, followed by  $A_2$  with the new location in  $S_5$  (26.7%);  $A_4$  with depot  $S_7$  (16.3%) had the third location in the hierarchy,  $A_3$  with depot  $S_6$  was on the fourth position (11.0%) and  $A_1$  was the fifth with the new depot located in  $S_4$  (10.5%).

## 6. Discussion

The performed calculations were the basis for recommending the location of a new depot in  $S_8$ , i.e. in the central part of the transport system network, in fact in the central part of the city. Due to several features, including the industrial nature of this area, the proximity of the main railway line, the size of the parcel (25.0 ha) and the possibility of triple distribution of the transport means from depot, the recommended location seems to be a reasonable solution of the considered problem. Its disadvantage is the need to build an additional section of track to connect the depot to the transport network; this section is the longest among all the solutions considered. It is worth mentioning, that the final decision was made regardless of the recommendations presented in this paper. Finally, the investment related to a new depot in location  $S_6$  was implemented. The selected solution, i.e. new depot in location  $S_6$  differs significantly from the recommended location  $S_8$ . Its position in the hierarchy is very low, i.e. the fourth out of five alternatives.

The complexity of the proposed methodology provides a wide perspective of the analysis. The selected solution  $S_6$  (alternative  $A_3$ ) is overperformed by the  $S_8$  (alternative  $A_5$ ) by 3 key criteria, i.e.  $LU(A_r)$  - C5;  $TL(A_r)$  - C4 and  $IC(A_r)$  - C2). The only advantage of  $S_6$  over  $S_8$  (significant in terms of value) is recognised on criterion  $OR(A_r)$  - C3, which is in fact the least important criterion in the analysis.

The discrepancy found between the implemented  $S_6$  solution and the recommended  $S_8$ , led to the conclusion that the main component of the decision was

based on the administrative aspect.

The nature of the proposed methodology and its implementation leads to the following methodological observations:

- 1) The proposed method fills the research gap in developing a comprehensive methodology for locating a depot in the structure of the public transport system.
- 2) The methodology is an extension of previously undertaken research work, in which the indication of the optimal location of the depot was treated separately or the problem was treated as a classic problem of building alternative solutions and selecting a compromise one. The proposed methodology effectively combines both approaches, i.e. optimization and multiple criteria decision aiding.
- 3) The MCDA method should be matched to the specificity of the problem under consideration and the decision maker's preferences. This guarantees that the result of analysis, i.e. the final ranking of the alternatives and the recommended solution, becomes reliable and the decision aiding process is credible.

## 7. Conclusions

The paper deals with the problem of location of fleet technical facility within the public transportation system. The authors propose a complex methodology, which is a combination of mathematical programming and decision aiding with the presence of several evaluation criteria. The methodology has five iteratively performed phases and it constitutes a universal approach that can be adopted either in the case where one of several existing depots needs to be decided, or in the case where all new depot locations are considered. The adaptation needs to be done in the Phase 2.1, where a set of alternatives is defined. Alternatively, this methodology may be applied in the process of developing the structure of the technical facilities for the public transport system of both trams and buses. The designed methodology was experimentally applied to select a new depot location with the presence of two other current locations. In this case a fleet of trams and a requested structure of tram depots was considered. Since the proposed methodology assumes the selection of the most suitable decision aiding method (Phase 4), the appropriate one was selected. This phase can be omitted while the similar tram location problem is considered. However, due to the subjective character of the

DM preferences, the authors advice including this phase while solving each problem. It should also increase the reliability of the obtained results.

The research performed in this paper has generated several promising directions of further steps. According to the authors, the following directions should be considered:

- 1) extending the set of criteria including investment costs;
- 2) introducing simulation for experimental evaluation of such criteria as operational reliability *OR* and troublesome location *TL*;
- 3) combining the problem of depot locating with other decision problems, including transport line construction and fleet composition.

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