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EVALUATION OF THE REQUIREMENT FOR PASSENGER CAR PARKING SPACES USING MULTI-CRITERIA METHODS

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Abstract. The present situation shows that the parking infrastructure in residential areas of Vilnius does not satisfy the existing level of motorization. Every evening people come home from work and end up parking cars on lawns, cycle and pedestrian paths, playgrounds, fire accesses and etc. In Lithuania, this problem emerged with the growing number of cars. There have been attempts to address parking shortage issues 20–30 years ago by building metal above-ground garages and underground car parks; but such solutions focused on existing burning needs alone. As a result, the current parking situation in residential areas is chaotic. This problem stems from the ineffectiveness of responsible institutions, which maintain the status quo. Consequently – as no car parking development projects are planned and implemented as well as no required statistical data is collected regarding conditions of car parking and etc. – people are forced to look for a solution by themselves, thus end up parking on lawns or playgrounds. This article aims to apply multi-criteria solutions (Multiple Criteria Decision Making – MCDM), which would allow indicating the worst passenger car parking conditions in residential areas from the social, economic and environmental points of view. Besides, it pursues identifying and substantiating the choice of territories that require the development of car parking solutions.

Keywords: car parking lots, MCDM, SAW, TOPSIS, COPRAS, AHP.

1. Introduction

The existing level of car ownership in Vilnius amounts to 569 passenger cars per 1000 inhabitants, which is rather high compared to other European cities. The city residents use privately owned or company cars. The recent worsened economic situation as well as growing fuel costs and dropping income of inhabitants resulted in notable decrease of the level of car ownership in Vilnius (Burinskienė *et al.* 2011). The city has the highest car ownership level in Lithuania, which significantly exceeds that of all other largest cities. It is 1.06 times higher than the average of the country. The total vehicle fleet and the fleet of passenger cars of Vilnius amounts to approx. 18% of the total vehicle fleet of Lithuania.

The growing car ownership level in Lithuania causes parking problems, which require much more complicated solutions if compared to those of traffic organisation or street capacity issues.

Different cities use different solutions for parking places and methods. Based on the Construction Technical Regulation STR 2.06.01:1999 "Transport Systems in Cities, Towns and Villages" cars can be parked:

- on-street, on the edge of a carriageway along the kerb;
- in special parking lanes off a carriageway;
- in parking lots;
- in specially designated areas;
- in multi-storey and underground garages.

As regards the classification of parking spaces, it is obvious that the Lithuanian STR 2.06.01:1999 merges two different categories – parking in the sense of traffic organisation and as an engineering structure – into one. For a clearer classification of parking lots and their impact on the transport system, it is necessary to consider the following:

- structural concepts of a parking lot (i.e. underground, surface, multi-storey above-ground, combined); and
- its position in respect of a carriageway (on a carriageway or in parking lanes off a carriageway).

As these considerations allow for a more efficient implementation of various analytical tasks, they should be used when creating the GIS car parking database. As a separate attribute, the type of a parking lot could be characterised by the car parking angle in respect of a carriageway. Parking lots situated off a carriageway can be divided into free and paid car parks.

When planning parking spaces on a carriageway or in special parking lanes, it is important to eliminate the cars looking for free parking as they additionally load the street network and cause a negative impact on the environment. A parking lot can function effectively when its occupancy does not exceed 85% (Zagorskas, Palevičius 2011). This indicator can be controlled with the help of a parking policy. Parking spaces on a carriageway can only be designated if the street has a sufficient capacity reserve. Such parking is not recommended on two-lane streets with intense traffic. In latter cases, parking spaces should be provided in special lanes; however, sufficient space for pedestrians and bicycles should be ensured. Parking lots off a carriageway will function effectively if drivers are systematically informed. Such information should be provided on the Internet as well as using street signs.

2. Overview of solutions in other countries

Commissioned by the government in the sixties of the last century, British researchers headed by Professor Sir Collin Buchanan were the first to study the capacity and regularities of the on-street parking in different urban areas to address urban traffic problems. The team investigated the traffic situation in different cities. The collected data was presented in the well-known Buchanan Report where the Professor was the first to introduce the concept of environmental capacity (Buchanan 1963).

The regularities of car parking and planning processes in Austrian cities have been studied by A. Pech since 1993 (Pech *et al.* 2009).

The scientist Michalak studied car parking problems in large cities of Poland (Michalak 2005, 2006, 2008).

The research of scientific literature revealed that intellectual parking systems are widely analysed and developed.

Subsequent to investigation of problems pertaining to the Malaysian car parking system, local researchers proposed a Wireless Mobile-based Car Parking System that uses a low-cost SMS service. Such SMS service enables drivers to receive information regarding the availability of car parking spaces. The system allows drivers to resend an SMS and request for another assignment of car parking spaces if they fail to get the previously assigned ones. The article demonstrates the design and implementation of the Wireless Mobile-based Car Parking System (WMCPS) by Breadth First Search (BFS) algorithm in finding the nearest parking space. The stimulation results revealed that this intelligent system can efficiently allocate and utilize spaces inside a car park (Khang *et al.* 2010).

To address the car-parking control problem, Korean researchers proposed a practical path planning algorithm. Regions within a reachable distance from a goal can be easily computed using the proposed scheme. A variety of candidate paths can be generated by using conventional back-propagation scheme. Finally, optimal solutions can be obtained with respect to performance measures such as collision safety, moving distance, control efforts and etc. The simulation results presented in the study clearly show that the proposed scheme provides useful solutions (Kim *et al.* 2010).

Taiwanese researchers have addressed the issues of autonomous parking and obstacle avoidance considering the increasing number of studies of a car-like mobile robot (CLMR). An autonomous parking controller can be convenient to a novice driver. However, if the controller is not designed adequately, it may endanger the car and the driver. Therefore, this research presents a novel multifunctional intelligent autonomous parking controller that is capable of effectively parking the CLMR in an appropriate parking space using the integrated data obtained by sensors from the surrounding environment. An ultrasonic sensor array system has been developed with group-sensor firing intervals. A binaural approach to the CLMR has been adopted for complete contactless sensory coverage of the entire workspace. The proposed heuristic controller can obtain the posture of a mobile robot in a parking space. In addition, the controller can ensure the ability of the CLMR to withstand collision to guarantee safe parking. Moreover, the CLMR can recognize the parking space and the obstacle position in a dynamic environment. Therefore, the proposed controller could ensure safe driving. Finally, practical experiments demonstrate that the proposed multifunctional intelligent autonomous parking controllers are feasible and effective (Li *et al.* 2010).

Other Taiwanese researchers have proposed a three-layer Bayesian hierarchical framework (BHF) for robust vacant parking space detection (Huang, Wang 2010).

Meanwhile Canadian researchers have developed a neuro-fuzzy model for autonomous parallel parking of a car-like mobile robot. In their approach, they have focused on the most difficult case of parallel parking when parking space dimensions cannot be identified. The proposed model uses the data from three sonar sensors mounted on the front left corner of the car to decide on the turning angle. Fifth-order polynomial reference paths for three different size parking dimensions have been used to generate the training data. The fuzzy model has been identified by subtractive clustering algorithm and trained by ANFIS (Adaptive Neuro-Fuzzy Inference Systems). The simulation results show that the model can successfully decide about the motion direction at each sampling time without knowing the parking space width, based on the direct sonar readings which serve as inputs. The results, which are based on real dimensions of a typical car, demonstrate the feasibility and effectiveness of the proposed controller in parallel parking (Demirli, Khoshnejad 2009).

In their article, South African researchers Bekker and Vivers (2008) noted that parking problems may be solved with the help of computer-based modeling using mechanical parking garages. Using the SAW method, the researchers have proved that the computer-based modeling they have proposed may be the major instrument looking for solutions to difficult real world problems.

Experience of foreign cities with a high level of car ownership shows that due to traditional planning and development of residential areas it is impossible to create the system of driveways and parking lots which would guarantee the complete driving comfort for the residents that own a car. This conclusion is based on the fact that only a restricted part of the territory can be allocated for driveways and parking lots in multi-storey residential areas.

The potential of driveways and parking places in such urban areas is determined (measured) by the communication capacity of the area.

The capacity of the area describes the maximum number of cars (moving or standing) in the studied urban area or the maximum number of cars accommodated at the same time by a particular urban area.

London was one of the first cities where in 1972 the standards defining the maximum number of parking spaces were introduced. Also, a strict parking policy – the system of maximum and minimum parking standards – was launched in Dutch cities. In this case, three standards are used for offices: 10, 20 and 40 parking spaces per 100 employees. The lowest standard (10 parking spaces/100 employees) is used in the least densely built-up city centres that are well serviced by the public transport. The minimum standard of 40 parking spaces/100 employees is intended for the extensively built-up areas.

In the multi-storey residential areas of Warsaw and other Polish cities, 1 parking space is allocated to 1 apartment but no less than 1 space per each 60 m^2 of living area. In Austrian cities, 1 apartment is provided with 1 parking space; while in German cities, the HBS standards demand for 1–1.5 parking spaces per each apartment (HBS 2009); and Switzerland allots 1 parking space per 80–100 m^2 of living area.

3. Determining the parking demand with the help of empirical method

In 2010–2011, the car parking survey was carried out in the main multi-storey residential districts of Vilnius: Lazdynai, Karoliniškės, Virsuliškės, Pilaitė, Šeškinė, Justiniškės, Fabijoniškės and Pašilaičiai.

To find out the existing situation, pictures of parked cars were made in all eight residential districts in the evening and at night when the parking demand is at the maximum (Table 1). The survey recorded all cars: those left standing in special lots, driveways and yards, as well as those parked on the grass, sidewalks and other prohibited areas.

Analysis of the parking survey results in multi-storey residential districts of Vilnius showed that 9.9% of cars get parked in prohibited areas (on sidewalks and green spaces), which is illegal since it impedes pedestrian traffic and pollutes the environment. In some districts, the situation is even more unfavourable since the number of vehicles parked in prohibited areas is significantly higher: cars end up parked on the rear turnaround areas of dead ends, driveways used by special transport (waste collection), carriageways of driveways closer than 10 m to residential houses and etc. To sum up, the total number of vehicles parked on prohibited areas amounts to 40–50% (in Lazdynai district, 18.3% of cars are parked on sidewalks and green areas; in Pilaitė – 11.9%; and in Šeškinė and Justiniškės – 11.8% each), which complicates the overall situation and possible solutions.

With the total built-up area of 1100 ha and 225 thousand in population, these eight residential districts of Vilnius (Fig. 1) can accommodate 48400 passenger cars at once. In 2010, the level of car ownership in Vilnius amounted to 569 veh/1000 inhabitants, which means that residents of this part of the city may have owned approx. 128 thousand passenger cars. In the same year, Vilnius had 319 thousand private passenger cars in total, thus, the share of the studied residential districts accounted for 40.4%.

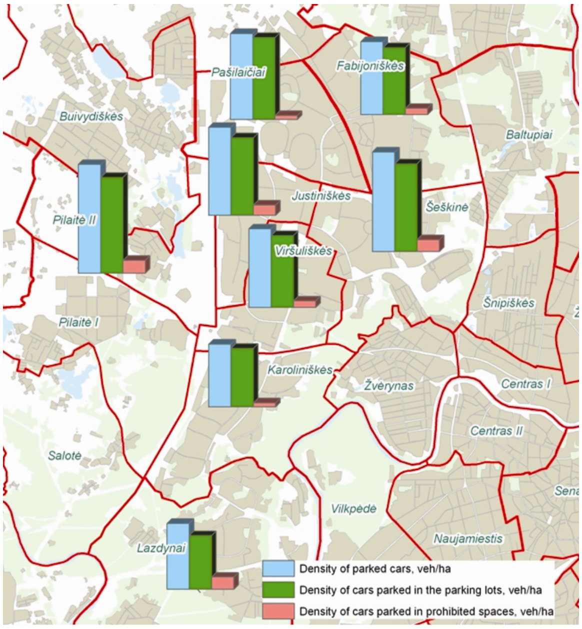

Fig. 1. Density of passenger cars parked in the main residential districts of Vilnius

Table 1. Characteristics of parking systems in the main residential districts of Vilnius

Residential district of the city	Total area of the built-up territory, ha	Density of parked cars, veh/ha	Density of cars parked in the parking lots, veh/ha	Density of cars parked in prohibited spaces, veh/ha	Density of local residents, res/ha
Lazdynai	133.24	36.9	30.1	6.8	30.2
Karoliniškės	172.71	35.2	32.9	2.3	71.9
Virsuliškės	80.93	44.1	40.4	3.7	56.8
Pilaitė	58.36	61.0	53.8	7.2	23.6
Šeškinė	143.26	55.8	49.2	6.6	79.4
Justiniškės	137.47	49.3	43.5	5.8	163.4
Fabijoniškės	212.4	40.8	37.4	3.4	94.9
Pašilaičiai	143.48	48.2	46.0	2.2	82.7
The mean value:		**44.7**	**40.3**	**4.4**	**75.36**

Based on the survey data, the largest number of cars parked above-ground was recorded in Pilaitė district, which also represents the largest density of parked vehicles (61 veh/ha) and the largest number of cars parked on the grass and sidewalks (7.2 veh/ha).

A rapidly increasing fleet of passenger cars and a high level of car ownership caused large parking problems in multi-storey residential areas of other Lithuanian cities as well. There are plans to essentially increase the number of parking spaces in residential areas of Kaunas and Panevėžys as the initial design envisaged the parking spaces outside the limits of residential areas.

The main and the largest multi-storey residential areas of Lithuanian cities were designed and built in accordance with the Soviet design standards, which provided for 180–200 parking spaces per 1000 inhabitants, with some exceptional cases where the number amounted to 220. The required parking spaces were planned based on the level of car ownership of the time, which amounted to 50–80 passenger cars per 1000 inhabitants. The growing demand for parking spaces in residential areas had to be solved by building garages or multi-storey parking lots instead of the existing parking lots or metal garages. Most garages were built outside the limits of a residential area, whereas, in residential areas only short-term parking spaces were planned. The former standards and recommendations (SNIP 1989) required to provide parking spaces (paid parking lots and garage cooperatives) outside the limits of the living environment. Taking into consideration a fairly strict control of construction standards and compliance in those days, each car was provided with its own parking space. During the period of 1985–1995, a more intense construction of temporary and stationary garages was carried out. Such garages were used for repairing a car or keeping it over a winter season. On the real estate market, such garages were in great demand and of great value; thus, people used to invest money in their construction. Once Soviet cars were pushed out of the market by relatively cheap and old European cars, the need to repair and protect a car as well as invest in its parking space (garage) disappeared.

A survey carried out in multi-storey residential districts of Vilnius showed that there are approx. 130–155 cars per 1000 inhabitants.

In accordance with the currently valid regulation, the existing number of parking spaces in residential areas should be increased by approx. 73%, which is hardly possible. This number of parking spaces would require large territories and funds.

It is of utmost importance to identify territories in which the development of parking spaces could be carried out. The residential parking should not be developed at the expense of green or public spaces, children's playgrounds, schools, kindergartens and etc. The most obvious territories are the existing underground garages, parking lots, parking lanes or territories of certain buildings of engineering infrastructure. In many cases development of parking spaces nearby existing driveways is unsuitable due to the required sanitary distance to residential houses.

4. Determining the significance of parking lot indices

In order to identify residential districts with the need of above-ground and underground garages, the expert estimate method was applied. To determine weights, the AHP method was used (Saaty 1980). The method is based on a pairwise comparison matrix:

$$P = \left\| p_{ij} \right\| \ (i, \mathrm{j}{=}1, 2, \dots, m). \tag{1}$$

The matrix P elements $\mathrm{p_{ij}}$ are the relationship between the unknown weights of indices. The experts compare in-between all the estimated indices R_i and R_j, using the scale 1–3–5–7–9, $i, j = 1, 2, \dots m$, where m – the number of the indices compared. The matrix elements vary from 1, when both indices are equally significant, to 9, when one index is much more significant than the other. The matrix P is inversely symmetric, i.e. $p_{ij} = 1/p_{ji}$. Consequently it means that it is possible to fill in the part of the matrix above or under the main diagonal.

The weights of the Saaty AHP method – vector ω – are the normalized components of eigenvector consistent with the maximum eigenvalue $\lambda_{\max}$ of the matrix P:

$$P\omega = \lambda_{\max}\omega. \tag{2}$$

The degree of consistency between the separate estimates of each expert is defined by the consistency index S_I and the consistency relationship S.

Consistency index is defined (Saaty 1980) as a relationship:

$$S_I = \frac{\lambda_{\max} - m}{m-1}, \tag{3}$$

where m – the matrix order.

The smaller the consistency index, the better the consistency of the matrix. In the ideal case $S_I = 0$.

In practice, the consistency degree of matrix P may be determined by comparing the calculated consistency index S_I of the matrix with a randomly generated consistency index S_A (based on the scale 1-3-5-7-9) of the inversely symmetric matrix of the same order (Saaty 1980).

The relationship between the calculated consistency index S_I and the average random index S_A of a particular matrix is called the consistency relationship and determines the degree of the matrix consistency:

$$S = \frac{S_I}{S_A}. \tag{4}$$

The matrix is consistent when the consistency relationship S is smaller than 0.1 (Saaty 1980):

$$S \leq 0.1. \tag{5}$$

Having evaluated the consistency level of 9 experts, it was assumed that the consistency relationship of them all meet the condition $S \leq 0.1$. Example of the comparison matrix of one of experts is given in Table 2.

Table 2. Example of an expert pairwise comparison of indices

Index No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	1	2	3	3	5	5	7	8
2	1/2	1	2	3	3	5	6	7
3	1/3	1/2	1	2	3	3	5	6
4	1/3	1/3	1/2	1	1	3	3	5
5	1/5	1/3	1/3	1	1	1	3	3
6	1/5	1/5	1/3	1/3	1	1	1	3
7	1/7	1/6	1/5	1/3	1/3	1	1	1
8	1/8	1/7	1/6	1/5	1/3	1/3	1	1

In order to estimate the effect of indices on the capacity of parking lots in residential areas, the significances of indices were determined. The first expert gave the largest significance to the level of car ownership and public transport development, density of population, total area of the built-up territory, number of population, and etc.

Table 3 gives the weights ω calculated by an expert using the AHP method. The maximum eigenvalue of the comparison matrix $\lambda_{\max}$ = 8.26, consistency index S_I = 0.037, and the consistency relationship S = 0.026 < 0.1. This shows that estimates produced by the expert are consistent.

Having evaluated the consistency of one expert, further, the consistency of opinions of the entire expert group was evaluated. The consistency level of the group of experts is determined by the coefficient of concordance W (Kendall 1970) (i = 1, 2, .., r; j = 1, 2, ... m), where r is the number of experts and m – the number of indices compared. For the calculation of the coefficient of concordance, the ranking of expert indices is necessary. Equal estimates are attributed the same rank – arithmetical mean of ordinary ranks.

Based on the comparison matrix of each expert, the AHP method determines the weights of indices ω_{ik}, where: $i = 1, 2, \ldots, m$; $k = 1, 2, \ldots, r$; m – the number of indices compared; r – the number of experts.

In a decreasing order of weights it is possible to rank estimates of each expert and to calculate the coefficient of concordance. Results of the ranking of indices e_{ik} are given in Table 4.

To calculate the coefficient of concordance W one must know: the sum of ranks of each index $e_i = \sum_{k=1}^{r} e_{ik}$ (the last but one column of the Table 3); the total average $\bar{e} = \frac{\sum_{i=1}^{m} e_i}{m}$; the sum of squares of deviation from the total average $\bar{e}$ of values e_i: $S = \sum_{i=1}^{m} (e_i - \bar{e})^2$.

The coefficient of concordance W is calculated according to the formula:

$$W = \frac{12S}{r^2 m(m^2 - 1)}, \tag{6}$$

where: m is the number of indices; and r – the number of experts.

Significance of the coefficient of concordance and consistency of estimates made by the group of experts are determined by the criterion χ^2 (Kendall 1970):

$$\chi^2 = W\, r\, (\mathrm{m} - 1) = \frac{12\mathrm{S}}{\mathrm{rm}\,(\mathrm{m} + 1)}. \tag{7}$$

If the value χ^2 calculated according to the formula (7) is larger than the critical value χ^2_{kr} obtained from the table of distribution χ^2 with the freedom degree $\nu = m - 1$ and selected significance level α is close to zero, this means that the expert estimates are in agreement.

Table 3. Weights calculated by the first expert using the AHP method

Index No.	1	2	3	4	5	6	7	8
Weights	0.322	0.230	0.158	0.102	0.074	0.053	0.035	0.027

Table 4. The matrix of the ranking of indices

Expert Criterion	1	2	3	4	5	6	7	8	9	Sum of ranks	Total rank
Level of car ownership	1	1	2	1	1	3	1	1	1	12	1
Level of public transport development	2	3	3	2	2	1	2	3	2	20	2
Density of population	3	4	5	5	5	5	3	4	5	39	5
Total area of the built-up territory	4	5	4	4	4	4	4	5	4	38	4
Number of population	5	2	1	3	3	2	5	2	3	26	3
Street density	6	6	6	6	6	6	6	6	6	54	6
Number of workplaces	7	7	7	7	7	7	7	7	7	63	7
Number of employed people	8	8	8	8	8	8	8	8	8	72	8

Table 5. The values of weights of indices

Criterion Expert	1	2	3	4	5	6	7	8
1	0.322	0.230	0.158	0.102	0.074	0.053	0.035	0.027
2	0.275	0.179	0.122	0.074	0.230	0.048	0.039	0.034
3	0.180	0.173	0.067	0.120	0.346	0.054	0.034	0.025
4	0.307	0.169	0.144	0.123	0.108	0.065	0.058	0.025
5	0.307	0.169	0.144	0.123	0.108	0.065	0.058	0.025
6	0.177	0.349	0.070	0.093	0.192	0.062	0.036	0.021
7	0.395	0.265	0.122	0.122	0.090	0.047	0.037	0.023
8	0.270	0.190	0.116	0.068	0.219	0.065	0.042	0.030
9	0.346	0.203	0.082	0.102	0.136	0.056	0.055	0.018
The average of weights	**0.287**	**0.214**	**0.114**	**0.103**	**0.167**	**0.057**	**0.044**	**0.025**
Rank	1	2	4	5	3	6	7	8

Table 6. The survey of expert questionnaire

Criteria	Min or Max	Weight	Units	Residential district							
				Lazdynai	Karoliniškės	Viršuliškės	Pilaitė	Šeškinė	Justiniškės	Fabijoniškės	Pašilaičiai
Number of population	+	0.167	Thou. pcs.	30.2	28.6	15.2	21.4	36.2	30.8	35.0	27.3
Density of population	+	0.114	Thou people/ha	30.2	71.9	56.8	23.6	79.4	163.4	94.9	82.7
Total area of the built-up territory	–	0.105	ha	133.2	172.7	80.9	202.8	143.3	137.5	212.4	143.5
Number of employed people in the district	+	0.025	Thou. pcs.	7.2	7.2	7.3	6.0	9.2	4.6	9.3	9.0
Number of workplaces	+	0.044	Thou. pcs.	7.0	7.9	5.0	5.6	6.0	5.7	6.0	5.5
Level of car ownership	–	0.287	veh./1000 people	434.2	395.2	375.5	358.3	429.0	380.4	443.7	470.1
Street density	+	0.057	km/km^2	3.09	3.26	3.45	2.42	3.58	3.85	4.40	3.64
Level of public transport development	+	0.214	points	7	8	9	6	8	8	7	7

In this case, where the total average of ranks $\bar{e} = 40.5$, the sum of squares of deviations $\bar{e}_i$ is S = 3132 and the coefficient of concordance $W = 0.921$. The coefficient of concordance is comparatively large, the calculated χ^2 value $\chi^2 = 58$ is larger than the critical $\chi^2_{kr} = 14.07$ with the freedom degree $\upsilon = 7$ and the significance level $\alpha = 0.05$, therefore opinions of the experts are in agreement.

Such being the case, the weights of indices ω_i are calculated as the arithmetical means of AHP weights of all the experts, i.e.:

$$\omega_i = \frac{\sum_{k=1}^{r} \omega_{ik}}{r}, \tag{8}$$

where: ω_{ik} is weights of the *i*-th index calculated by the *k*-th expert.

The values of weights calculated by all experts are given in Table 5.

In order to identify the residential areas that require above-ground and underground garages, an experimental survey was undertaken (Table 6), during which 9 experts were interviewed. The group of experts was composed of territorial planning, and transport system specialists. The experts were selected according to their experience, which had to amount to at least 10 years (Zavadskas *et al.* 2010a).

To ascertain the efficiency indices of parking lots, the authors used a decision-making system that requires determining the significance of defined indices.

The significances of efficiency indices of parking lots were determined by using a pairwise comparison method developed by Saaty (1977).

It has been three decades since this method was started to apply in scientific research work. The method is used rather widely in scientific fields of management, technologies and civil engineering (Turskis, Zavadskas 2010).

5. Determining the rationality of parking lots by the COPRAS method

The COPRAS (Multi-attribute COmplex PRoportional ASsessment of alternatives) method was developed in 1996 by researchers of Vilnius Gediminas Technical University Zavadskas and Kaklauskas (1996).

So far this method has not been applied to determine the rationality of parking lots; however, it has been widely used and applied in various recent scientific articles, e.g. evaluating the priority of the construction sector in European countries (Kildienė *et al.* 2011), construction projects (Kanapeckiene *et al.* 2010), advancement of urban environments (Kaklauskas *et al.* 2010), measurement (Antucheviciene *et al.* 2011, 2012) and other.

Values r_{ij} of all R_i indices can be joined into one qualitative estimate – the value of method criteria – provided they do not depend on measuring units, i.e. are dimensionless. The majority of methods are used for different rearrangement of initial data r_{ij}, though the rearranged values r_{ij} mostly vary from zero to one. The methods COPRAS and SAW use the so-called classical normalization (Podvezko 2011):

$$\tilde{r}_{ij} = \frac{r_{ij}}{\sum_{j=1}^{n} r_{ij}} \quad (i = 1, \ldots, m; \ j = 1, \ldots, n; \ \sum_{j=1}^{n} \tilde{r}_{ij} = 1). \tag{9}$$

This method assumes direct and proportional dependence of priority and utility degree of study alternatives on the system of indices adequately describing the alternatives as well as on values and significances of indices. Calculations were made in five steps.

Step 1:

$$d_{ij} = \frac{r_{ij} \cdot \omega_i}{\sum_{j=1}^{n} r_{ij}}, \quad i = \overline{1,m}; \quad j = \overline{1,n}, \tag{10}$$

where r_{ij} is the value of the *i*-th criterion in the *j*-th alternative of a solution; m – the number of criteria; n – the number of compared alternatives; q_i – significance of the *i*-th criterion.

Step 2. Calculate the sums of weighted normalized indexes describing the *j*-th version. The versions are described by minimizing indexes S_{-j} and maximizing indexes S_{+j}. The lower value of minimizing indexes is better as well as the greater value of maximizing indexes. The sums are calculated according to the formula:

$$S_{+j} = \sum_{i=1}^{m} d_{+ij}; \quad S_{-j} = \sum_{i=1}^{m} d_{-ij}; \quad i = \overline{1,m}; \quad j = \overline{1,n}. \tag{11}$$

Step 3. Determine the significance of comparative versions on the basis of described characteristics of positive ("pluses") and negative ("minuses") alternatives. The relative significance Q_j of each alternative a_j is found according to the formula:

$$Q_j = S_{+j} + \frac{S_{-\min} \cdot \sum_{j=1}^{n} S_{-j}}{S_{-j} \cdot \sum_{j=1}^{n} \frac{S_{-\min}}{S_{-j}}}, \quad j = \overline{1,n}. \tag{12}$$

Step 4. Determine the priority of alternatives. The higher is Q_j, the higher is the efficiency (priority) of the alternative.

Step 5:

$$N_j = \frac{Q_j}{Q_{\max}} \cdot 100, \tag{13}$$

where N_j is the utility degree.

Calculations using the COPRAS method showed that among the eight studied residential districts the best parking conditions are in Justiniškės district (Table 7), while the worst – in Pilaitė district.

Table 7. Priority order obtained by the COPRAS method

Residential district	Qj	Rank
Justiniškės	0.1501	I
Šeškinė	0.1349	II
Fabijoniškės	0.1290	III
Viršuliškės	0.1286	IV
Karoliniškės	0.1285	V
Pašilaičiai	0.1217	VI
Lazdynai	0.1170	VII
Pilaitė	0.1032	VIII

6. Determining the efficiency of parking lots with the help of the SAW method

As experience in the field of multi-criteria method application shows, the ranking of objects derived from different methods can often coincide or slightly differ. In the initial stage of an evaluation, it is recommended to use the simplest method, i.e. VS – the sum of places: its results (ranking of objects) only slightly differ from the results of complicated mathematical methods, while the calculation is simple and requires no computer programs (Podvezko 2008).

The criterion V_j of the method VS is calculated according to the formula:

$$V_j = \sum_{i=1}^{m} m_{ij}, \tag{14}$$

where m_{ij} is the place of the *i*-th index for the *j*-th object. The best value of the criterion V_j is the lowest value.

The idea of qualitative multi-criteria methods is well demonstrated by the SAW method (Hwang, Yoon 1981). The criteria S_j of this method is the sum of weighted values of the indices:

$$S_j = \sum_{i=1}^{m} \omega_i \tilde{r}_{ij}, \tag{15}$$

where: ω_i is the weight of the *i*-th index; and $\tilde{r}_{ij}$ – normalized value of the *i*-th index for the *j*-th object.

The best value of the criterion S_j is the highest value.

In modern scientific literature, the SAW method has been applied to find solutions to the problem of insufficient car parking spaces (Bekker, Vivers 2008) as well as in the process for selection of construction contractors (Zavadskas *et al.* 2010b) and other.

Results are given in Table 8.

Table 8. Priority order obtained by the SAW method

Residential district	S_j	Rank
Justiniškės	0.1493	I
Šeškinė	0.1341	II
Viršuliškės	0.1307	III
Fabijoniškės	0.1290	IV
Karoliniškės	0.1280	V
Pašilaičiai	0.1212	VI
Lazdynai	0.1164	VII
Pilaitė	0.1043	VIII

7. Determining the efficiency of parking lots with the help of the TOPSIS method

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method was developed by Yoon and Hwang (1981). Methodology for determining the order preference of alternatives is based on the concept that the optimum alternative has the smallest distance to the ideal decision and the largest distance to negative-ideal decision. This method assumes the determination of rationality of alternatives by the closeness to the ideal point:

$$\tilde{r}_{ij} = \frac{r_{ij}}{\sqrt{\sum_{j=1}^{n} r_{ij}^2}} \quad (i = 1, \ldots, m;\ j = 1, \ldots, n), \tag{16}$$

where $\tilde{r}_{ij}$ is the normalized value of the i-th index for the j-th object. The best solution (alternative) V^* and the worst one V^- are calculated according to the formulas:

$$V^* = \{V_1^*, V_2^*, \ldots V_m^*\} = \left\{\left(\max \omega_i \tilde{r}_{ij} \,/\, i \in I_1\right), \left(\min \omega_i \tilde{r}_{ij} \,/\, i \in I_2\right)\right\},$$

$$V^- = \{V_1^-, V_2^-, \ldots V_m^-\} = \left\{\left(\min \omega_i \tilde{r}_{ij} \,/\, i \in I_1\right), \left(\max \omega_i \tilde{r}_{ij} \,/\, i \in I_2\right)\right\}, \tag{17}$$

where: I_1 is a set of numbers of maximized indices, and I_2 – a set of numbers of minimized indices.

The total distance of each compared alternative to the best solutions D_j^* and the total distance to the worst solutions D_j^- are calculated according to the formulas:

$$D_j^* = \sqrt{\sum_{i=1}^{m} (\omega_i \tilde{r}_{ij} - V_i^*)^2}\ , \tag{18}$$

$$D_j^- = \sqrt{\sum_{i=1}^{m} (\omega_i \tilde{r}_{ij} - V_i^-)^2}\ . \tag{19}$$

The TOPSIS method criterion C_j^* is calculated according to the formula:

$$C_j^* = \frac{D^-}{D_j^* + D_j^-} \quad (j = 1, \ldots, n). \tag{20}$$

$$(0 \le C_j^* \le 1)$$

The best alternative corresponds to the largest value of the criterion C_j^*.

In modern scientific literature, the TOPSIS method has been applied in fields of excavation (Fouladger *et al.* 2011), renovation and other (Fouladgar *et al.* 2012a, b; Lashgari *et al.* 2012; Kalibatas *et al.* 2011; Medineckiene *et al.* 2011).

The following calculation results were obtained with the help of the TOPSIS method (Table 9).

Table 9. Priority order obtained by the TOPSIS method

Residential district	C_j^*	Rank
Justiniškės	0.785	I
Šeškinė	0.552	II
Fabijoniškės	0.509	III
Karoliniškės	0.469	IV
Viršuliškės	0.437	V
Pašilaičiai	0.430	VI
Lazdynai	0.355	VII
Pilaitė	0.265	VIII

8. Multi-criteria evaluation by using the weighted average method

Calculations made using four methods (empirical, the COPRAS, the SAW and the TOPSIS) produced different results. The difference in results could arise due to physical value of indices, the level of mathematical tools and computer software, various objective circumstances, and

Table 10. The average method

Alternative	Method				
	Empirical	COPRAS	SAW	TOPSIS	The average method
Lazdynai	7	7	7	7	7
Karoliniškės	2	5	5	4	4
Viršuliškės	4	4	3	5	4
Pilaitė	8	8	8	8	8
Šeškinė	7	2	2	1	3
Justiniškės	5	1	1	1	2
Fabijoniškės	3	3	4	3	3.25
Pašilaičiai	1	6	6	6	4.75

etc. To find out which district has the best or the worst parking conditions, the average method is applied (Hwang, Yoon 1981).

Calculations according to the average method demonstrated that the best parking conditions are in Justiniškės district and the worst – in Pilaitė district (Table 10). The results showed that multi-criteria methods could be applied for parking lot development projects, considering the existing infrastructure of the district (bicycle paths, access to public transport, population in the district, and etc.).

9. Conclusions

1. The analysis of worldwide literature carried out by the authors of the article testifies that nobody in the world has created or adjusted a complex sustainable city model in respect of the development of infrastructure for transport systems. The article determined that communication capacity depends on the location of residential area within a city as well as the level of car ownership, population composition, and other factors.
2. Analysis of multi-criteria evaluation showed that the results can be applied in projects for expansion of parking lots. The existing social, economic as well as transport infrastructure has to be correctly evaluated. Calculations revealed the residential districts that are in the greatest need on parking development, i.e. Pilaitė (8.00), Lazdynai, Pašilaičiai, and etc.
3. The use of the pairwise comparison method developed by Saaty (1977) showed that the values of objective significances of indices depend on the experience, knowledge and even the state of mind of experts when filling in the questionnaire, as well as other circumstances. Based on the results of expert judgment it was assumed that the level of car ownership has the highest significance (with the value of 0.287).
4. Empirical analysis showed that a rapidly growing number of passenger cars and the increasing level of car ownership resulted in a great demand of parking spaces in residential areas, which presently manage to satisfy the need by as little as 50–60%. To increase the capacity of streets, it is suggested to decrease the number of cars parked on carriageways of the main streets of Vilnius by 10%.
5. The analysis of recent studies shows that in the future, the number of people living in residential areas will increase and this will probably cause the growth in the relative number of passenger cars. In order to avoid the lack of parking spaces in residential areas, aboveground and underground garages should be built.

The density of passenger cars parked in the multistorey residential areas of Vilnius amounts to 49–61 veh/ha. The residential parking should not be developed at the expense of green or public spaces, children's playgrounds, schools, kindergartens and etc. The current regulation on the size of such territories is not clear enough. Residents and municipalities have been trying to find solutions outside the applicable regulations. The most obvious territories are the existing underground garages, parking lots, parking lanes or territories of certain buildings of engineering infrastructure.

References

Antucheviciene, J.; Zakarevicius, A.; Zavadskas, E. K. 2011. Measuring congruence of ranking results applying particular MCDM methods, *Informatica* 22(3): 319–338.

Antucheviciene, J.; Zavadskas, E. K.; Zakarevicius, A. 2012. Ranking redevelopment decisions of derelict buildings and analysis of ranking results, *Journal of Economic Computation and Economic Cybernetics Studies and Research* 46(2): 37–62.

Bekker, J.; Viviers, L. 2008. Using computer simulation to determine operations Policie for a mechanised car park, *Simulation Modelling Practice and Theory* 16(6): 613–625. http://dx.doi.org/10.1016/j.simpat.2008.03.002

Buchanan, C. 1963. *Traffic in towns*. London: Penguin Books in association with H.M.S.O. 224 p.

Burinskienė, M.; Rudzkienė, V.; Venckauskaitė, J. 2011. Effects of quality of life on the price of real estate in Vilnius city, *International Journal of Strategic Property Management* 15(3): 295–311. http://dx.doi.org/10.3846/1648715X.2011.617857

Demirli, K.; Khoshnejad, M. 2009. Autonomous parallel parking of a car-like mobile robot by a neuro-fuzzy sensor-based controller, *Fuzzy Sets and Systems* 160(19): 2876–2891. http://dx.doi.org/10.1016/j.fss.2009.01.019

Fouladgar, M. M.; Yazdani-Chamzini, A.; Zavadskas, E. K. 2011. An integrated model for prioritizing strategies of the Iranian mining sector, *Technological and Economic Development of Economy* 17(3): 459–483. http://dx.doi.org/10.3846/20294913.2011.603173

Fouladgar, M. M.; Yazdani-Chamzini, A.; Lashari, A.; Zavadskas, E. K.; Turskis, Z. 2012a. Maintenance strategy selection using AHP and COPRAS under fuzzy environment, *International Journal of Strategic Property Management* 16(1): 85–104. http://dx.doi.org/10.3846/1648715X.2012.666657

Fouladgar, M. M.; Yazdani-Chamzini, A.; Zavadskas, E. K. 2012b. Risk evaluation of tunneling projects, *Archives of Civil Mechanical Engineering* 12(1): 1–12.

HBS Handbuch für die Bemessung von Straßenverkehrsanlagen [Manual for the design of road traffic systems], 2009, 12–13 (in German).

Huang, C-C.; Wang, S-J. 2010. A hierarchical Bayesian generation framework for vacant parking space detection, *IEEE Transactions on Circuits and Systems for Video Technology* 20(12): 1770–1785. http://dx.doi.org/10.1109/TCSVT.2010.2087510

Hwang, C. L.; Yoon, K. 1981. *Multiple attribute decision-making methods and applications. A state-of-the-art survey*. Lecture Notes in Economics and Mathematical Systems. Springer Verlag, Berlin, Heidelberg, New York. 259 p.

Kaklauskas, A.; Zavadskas, E. K.; Naimaviciene, J.; Krutinis, M.; Plakys, V.; Venskus, D. 2010. Model for a complex analysis of intelligent built environment, *Automation in Construction* 19(3): 326–340. http://dx.doi.org/10.1016/j.autcon.2009.12.006

Kalibatas, D.; Zavadskas, E. K.; Kalibatienė, D. 2011. The concept of the ideal indoor environment in multi-attribute assessment of dwelling-houses, *Archives of Civil and Mechanical Engineering* 11(1): 89–101.

Kanapeckiene, L.; Kaklauskas, A.; Zavadskas, E. K.; Seniut, M. 2010. Integrated knowledge management model for construction projects, *Engineering Applications of Artificial Intelligence* 23(7): 1200–1215. http://dx.doi.org/10.1016/j.engappai.2010.01.030

Kendall, M. 1970. *Rank correlation methods*. 4th ed. London: Griffin. 272 p.

Khang, S. C.; Hong, T. J.; Chin, T. S.; Wang, S. 2010. Wireless mobile-based shopping mall car parking system (WMCPS), in *IEEE Asia-Pacific Services Computing Conference (APSCC)*, 2010, Hangzhou, China, 573–577. http://dx.doi.org/10.1109/APSCC.2010.116

Kildienė, S.; Kaklauskas, A.; Zavadskas, E. K. 2011. COPRAS based comparative analysis of the European country management capabilities within the construction sector in the time of crisis, *Journal of Business Economics and Management* 12(2): 417–434. http://dx.doi.org/10.3846/16111699.2011.575190

Kim, D.; Chung, W.; Park, S. 2010. Practical motion planning for car-parking control in narrow environment, *IET Control Theory & Applications* 4(1): 129–139. http://dx.doi.org/10.1049/iet-cta.2008.0380

Lashari, A.; Yazdani-Chamzini, A.; Fouladgar, M. M.; Zavadskas, E. K.; Shafiee, S.; Abbate, N. 2012. Equipment selection using fuzzy multi criteria decision making model: key study of Gole Gohar iron mine, *Inzinerine Ekonomika – Engineering Economics* 23(2): 125–136.

Li, T-H. S.; Yeh, Y-C.; Wu, J-D.; Hsiao, M-Y.; Chen, C-Y. 2010. Multifunctional intelligent autonomous parking controllers for carlike mobile robots, *IEEE Transactions on Industrial Electronics* 57(5): 1687–1700. http://dx.doi.org/10.1109/TIE.2009.2033093

Medineckiene, M.; Bjork, F. 2011. Owner preferences regarding renovation measures – the demonstration of using multi-criteria decision making, *Journal of Civil Engineering and Management* 17(2): 284–295.

Michalak, H. 2005. Wybrane problemy projektowania garaży podziemnych na terenach zurbanizowanych [Main designing problems of underground garages in urban territories], *Inżynieria i Budownictwo* 61(11): 599–603.

Michalak, H. 2006. Rozwiązania funkcjonalne i konstrukcyjne garaży wielokondygnacyjnych a efektywność wykorzystania ich powierzchni [Functional and constructive solutions for multi-purpose garages effectively using the covered area], *Inżynieria i Budownictwo* 62(5): 251–254.

Michalak, H. 2008. Wybrane problemy projektowania i realizacji garaży podziemnych [Exceptional problems of design and installation of underground garages], *Inżynieria i Budownictwo* 64(2): 1–8.

Pech, A.; Warmuth, G.; Jens, K.; Zeininger, J. Parkhäuser–Garagen. 2009. *Grundlagen, Planung, Betrieb* [Basics, planning, operation]. New York: Springer. 454 p. (in German). http://dx.doi.org/10.1007/978-3-211-89239-8_9

Podvezko, V. 2008. Comprehensive evaluation of complex quantities, *Business: Theory and Practice* 9(3): 160–168. http://dx.doi.org/10.3846/1648-0627.2008.9.160-168

Podvezko, V. 2011. The Comparative Analysis of MCDA Methods SAW and COPRAS, *Inzinerine Ekonomika – Engineering Economics* 22(2): 134–146.

Saaty, T. L. 1977. A scaling method for priorities in hierarchical structures, *Journal of Mathematical Psychology* 15(3): 234–281. http://dx.doi.org/10.1016/0022-2496(77)90033-5

Saaty, T. L. 1980. *The analytic hierarchy process: planning, priority setting, resource allocation*. New York: McGraw-Hill. 287 p.

SNIP 2.07.01-89 Building regulations. 1989 (in Russian).

STR 2.06.01:1999 Miestų, miestelių ir kaimų susisiekimo sistemos [Transport and Communication Systems in the Cities, Towns and Villages]. Law of Environment Minister of Republic of Lithuania, No 61. 31 p.

Turskis, Z.; Zavadskas, E. K. 2010. A novel method for multiple criteria analysis: grey additive ratio assessment (ARAS-G) method, *Informatica* 21(4): 597–610. http://dx.doi.org/10.3846/transport.2010.52

Zagorskas, J.; Palevičius, V. 2011. Estimation of efficiency of retail centres car parking-lots, in *The 8th International Conference "Environmental Engineering"*, 19–20 May, 2011, Vilnius, Lithuania. Selected papers, Ed. by D. Čygas, K. D. Froehner, Vol. 3, 1014–1017.

Zavadskas, E. K.; Kaklauskas, A. 1996. *Pastatų sistemotechninis įvertinimas* [Multiple Criteria Evaluation of Buildings]. Vilnius: Technika. 275 p. (in Lithuanian).

Zavadskas, E. K.; Turskis, Z.; Ustinovičius, L.; Sevcenko, G. 2010a. Attributes weights determining peculiarities in multiple attribute decision making methods, *Inzinerine Ekonomika – Engineering Economics* 21(1): 32–43.

Zavadskas, E. K.; Vilutienė, T.; Turskis, Z.; Tamošaitienė, J. 2010b. Contractor selection for construction works by applying SAW-G and TOPSIS grey, *Journal of Business Economics and Management* 11(1): 34–55. http://dx.doi.org/10.3846/jbem.2010.03

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