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SIGNIFICANCE FOR ROAD QUALITY OF ASPHALT PAVEMENT INDICATORS TO EVALUATE VIOLATION TOLERANCE OF LIMIT STATES

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Abstract. Pavement must have the characteristics that allow safe, fast, comfortable, economical and reliable vehicle traffic. The normative documents introduce limit values and permissible deviations of the controlled parameters of the road pavement, for which penalty deductions are levied if they are not satisfied or exceeded. The asphalt pavement installation rules for the ĮT ASFALTAS 08 contain 10 such indicators, whose relevance in respect of road quality is investigated in this paper. The relative weights of each indicator (defect) have been determined using assessments from 91 experts. The methods used in the study are rank correlation, ARTIW-L, ARTIW-N (Average Rank Transformation into Weight Linear and Non-linear), and DPW (Direct Percentage Weight). The expert team's opinions are consistent because the empirical concordance coefficient value of 0.715 is 34.6 times higher than the minimum concordance coefficient value of 0.021. The most important indicators for the experts are the lower degree of compaction, the lower thickness of the layer, and the lower amount of binder. A pilot project dedicated to determining the required number of experts

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has shown that the number of experts in a team, exceeding 20, has almost no effect on the average of ranks and percentage weights of the criteria.

Keywords: asphalt pavement, criteria weights, expert evaluation, limit values, MCDM, permissible deviation, quality indices, quality assurance.

Introduction

The participants in the road construction process and road users have direct or indirect benefits related to the elaboration of new transport infrastructure (Sivilevičius et al., 2024). Once the road pavement layer has been laid, it is checked for proper installation. Quality control is carried out by inspecting the installed section of road, measuring the geometric parameters of the layer, and examining the composition and structural characteristics of the asphalt. The installed layer is to be monitored by the technical supervisor, who will compare the actual values of the quality indicators, established by standardized methods, aiming for the design (rational or best) values. The higher the road pavement quality, the larger benefit for road.

The rules for the installation of asphalt layers in asphalt pavement construction (ĮT ASFALTAS 08, 2008) that were in force until 1 March 2024 provided the parameters that had to be monitored. The rules also contain limit values (LV) or permissible deviations (PD) of 10 parameters (indicators), for which penalty deductions are made in case of non-compliance or exceedance. For all asphalt layer indicators, deviations from the best values are allowed, but not more than the limits set in the standards. The limit values in compliance with permissible deviations for asphalt pavement parameters are established on the basis of production experience, research results, economic rationality, and the technological capacity of the equipment used (asphalt mixing plants, pavers, and compactors). They must be realistic (achievable) within the technological requirements for the installation of the asphalt layers. The limit values and permissible deviations in national regulatory documents tend to change, becoming more and more strictly over time. A section of road pavement laid outside the limit values or exceeding permissible deviations is considered regarding the significance of observed defects. Penalty deductions due to defects are an effective economic tool forcing the contractor to increase the pavement quality, i.e., to maximize the quality of the asphalt pavement for subsequent exploitation.

Failure to comply with the limit values of the asphalt layer quality indicators and exceeding the permissible deviations results in deteriorating quality of road pavement; it becomes weaker, shorter-lasting, and poorer performing road pavement and transport performance indicators. The larger deviations from the required parameters result in the poorer quality of the asphalt pavement. It is likely that the normative LV and PD for each parameter of the asphalt pavement layer have different significance for the road quality. Their significance can be determined by means of expert subjective opinion surveys, which allow the relative weights of the parameters to be evaluated quantitatively (numerically).

Deviations from the design content of asphalt mix components, non-compliance with the required values for the structure and texture of the asphalt layer and violation of the normative limit values of geometric parameters of the asphalt layer contribute to the deterioration of road pavement quality.

1. Literature review

The quality of the asphalt layer depends on the quality of the mix produced in the asphalt mixing plant (AMP), the conditions under which the mix is stored and transported to the construction site, the technological characteristics of the paving and compaction process, and the weather conditions (Hanzik et al., 2015; Blažejowski & Styk, 2009). The qualities of hot mix asphalt (HMA) produced in an asphalt mixing plant (AMP) are influenced by the quality of the materials used, the design of the composition, and the quality of the production (Petkevičius & Sivilevičius, 2008).

The structure of asphalt as a composite material consists of inclusions (mineral grains of different sizes), a matrix (bituminous binder), and air voids. Their mass ratio may deviate from the design (rational) values due to inadequate dose mass of the final batching materials or an insufficient mixing quality. The quantity of deviated components in the asphalt mixture is increased by the segregation heterogeneity of the hot fractions (Sivilevičius & Vislavičius, 2008). Deviations from the design optimum value and variation in the amount of bituminous binder in the produced asphalt mix can be reduced by upgrading the bitumen dosing system in AMP (Bražiūnas & Sivilevičius, 2010).

Asphalt mixture consists of asphalt coarse and fine aggregate, and a number of additions occasionally used to improve its engineering properties. The purpose of mixture design is to select an optimum bitumen content for a desired aggregate structure to meet prescribed criteria (Abreha, 2007). The models of constrained and unconstrained non-linear optimization are developed allowing us to choose the best HMA mixture gradation based on mineral materials, whose gradation is known, when the total percent passing of HMA mixture aggregates is considered to be equally important for all sieves or when the preference is given to some of the sieves (Sivilevičius et al., 2011).

The Superpave design mainly uses volumetric properties for the mix design, similar to the Marshall Method. The asphalt binder content, determined from the Superpave mix design procedure is lower than that of predicted by the Marshall

Mix design procedure (Jitsangiam et al., 2013). The effect on Marshall Stability (MS) of HMA parameters, namely the particle diameters of aggregates, quantity of bitumen in the HMA, different environmental temperatures and the exposure times was investigated by Özgan et al. (2013). Changes in gradation make a change in aggregate specific surface, thus the mixture needs different bitumen content to coat aggregate particles, to bind them one from another, and to make a stiff material resistant to rutting (Remišová, 2015).

Aggregates are usually classified by their size when blending the aggregate proportions in the mixture. Generally, aggregates larger than 4.75 mm are categorized as coarse, whereas those smaller than 4.75 mm are assigned to fine aggregates. Filler refers to aggregate particles finer than 75 µm in size (Zulkati et al., 2012). According to Lithuanian standards, coarse aggregates are defined by grains of diameter larger than 2 mm, fine aggregates – those of grains corresponding to the interval bounds of 0.063 and 2 mm, and the mineral filler for grains with a diameter smaller than 0.063 mm. The presence of filler in the asphalt mixture is even more important because of its possible interaction with bituminous binder.

The presence of moisture in asphalt pavements detrimentally affects the bond between the aggregate and the binder (adhesive failure) and the bond within the binder (cohesive failure). The loss of these bonds leads to the deterioration of asphalt pavements (Kassem et al., 2013).

It is pointed out that the main indices characterising the condition and service life of asphalt pavement and its structure are HMA mixture resistance to binding tension, tensile elasticity modulus, and fatigue resistance. The values of these indices highly depend on the component content, the structure of HMA mixture, and its compaction ratio or level (Petkevičius et al., 2009).

The resilient modulus of flexible pavement material is affected by many factors, including the temperature profile in the pavement, pavement drainage and moisture, frost and pavement compaction (Alkasawneh et al., 2007). The compaction of asphalt concrete, quantified by air voids, is a significant performance factor. Low air void levels often result in bleeding, rutting, or shoving. High air void levels often result in durability issues (e.g., moisture damage, oxidation, ravelling, or cracking) (Williams et al., 2015). Several factors influence compaction of HMA mixture; some are related to the environment, some are determined by mixture and structural design, and some – by contractor during construction. The temperature of asphalt mixture has the biggest influence on the compaction of asphalt mixtures and their properties (Androjić & Dimiter, 2015).

The temperature of asphalt mixture during its laying out is not homogeneous. Apart from the aspect of the mass cooling during its transportation, the losses of heat are a result of climatic and weather conditions, the operation and compaction method of rollers, water and the location of the profile (Mieczkowski, 2010). The effects of compaction level and the binder content on performance properties of asphalt mixtures for designed asphalt concrete type when considering wearing and binder courses were investigated by Hýzl et al. (2016). The case of HMA mixture for compacting describes workability of the HMA mixture (Haryanto & Takahashi, 2007).

Evaluation methods and tools used to assess pavement conditions serve as the main information during exploitation for infrastructure engineers, technicians, budget planners, and decision makers (Thodesen et al., 2012). Many past studies (LaVassar et al., 2009) have investigated whether the contractor performed quality control (QC) test (from samples taken at the plant) is statistically analogous to the agency performed quality assurance (QA) tests (samples taken behind the paver). Many studies yielded that processed QA and QC data represented statistical terms of different populations (Karimi et al., 2012). Sivilevičius et al. (2008) proposed a multi-attribute model for an efficient quality assessment of the AMP. To solve this problem, nine main quality attributes were selected and weighted by an expert ranking method.

Many HMA plants store the mixture in heated silos before it is ready to be transported to construction sites. The time that the mixture is stored in the silo is not controlled and varies widely, depending on several factors. As the mixture is exposed to elevated temperatures, short-term aging of the binder may occur (Jacques et al., 2016). The aging asphalt binder has a crucial impact on durability for bituminous bound materials. Since asphalt binder is organic by nature, the thermal and oxidative aging process affected by chemical and structural changes are recognised in time and related to certain time intervals, starting from production, installation, and exploitation of asphalt mixes (Hofko et al., 2015). Analysing effects related to the changes of asphalt binders, resulting in the performance measures up to all critical states of asphalt mixtures, it was identified to be a governing factor, affecting the pavement performance. Liu and Wen (2015) developed a methodology to predict the rheological and damage properties of asphalt binders, subjected to aging.

The actual composition of the produced asphalt mix is determined from the considered representative samples, eventually differing from each other and the job mix formula (JMF) due to segregation processes (Vislavičius & Sivilevičius, 2013). When the mixture segregates, the bitumen content usually is higher for the finer material and lower for the coarser material (a fact to account when the laboratory samples were prepared) (Brown et al., 1989).

For the quality control of the newly constructed road sections, the Ground Penetrating Radar (GPR, georadar) can be employed as the instrument for fast and efficient determination of the thickness of layers (Ožbolt et al., 2012). To improve the quality control of road construction works, following the recommendations by Baltrušaitis et al. (2022), one can use the developed GPR mathematical model for the control of the compaction degree of asphalt layers installed using the asphalt concrete mixtures AC32PS, AC22PS, AC16AS, and AC16PD. Compared to conventional destructive methods, the application of the GPR method yields a significant increase in the reliability of measurement by determining the compaction degree of the installed layer in a significantly large area.

The method, employing the straightedge, was the first method of longitudinal road unevenness quantification. It is based on the measurement of maximum clearance between the road surface and the 3-m straightedge laid on it. The system of European standards EN 13036 addresses the different kinds of road and airfield unevenness and irregularities; straightedge method is considered a recognized estimation method (CEN 2003) (Múčka, 2012a).

International Roughness Index (IRI) refers to the cumulative vertical displacement of a quarter-vehicle model at a speed of 80 km/h. Different measurement methods are used in different countries. The IRI summarises the roughness qualities that impact vehicle response and is most appropriate when a roughness measure is desired that relates to an overall vehicle operating cost, an overall ride quality, the dynamic wheel loads, and an overall pavement condition (Sayers & Karamihas, 1998). The study by Múčka (2012a) presents the regression relationships between two commonly used indicators of longitudinal road unevenness and the straightedge index. Five differently defined straightedge indices, i.e., the deviations between straightedge and profiles, were considered. The results were calculated as a function of a straightedge length in the range of 3 to 7.8 m. The study by Múčka (2012b) compares three alternative straight-line approximations of the longitudinal road-profile power spectral density. Pavement friction is one of the primary factors affecting highway safety. Pavements with an adequate pavement friction reduce the number of wet skidding crashes (Kassem et al., 2013).

Friction properties of the road pavement have a great influence on the safety of automobile motion. These properties are characterised by the tyre-to-road adhesion coefficient, which is measured during the routine and investigations of roads acceptance (Pokorski et al., 2015). Past experimental studies show that tire-pavement friction values are related to conditions surrounding the tire, such as a pavement temperature, an ambient temperature, a contained air temperature, and pavement parameters. For measurements processed at different temperature conditions, the road agencies generally apply correction factors (Anupam et al., 2013). The seasonal and the long-term variations have a significant effect on skid resistance evaluation. The development model addresses that skid resistance is strongly related to the past level of pavement friction, traffic, temperature, and precipitation (Plati & Georgouli, 2014). The effect of pavement macrotexture on crashes was also observed to vary by the pavement type. Results obtained indicated that maintaining pavement macrotexture greater than or equal to 1.016 mm on asphalt pavements would reduce crashes and enhance safety through improved braking performance on Interstates (Pulugurtha et al., 2012).

The Asphalt Institute provides two design methods for the design of HMA overlay on a conventional asphalt pavement (Asphalt Overlays..., 1999). The first method, known as the effective thickness method, determines the required overlay thickness by subtracting the effective thickness of the existing pavement from the required thickness of a new full depth asphalt pavement to carry the same traffic volume (Sarker et al., 2015).

Sarker et al. (2015) present a mechanistic-empirical approach for overlay thickness design of low-volume pavements through a combination of non-destructive deflection testing and pre-established pavement damage models. The thickness of the paved asphalt layer, less the thickness established in design, weakens the asphalt layer, reducing the reliability and durability of the pavement structure. One must note that non-destructive deflection testing techniques measure only upper surface of the asphalt layer. This deflection, limited by normative requirement, is a result of reduction of the complex structure consisting of structural layers, such as the pavement structure layers, designed according to normative documents, and the layers of basement. Thus, a deformable behaviour, as well as the design of a rational structure, depends on selected design layers of pavement structure (their height and the modulus of deformation) and that of the basement layers (Lehmann et al., 2020). Therefore, an expert who understands the accuracy of the methods for determining the modulus of deformation and other parameters must take into account the nature of the measured total deflection of upper surface in concert the accuracy of indicators and their weights when considering complex structure components.

Ai et al. (2022) proposed a comprehensive evaluation method for very thin asphalt overlays based on the analytic hierarchy process (AHP) and the technique for order of performance by similarity to ideal solution (TOPSIS). Four road performance indicators (a pavement condition indicator, a British pendulum number, a texture depth and an international roughness index) were selected as the evaluation indices, and their weights were calculated using the AHP according to the questionnaires collected from specialists. Multi-Criteria Decision Making (MCDM) methods allow determining the significance of the quality indicators of the asphalt pavement layers.

2. The investigated asphalt pavement quality indicators

The suitability of the asphalt layer of the asphalt pavement was determined by the quality indicators assessed in ĮT ASFALTAS 08 (2008), for which penalty deductions were levied for non-compliance with the limited values or for exceeding the permissible deviations. The following parameters were established and assessed during the quality control (QC) of the asphalt layer: A – lower thickness of the layer; B – lower binder content; C – lower or higher fraction > 2 mm (coarse aggregate) or 0.063 to 2 mm (fine aggregate) amount; D – lower or higher fraction < 0.063 mm (mineral filler) amount; E – lower degree of compaction; F – exceedance of the limited values for roughness measured in accordance with the IRI requirements; G – exceedance of the limited values for roughness measured with a 3 m straightedge; H – exceedance of the pavement cross-slope permissible deviation; I – exceedance of the pavement width permissible deviation; J – lower coefficient tire – road friction.

The significance of the quality indicators (criteria) of the new asphalt pavement layer on the quality of the road was assessed by a team of experts. The qualification, knowledge, the scientific and practical experience, and an ability to understand the content of the questionnaire influenced the results of the assessments. Each expert ranked the criteria in the questionnaire from the most important criteria (rank 1) to the least important criteria (rank 10). Tied ranks were not considered. Each expert also weighted the importance of the criteria by giving them direct percentage weights, so that the most important criteria would have the higher percentage weights and a sum of all weights was equal to 100.0%.

It was expected that the main quality indicators, related to non-compliance with limited values or exceeding of permissible deviations (most difficult to identify practically) had to be assigned the highest number of penalty deductions. Such an approach results in subjective assessments by the experts, giving quantitative priorities to the criteria. One must note that acknowledged experts (practitioners in road engineering) that agreed to participate in the current study were selected.

3. Methods for calculating the significance of criteria

The impact of individual quality indicators describing the object under study on the objective under consideration varies; hence, it is important to determine the significance, i.e., the weight, of these indicators when applying quantitative multi-criteria assessments. The most commonly applied assessment is subjective, where the weights of the indicators are determined by specialised experts (Podvezko, 2008).

An expert who has good knowledge of the subject and understands the nature of the indicators (criteria), characterising them, can rank them in order of importance, i.e., to assign ranks to the criteria. The significance of any two adjacent criteria, weighted by their ranks in the absence of associated (tied) ranks, differs by one, i.e., by the same number. Often direct weighting in percentages or in unit fractions is used. In other cases, also based on expert assessment, the weights of the criteria are determined indirectly, e.g., employing the AHP method (Saaty, 1980). The weights determined by the direct and indirect weighting methods usually differ in respect of different increments.

91 experts with practical experience in road design, construction, maintenance and survey, and having the certificate of competence, were employed in this study. The high level of qualification and the large number of experts in the team allowed obtaining the reliable results. This does not mean that all the experts gave the same assessment of the importance and priority of the criteria. The theory of expert research methods suggests that the opinions of a team of experts may differ; however, the differences should not be too big (Kendall & Gibbons, 1990).

The consistency of the opinions of the team of experts was determined from the ranks given to the criteria by calculating Kendall's concordance coefficient W by the Equation (1):

$$W = \frac{12S}{n^2\left(m^3 - m\right)}, \tag{1}$$

where m – is the number of criteria (i = 1, 2, ..., m); n – is the number of experts (j = 1, 2, ..., n); S – is the sum of the ranks for each m-th criteria $\sum_{j=1}^{n} R_{ij}$ deviations from the overall average rank $\bar{R} = 1/2n\left(m+1\right)$ sum of squares.

The sum of the squares S is calculated by the Equation (2):

$$S = \sum_{i=1}^{m}\left[\sum_{j=1}^{n} R_{ij} - \frac{1}{2}n\left(m+1\right)\right]^2. \tag{2}$$

The consistency of the opinions of the team of experts assessing the subject matter can be determined in a classical way by calculating the chi-square (χ^2) statistic according to Equation (3):

$$\chi^2 = \frac{12S}{nm\left(m+1\right)}, \tag{3}$$

which, when the opinions of the experts are in agreement (non-contradictory), must be higher than the critical $\chi^2_{v,\alpha}$ value, depending on the number of degrees of freedom $v = m - 1$ and on the chosen significance level α. The level of significance used in practice is α = 0.05 or even stricter one, namely α = 0.01 where the $\chi^2_{v,\alpha}$ values are given in the mathematical statistics table (Montgomery, 2013).

The consistency of the experts' opinions can be determined by calculating the minimum concordance coefficient $W_{\min}$ value applying Equation (4) (Maskeliūnaitė & Sivilevičius, 2021):

$$W_{\min} = \frac{\chi^2_{v,\alpha}}{n\left(m-1\right)}. \tag{4}$$

When the empirical concordance coefficient W is larger than the minimum value W_{min}, the team of experts can be considered to be free of contradictory opinions.

How many times higher is the W than W_{min} and how many times greater is χ^2 than $\chi^2_{v,\alpha}$ is indicated by the compatibility coefficient k_{c}, which is calculated from formula (5) (Sivilevičius & Martišius, 2023):

$$k_{\text{c}} = \frac{\chi^2}{\chi^2_{v,\alpha}} = \frac{W}{W_{\text{min}}}. \tag{5}$$

The opinions of a team of experts in assessing the importance of asphalt pavement quality indicators to road quality can be considered to agree when k_{c} is greater than 1. The larger value corresponds to the more homogeneous opinion case, and the averages of their estimates (ranks, percentage scores) can be taken as reliable significance for each criterion. Similarly, larger k_{c} indicates that fewer experts can be interviewed to obtain reliable data. The minimum number of experts in the team depends on the variance of the ranks, the required precision and the probability, i.e., it is calculated from the sample size formula.

From the average of the ranks $\bar{R}_i$, corresponding each i-th criteria using the ARTIW-L (Average Rank Transformation into Weight – Linear) method, the normalised relative weight of the i-th criteria is calculated as follows:

$$\omega_i^{\text{ARTIW-L}} = \frac{m - \bar{R}_i + 1}{\sum_{i=1}^{m} \bar{R}_i}. \tag{6}$$

The weight $\omega_i^{\text{ARTIW-L}}$ is functionally related to the mean of the ranks $\bar{R}_i$ by a negative linear relationship.

Also, from the average $\bar{R}_i$ of each i-th criteria (i = 1, 2, ..., m) using the ARTIW-N (Average Rank Transformation into Weight – Non-linear) method, the normalized relative weight of the criteria is calculated as follows:

$$\omega_i^{\text{ARTIW-N}} = \frac{\min\limits_i \bar{R}_i}{\bar{R}_i \cdot \sum_{i=1}^{m} \frac{\min\limits_i \bar{R}_i}{\bar{R}_i}}. \tag{7}$$

The normalized relative weight $\omega_i^{\text{ARTIW-N}}$ is related to the mean of the ranks by functional negative curvilinear relationship $\bar{R}_i$.

The relative weight of all criteria can be calculated using the DPW (Direct Percentage Weight) method by Equation (8):

$$\bar{\omega}_i^{\text{DPW}} = \frac{\sum_{j=1}^{n} P_{ij}}{100n}, \tag{8}$$

where P_{ij} is the percentage weighting given by the j-th expert (j = 1, 2, ..., n) to the i-th criteria (i = 1, 2, ..., m), note that

$$P_j = \sum_{i=1}^{m} P_{ij} = 100.0\%.$$

The normalized relative weights of criteria $\bar{\omega}_i^{\text{DPW}}$ are correlated in a negative or positive curvilinear relationship with the respective weights of these criteria $\omega_i^{\text{ARTIW-L}}$ and $\omega_i^{\text{ARTIW-N}}$.

The average of the subjective normalized relative weights of the criteria $\bar{\omega}_i$ calculated by the three different MCDM methods is more reliable than the weights calculated by any of these methods. Assuming that none of these methods has a theoretical advantage over the other methods, the average of the weights is calculated using Equation (9):

$$\bar{\omega}_i = \frac{\omega_i^{\text{ARTIW-L}} + \omega_i^{\text{ARTIW-N}} + \bar{\omega}_i^{\text{DPW}}}{3}. \tag{9}$$

The reliability of the obtained result could be further improved by applying the AHP.

4. Results and discussion

4.1. Consistency of opinions of the expert team

Table 1 presents the significance of all the asphalt pavement parameters for which non-compliance with the limit values (LV) or exceedance of the permissible deviations (PD) results in penalty deductions according to the requirements of ĮT ASFALTAS 08 (2008), as determined by a team of 91 experts.

The concordance coefficient W, calculated by Equation (1), is equal to:

$$W = \frac{12S}{n^2\left(m^3 - m\right)} = \frac{12 \times 488304}{91^2\left(10^3 - 10\right)} = 0.715.$$

The minimum value of the concordance coefficient $W_{\min}$ calculated by Equation (4), where $v = m - 9$ and $\alpha = 0.05$, is equal to:

$$W_{\min} = \frac{\chi^2_{v,\alpha}}{n(m-1)} = \frac{16.92}{91(10-1)} = 0.021.$$

The chi-square (χ^2) statistic calculated by Equation (3) is equal to:

$$\chi^2 = \frac{12S}{nm(m+1)} = \frac{12 \times 488304}{91 \times 10(10+1)} = 585.38.$$

The coefficient of compatibility of the opinions of the team of experts k_c calculated by Equation (5) is equal to:

$$k_c = \frac{\chi^2}{\chi^2_{v,\alpha}} = \frac{W}{W_{\min}} = \frac{585.38}{16.92} = \frac{0.715}{0.021} = 34.6.$$

The above calculated values yield that the evaluations of 91 experts are in agreement, i.e., not contradictory, regarding the relevance of asphalt pavement performance defects to road quality.

Table 1. Significance for asphalt quality of road pavement indicators for which penalty deductions are calculated for non-compliance with limit values and permissible deviations

Formula and method	Quality indicator (criterion) i = 1, 2, ..., m										Total
	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	
$\sum_{j=1}^{n} R_{ij}$	213	221	453	481	179	582	652	671	849	704	5005
$\bar{R}_i = \sum_{j=1}^{n} R_{ij} / n$	2.341	2.429	4.978	5.286	1.967	6.395	7.165	7.373	9.330	7.736	55.000
$\sum_{j=1}^{n} R_{ij} - \frac{n(m+1)}{2}$	−287.5	−279.5	−47.5	−19.5	−321.5	81.5	151.5	170.5	348.5	203.5	0
$\left[\sum_{j=1}^{n} R_{ij} - \frac{n(m+1)}{2}\right]^2$	82 656	78 120	2256	381	103 362	6642	22 952	29 071	121 452	41 412	488 304
ARTIW-L method: $\omega_i^{\text{ARTIW-L}} = \frac{m+1-\bar{R}_i}{\sum_{i=1}^{m} \bar{R}_i}$	0.1575	0.1559	0.1095	0.1039	0.1642	0.0837	0.0697	0.0659	0.0304	0.0593	1.0000
Priority	2	3	4	5	1	6	7	8	10	9	55
ARTIW-N method: $u_i = \frac{\min_i \bar{R}_i}{\bar{R}_i}$	0.8403	0.8099	0.3951	0.3721	1	0.3076	0.2745	0.2668	0.2108	0.2543	4.7314
$\omega_i^{\text{ARTIW-N}} = \frac{u_i}{\sum_{i=1}^{m} u_i}$	0.1776	0.1712	0.0835	0.0786	0.2114	0.0650	0.0580	0.0564	0.0446	0.0537	1.0000
Priority	2	3	4	5	1	6	7	8	10	9	55
DPW method: $\bar{\omega}_i^{\text{DPW}} = \frac{\sum_{j=1}^{n} P_{ij}}{100n}$	0.1792	0.1603	0.1014	0.0926	0.1798	0.076	0.0625	0.06	0.0324	0.0558	1.0000
Priority	2	3	4	5	1	6	7	8	10	9	55
Average weight of three methods	0.1714	0.1625	0.0981	0.0917	0.1851	0.0749	0.0634	0.0608	0.0358	0.0563	1.0000
Priority	2	3	4	5	1	6	7	8	10	9	55

4.2. Ranks and relative weights of criteria

The very high level of agreement between the expert team's opinions allowed the average of the asphalt pavement ratings for each criterion to be used as a reliable result of the considered problem. In practice, it is common for more important criteria to have larger significance estimates against the less important criteria. Therefore, the averages of the ranks of the criteria $\bar{R}_i$ were transformed into normalized relative weights $\omega_i^{\text{ARTIW-L}}$ and $\omega_i^{\text{ARTIW-N}}$ using the Average Rank Transformation into the Weight-Linear (ARTIW-L) method and the Non-linear (ARTIW-N) method (Table 1). This table also gives the weights of the criteria ω_i^{DPW} calculated by the DPW method.

An analysis of the relative weights and the priorities of the criteria (Table 1) shows that the most important for experts are the following criteria: the lower degree of compaction of the asphalt layer (E), the lower thickness of the layer (A) and the lower amount of binder (B). Of moderate significance are lower or higher content of fraction >2 mm or 0.063–2mm and fraction <0.063 mm (D) and exceedance of limited values for roughness measured in accordance with the IRI requirements (F). The experts consider that the exceedance of the limits for roughness measured with a 3 m length straightedge (G), the exceedance of the permissible deviation for the cross slope of the pavement (H), and the lower coefficient of grip of the tire-road friction (J) are even less important. The least significant for road quality is the exceedance of the pavement width permissible deviation (I).

The relative weights of all the criteria, from the most significant to the least significant, led to the following sequence: $E \succ A \succ B \succ C \succ D \succ F \succ G \succ H \succ J \succ I$.

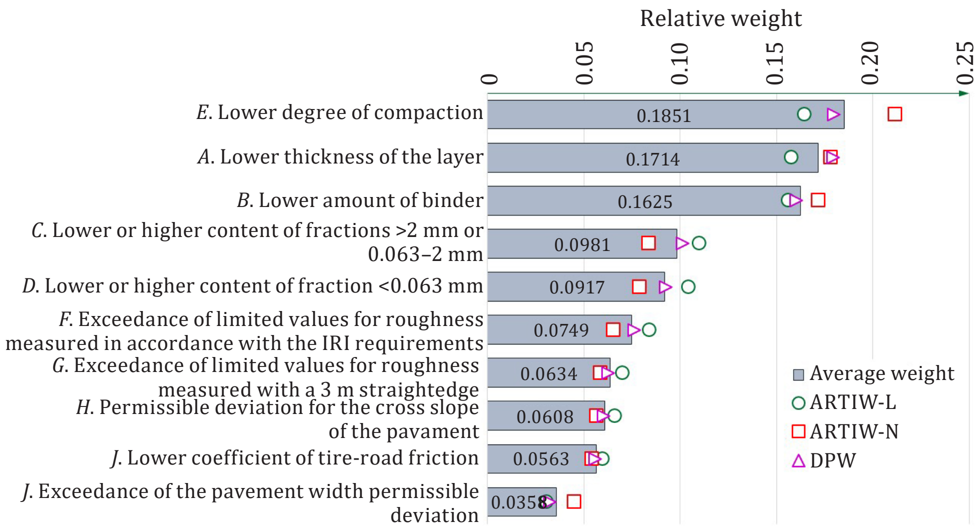

Figure 1. Relative weights and averages of the significance of the asphalt pavement indicators for road quality, calculated by different methods

4.3. Regression models for the relative weights of criteria

The relative weights of each criteria calculated by the three methods, although slightly different, are of the same priority when compared to the other criteria. The regression analysis shows that the weights of the criteria $\omega_i^{\text{ARTIW-L}}$ calculated by the ARTIW-L method with a linear negative functional relationship $\omega_i^{\text{ARTIW-L}} = 0.2 - 0.0182\bar{R}_i$ are related to the average of the ranks of these criteria $\bar{R}_i$. The weights of the criteria $\omega_i^{\text{ARTIW-N}}$ calculated by the ARTIW-N method are correlated with the functional negative curvilinear dependence $\omega_i^{\text{ARTIW-N}} = 0.4158\bar{R}_i^{-1}$. The coefficients of determination of the regression equations calculated by both methods are $R^2 = 1$ (Figure 2a).

The pairwise correlation of the relative weights of the criteria calculated by the DPW, ARTIW-L and the ARTIW-N methods (Figure 2b, c, d) shows that $\omega_i^{\text{ARTIW-N}}$ with $\omega_i^{\text{ARTIW-L}}$, $\bar{\omega}_i^{\text{DPW}}$ with $\omega_i^{\text{ARTIW-L}}$ and $\bar{\omega}_i^{\text{DPW}}$ with $\omega_i^{\text{ARTIW-N}}$ are linked by positive and negative curvilinear correlations ($y = a + bx + cx^2$) and their coefficients of determination R^2 are equal to 0.9882, 0.9937 and 0.991, respectively. From the processed equations or regression curves, the weight of the criteria calculated by one method can be used to determine the weight of that criteria calculated by another method.

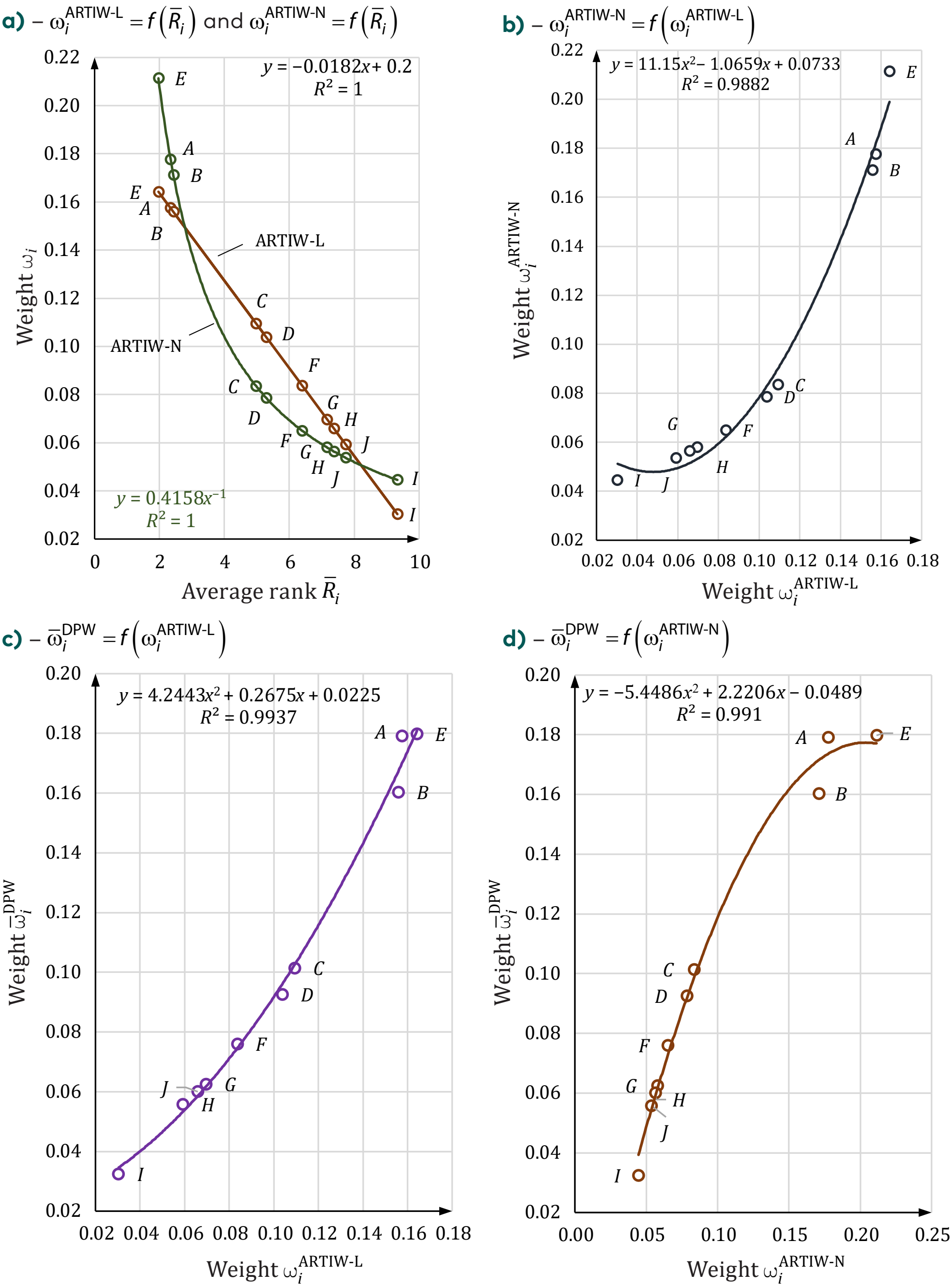

Figure 2. Regression models for the significance of the asphalt pavement quality criteria determined by the different MCDM methods.

4.4. Benchmarking of criteria weights

How many times one criterion is more important than another when considering the quality of the road pavement is deduced from the weight ratios of the criteria compared in pairs (Table 2).

Table 2. Relative weights of the significance for road quality of the indicators of the asphalt pavement layer

Quality of asphalt pavement		Indicators (criteria) *i* = 1, 2, ..., *m*									
		E	**A**	**B**	**C**	**D**	**F**	**G**	**H**	**J**	**I**
Indicator (criterion) *i* = 1, 2, ..., *m*	**E**	1	1.08	1.14	1.89	2.02	2.47	2.92	3.04	3.29	5.17
	A		1	1.05	1.75	1.87	2.29	2.70	2.82	3.05	4.79
	B			1	1.66	1.77	2.17	2.63	2.67	2.89	4.54
	C				1	1.07	1.31	1.55	1.61	1.74	2.74
	D					1	1.22	1.45	1.51	1.63	2.56
	F						1	1.18	1.23	1.33	2.09
	G							1	1.04	1.13	1.77
	H								1	1.08	1.70
	J									1	1.57
	I										1

In this table, the criteria are presented in descending order of their relative weights from left to right in rows and from top to bottom in columns. The criteria are compared in pairs by dividing the relative weight of the most important criteria on the left-hand side of the table (row) by the weight of the criteria at the top of the table (column). The ratio of the relative weights of the criteria indicates the dominance of the more important criteria against the less important criteria.

The calculation data (Table 2) show that the most important criterion E (lower compaction degree) is only 1.08 and 1.14 times more important than criterion A (lower thickness of the layer) and criterion B (lower binder content), respectively. It is even 5.17 times more significant than criterion I (exceeding the permissible deviation of the pavement width).

4.5. Impact of the number of experts in the team on the significance of the criteria

The experts participating in the study and the ranks (R) and percentage weights (P) given to their criteria were listed in random order from 1 to 91. The random order of the experts allowed them to be included in any sample set with equal probability. The entire team of experts was divided into 9 sub-teams: the first from $E1$ to $E11$, the second from $E1$ to $E21$, the third from $E1$ to $E31$, the fourth from $E1$ to $E41$, the fifth from $E1$ to $E51$, the sixth from $E1$ to $E61$, the seventh from $E1$ to E71, the eighth from $E1$ to $E81$ and the ninth from $E1$ to $E91$. By increasing each sub-team by ten experts, a uniform change of step in the sample size was set.

The arithmetic means $\overline{R}_i$ and $\overline{P}_i$ of the ranks and percentage weights of all m criteria were calculated for each sample of different size n (Figures 3a and 4a). The standard deviations σ_R and σ_P of the ranks and the percentage weights of the criteria were also calculated (Figures 3b and 4b).

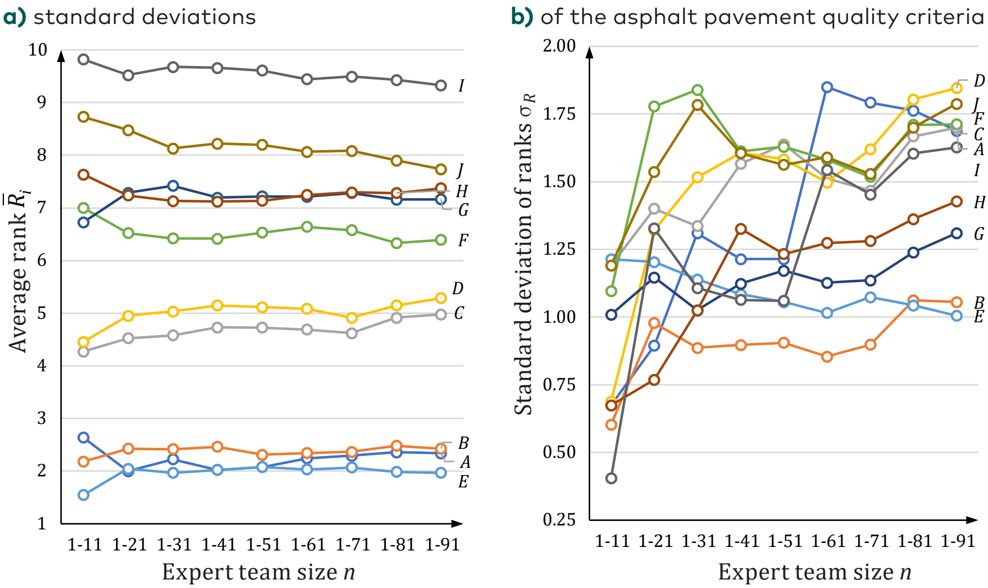

Figure 3. Dependence of the rank means on the number of experts in the team: (a) standard deviations; (b) of the asphalt pavement quality criteria

The study shows that increasing the number of experts (sample) from $n = 21$, the average ranks of the criteria $\overline{R}_i$ changed slightly (Figure 3a). The standard deviations of the criteria ranks σ_R for a small number of experts n (up to 21) are significantly lower than the ranks calculated from the larger sample σ_R (Figure 3b). The largest differences σ_R are obtained for the lower layer thickness (criterion A), as from 10.07.2018 no penalty deductions are calculated for this defect, but the layer has to be changed by a new one. Therefore, the experts assessed the significance of this defect very differently. In assessing the significance of this criterion, the team of 61 experts assigned it the rank of 1 (twenty-one experts) and the rank of 10 (two experts), which increased the variation of opinions ($\sigma_R = 1.85$, i.e., the largest value). By increasing the team of experts, the ranks $R_{ij} = 10$ corresponding to the criterion A by these two experts decreased the impact on the variation of opinions and stabilization was achieved for $n = 81$. The ranks σ_R for most of the criteria ranged between 0.9 and 1.9. Therefore, when more than $n = 21$ experts are interviewed in the pilot project, the variation in opinions on the significance of the criteria, expressed in terms of ranks, becomes insignificant.

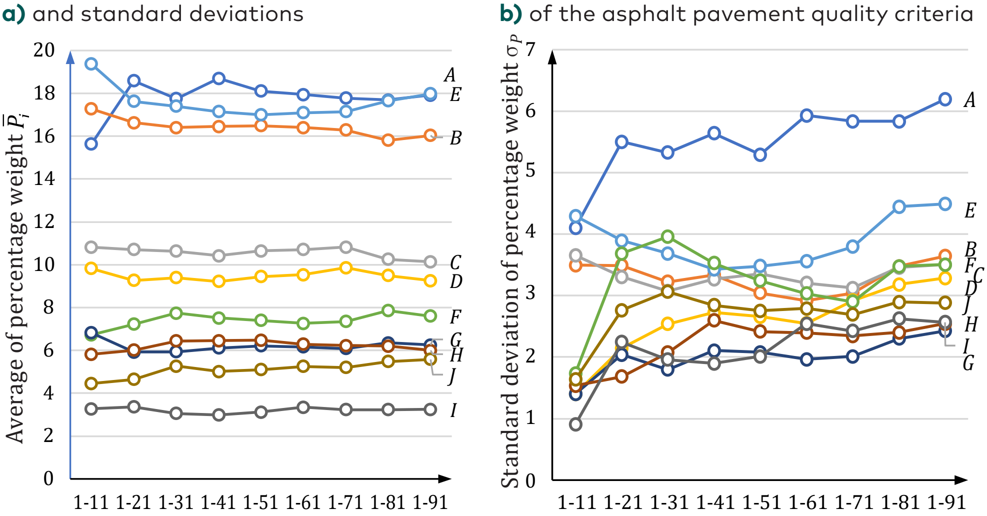

Figure 4. Dependence of the percentage weight means on the number of experts in the team: (a) and standard deviations; (b) of the asphalt pavement quality criteria

The averages of the percentage weights of the criteria $\overline{P}_i$ stabilized after interviewing more than $n = 31$ experts (Figure 4a). The standard deviations, which show their variation σ_P, are significantly less for the small sample of experts, i.e., for $n = 11$. When the number of experts n increased from 21 to 91, the σ_P values varied within bounds of 2% and 4% (Figure 4b). They were largest when considering the most of criteria for cases $n = 81$ and $n = 91$, respectively. The larger standard deviations σ_P indicate that an increment of the number of experts in the team is necessary to obtain the reliable results for the significance of the criteria.

The minimum number of experts in the team $n_{\min}$ can be calculated using the sample size methodology (Navikas et al., 2016; Navikas et al., 2018):

$$n_{\min} = \frac{t^2 \sigma_R^2}{\Delta_R^2}, \tag{10}$$

where t is the value of t (Student's) distribution, which depends on the probability employed to assess the importance of the criterion. When the probability $P = 95\%$ (significance level is $\alpha = 0.05$ for one-side test), $t = 1.96$. The σ_R is a standard deviation of the ranks R_{ij} of the evaluated criteria; Δ_R is the absolute error experts rank values of the i-th criteria, indicating the accuracy of the survey results.

When $t = 1.96$, the maximum value is $\sigma_R = 1.9$ (Figure 3b) and $\Delta_R = 1$, the estimated value is $n_{\min} = 13.9$, and for $\Delta_R = 0.5$, the $n_{\min} = 55.5$.

The average of the ranks $\bar{R}_i$ given to the most variable criteria F, J by the team of 91 experts differs from the population mean R_{iP} with tolerance $\pm\Delta_R$ which for the considered case is:

$$\Delta_R = \sqrt{\frac{t^2 \times \sigma_R^2}{n}} = \sqrt{\frac{1.96^2 \times 1.9^2}{91}} = 0.39.$$

Sample mean of the ranks $\bar{R}_i \approx 9$ for the least important criteria I, ensuring the guarantee of 95% probability that the mean of the population of ranks R_{iP} differs from $\bar{R}_i$ up to $0.39/9 \times 100 = 4.3\%$.

The least variable ($\sigma_R \approx 0.9$) average of the ranks for the most important criteria B and E is $\bar{R}_i = 2.0$, as determined by 91 experts, with an absolute error $\Delta_R = 0.185$. This yields that the mean of the population of ranks R_{iP} differs from the sample mean $\bar{R}_i$ up to $0.185/2 \times 100 = 9.2\%$.

Conclusions

1. The quality of the asphalt pavement and/or the new base layers installed is checked by testing the individual properties specified in the national normative documents. The rules for the installation of asphalt layers (in Lithuania: *ĮT ASFALTAS 08*) contain 10 quality indicators for which penalty deductions are made for non-compliance with the limit values (LV) or for exceeding the permissible deviations (PD). The magnitudes of the LVs and PDs, the monitored quality indicators, correspond to permissible deviation magnitudes. The latter, if exceeded, obliges the contractor to remedy the defect or is imposed by a penalty. The statement that the significance of asphalt layer defects varies with respect to the quality of the road has been proven by applying expert investigation methods. A large team of 91 experts has assessed ten criteria with ranks and percentage weights, which have been employed to calculate the subjective normalized relative weights of the criteria.
2. The relative weights of each criterion have been calculated from the average ranks of the criteria by using the ARTIW-L and ARTIW-N methods and from the percentage weights using the DPW method. The concordance coefficient for the ranks of the criteria 0.715 is 34.6 times larger than its lowest value of 0.021,

corresponding to a significance level of 0.05. This indicates a very high degree of consistency between the opinions of the experts' team involved in the study. The consistent opinions allow the averages of the criteria weights to be used as a reliable result of the task.

3. The weights of the criteria calculated by the different MCDM methods differ slightly; however, the priorities of the criteria are the same. None of these methods has a theoretical advantage over the other ones, so the average of the weights of the three methods for each criterion is the final estimate of the significance of the criteria. The relative weights of all the asphalt pavement layer quality indicators (criteria) determined by the DPW method correspond to the relative weights of the criteria calculated from the rank averages by the ARTIW-L and ARTIW-N methods. The most important criteria of the largest weight values have been calculated by the ARTIW-N method, and the criteria with the largest average significance have been calculated by the ARTIW-L method.
4. The average of the team's opinions, expressed in relative weights, shows that the most significant factors for road quality are the degree of compaction of the asphalt layer (weight 0.1851), the lower thickness of the layer (0.1714), and the lower binder content (0.1625). Smaller or larger content of fractions >2 mm (coarse aggregate) or 0.063–2 mm (fine aggregate) (0.0981), smaller or larger content of fraction <0.063 mm (mineral filler) (0.0917), the exceedance of the limit values for roughness, measured according to the requirements of IRI (0.0749), are of the medium significance. The less important criteria for the experts are the following: the exceedance of the limits for roughness measured with a 3 m straightedge length (0.0634), the exceedance of the permissible deviation for the cross slope of the pavement (0.0608), and the lower coefficient of tire–road friction (0.0563). Exceptionally, the least significant criterion is the exceedance of the pavement width permissible deviation (0.0358), which is more than 5.2 times less significant against the most important criterion – the compaction ratio.
5. The correlation and regression analyses show that the means of the criteria ranks are negatively functionally related to the criteria weights calculated by the ARTIW-L and ARTIW-N methods. This relationship is linear for the ARTIW-L method and curvilinear for the ARTIW-L method. The pairwise relationship between the criteria weights calculated by either of the two methods is positive quadratic correlation. Knowing the weight of the criteria calculated by one method, the regression equations or curves can be used to determine the weight of the criteria calculated by the other method.
6. The arithmetic means and standard deviations of the ranks and percentage weights of criteria, evaluated by each sub-team, have been calculated for each team (sub-team) by randomly ordering the number of experts in the team, limited by an equal number of ten experts, increasing the number of experts in

the sub-team from 11 to 91. Averages of the ranks of the most important criteria (E, A, B) are the smallest, as are their standard deviations indicating that the experts' opinions on their significance are uniform. The mean of ranks for the least important criteria (I, J, H) and their standard deviations are the largest, indicating the largest differences in the experts' opinions (Figure 3). The sample means for the most important and least variable (standard deviation 0.9) ranks of criteria B and E are approximately equal to 2, and the absolute error of their determination is 0.185. This yields that the difference between the sample and population means is less than 9.2%. For the least important and most variable (standard deviation 1.9) criterion I, the sample mean of the ranks is approximately 9, and the absolute error of its determination is 0.39. The calculation shows that the difference between the sample and population mean ranks is less than 4.3%. The relative error of ten percent indicates that the results of the significance determination of the criteria by the 91 expert team are reliable. Their reliability hardly increases when the team consists of more than 20 experts.

Disclosure Statement

The authors confirm that they do not have any competing financial, professional, or personal interests from other parties.

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