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A NEW SYNTHESIS METHOD OF STRUCTURAL, TECHNOLOGICAL AND SAFETY DECISIONS (SYMAD-3)

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Abstract. The paper provides a new synthesis method of multiple attribute decisions (SyMAD-3 – *Synthesis of Multiple Attribute Decisions using three methods*) intended for combining multi-stage and multiple attribute decisions into a single common estimate. The method is applied for selecting a construction project on the basis of its structural, technological and safety decisions. To increase the reliability of the decision, three multiple attribute decision-making methods based on quantitative measurements were applied to help the person making a decision to monitor the results of a relevant decision obtained employing three methods of the same class. The algorithm of the proposed method includes methods for identifying the integrated significances of attributes and multiple attribute decision-making methods (SAW – *Simple Additive Weighting*, TOPSIS – *Technique for Order Preference by Similarity to Ideal Solution*, and COPRAS – *COmplex PRoportional ASsessment*) based on quantitative measurements.

Keywords: multiple criteria, multiple attribute decision making methods, construction, technological, architectural, safety, decision synthesis, reliability.

1. Introduction

The abundance of technological processes provides opportunities for various decisions on structural engineering. Using a variety of construction materials and applying certain work processes, an eye piercing aggregate of structural elements has been produced. The following questions may arise when observing technological progress, the architectural complexity and height of buildings and analysing accidents and occupational diseases: *Is work safety always ensured in the technological process? How much attention is devoted to ensuring a safe working procedure?*

The developed countries pay much attention to the working conditions of employees, i.e. they are aimed at making sure that working conditions do not jeopardise human health or pose a risk to their life (Hoła 2009; Liaudanskienė *et al*. 2009; Reinhold, Tilt 2009; Perera *et al*. 2009; Kazlauskaite, Buciuniene 2008; Hernaus *et al.* 2008; Reinhold *et al.* 2008; Grybaitė, Tvaronavičienė 2008; Zou *et al.* 2007). Occupational health and the problem of safety are especially relevant, because any violation system foundation causes not only moral damage, but can also frequently lead to health problems, and sometimes even risk to the life of employees (McCabe *et al.* 2008).

In order to prevent accidents and occupational diseases, improve productivity and job satisfaction of employees, it is necessary to take measures ensuring safety on construction sites (Giretti *et al.* 2009; Stankuvienė *et al.* 2008; Idoro 2008; Enshassi *et al.* 2007). In the course of various construction processes, safety at work can be ensured not only using collective and individual protective equipment, occupational risk assessment and coaching staff on health and safety issues – accidents can also be prevented by ensuring the proper organisation of work and working conditions (Sawacha *et al.* 1999; Jorgensen *et al.* 2007), which is often the case that the organisation of work directly depends on the decision regarding structural and technological solutions. Thus, one way to help with reaching a decision in the construction sector is to combine all structural, technological, and safety decisions. Then, the focus would be on one object consisting of the elements of three main areas, namely, the structural elements of a building, the technology of construction processes and safety solutions to construction processes.

In the case where a set of a possible alternative to a problem is known in advance and information about the attributes is provided in quantitative measurements, it is recommended to use multiple attribute decision-making (MADM) methods providing a quantitative evaluation of each alternative on the basis of which ranking alternatives is carried out to solve the problem. These methods are widely applied for analyzing various types of construction problems (Edalat *et al.* 2010; Zavadskas *et al.* 2008a, b; Tupenaite *et at.* 2010; Liaudanskienė *et al*. 2009) and assessing real estate investment projects (Ginevičius *et al.*2009).

There are quite a few research papers in which the methods based on quantitative measurements are used for multiple criteria decision-making. Some works describe the use of only one method (Liaudanskienė *et al.* 2009;

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Zavadskas *et al.* 2008a, etc.), whereas others compare the results obtained using several methods (Tupenaite *et al.* 2010; Ustinovichius 2007; Zavadskas *et al.* 2010, etc.). Decision models (Kaklauskas *et al.* 2011; Šarka *et al.* 2008; Marzouk *et al.* 2011; Vasilecas *et al.* 2011, etc.) and decision support systems (Zavadskas *et al.* 2008b) have been developed or are being developed for solving engineering and investment problems of various construction projects. Multiple criteria decision-making methods are used for developing similar models in cases of certainty (when quantitative methods are used) and under uncertainty (when game theory methods are used).

Given the fact that the accuracy of some attributes in construction investment projects may vary (Popov *et al.* 2010; Zavadskas *et al.* 2008a) and that each decision-making method has its own sensitivity with respect to fluctuations in the input data (Simanaviciene, Ustinovichius 2010) and with respect to the normalisation of the decision matrix (Zavadskas *et al.* 2007), the authors of the paper propose the application of several rather than one decision-making method in order to increase the reliability of the outcomes of the multiple criteria decision (to get a prioritised list of alternatives). To achieve the aim of this work, questionnaires containing the questions related to the evaluation of structural, technological and safety decisions were distributed to respondents.

This paper provides a new synthesis method of multiple attribute decisions – SyMAD-3 (*Synthesis of Multiple Attribute Decisions using three methods*) – intended for combining multi-stage and multiple attribute decisions into a single common decision. To increase the reliability of the decision, three multiple attribute decision-making methods based on quantitative measurements were applied. The algorithm of the proposed method uses methods for identifying the integrated signifycances of attributes (Ustinovichius 2007) and those for multiple attribute decision-making (SAW – *Simple Additive Weighting*, TOPSIS – *Technique for Order Preference by Similarity to Ideal Solution*, and COPRAS – *COmplex PRoportional ASsessment*) (Tupenaite *et al.* 2010; Ustinovicius *et al.* 2007; Zavadskas *et al.* 2010, etc.). The aim of the proposed method is the synthesis of multi-stage and multiple attribute decisions through the application of multiple attribute decision methods. This paper presents a practical application of the method for selecting the external wall of a building from possible project alternatives considering the main elements of the construction project: structural elements of the building, technology for construction processes and safety solutions to construction processes. The selected alternative decision, regarding structural elements, should comply with the requirements for the technological process that would ensure the quality of work and work safety requirements.

2. The synthesis method of multi-stage and multiple attribute decisions applying three methods (SyMAD-3), intended for identifying the efficiency of the proposed alternatives presented in the form of a decision tree

Decision synthesis is a decision that links multiple decisions into a joint project in concordance with decision tables of the alternatives. To perform decision synthesis, a decision tree showing all possible combinations of decision alternatives is made. Multiple attribute design often needs a decision to be made analysing and combining several problems into one. The primary idea of creating the synthesis method of multiple attribute decisions was mentioned in literature by Zavadskas (Zavadskas 1991). A revised method of multiple attribute decision synthesis was developed, practically tested (Šarka *et al.* 2008) and applied for determining the most effective decisions on construction problems.

The synthesis of multi-stage and multiple attribute decisions provides the possibility of making an efficient decision when there is a need to evaluate multiple, often conflicting, situations. The first point that needs to be discussed dealing with this problem is that it is usually not possible to identify one decision, judgement or action that would be optimal in all respects. Unlike classical methods for the study on relationships with alternatives, multiple attribute methods do not require objectively best decisions (Šarka *et al.* 2008). The essence of the method is the synthesis of several inter-related technical decisions by selecting only two by default (or more) best alternatives at each stage. Thus, it is recommended that this method should be applied in case there are more than three decision stages. However, by selecting only two alternatives at each stage of a decision, the possibility of observing the results of potential combinations is lost. Yet, if we retain all potential alternative combinations, a very large number of alternative combinations will be obtained, and therefore will be difficult to assess using the above described method.

In order not to lose interim information about possible decisions, the authors of the article propose a new synthesis method of multiple attribute decisions based on the decision tree diagram used for establishing a problem analysis model by integrating structural, technological and safety decisions. With reference to data in the decision tree diagram, a new decision matrix (Y) is produced and employed for ranking alternative decision combinations in light of rationality.

The key principle of the provided decision synthesis method is as follows: using three quantitative multiple attribute methods (TOPSIS, SAW and COPRAS) and those for identifying the significance of attributes, to assess the rationality of construction choices in constructing an external wall of a building in terms of the proposed structural design, construction techniques and safety requirements recommended for implementing the selected project.

Based on the model of the analysis of multi-stage decisions extrapolated in the previous research done by the authors, the current article presents a new synthesis method of multi-stage and multiple attribute decisions (SyMAD-3). The provided multi-stage decision tree model shows the structure of the analysis of decisions that belong to different stages. The diagram of the decision analysis tree is described below using the following notation technique:

1) A set of stages in decision analysis $K = \{k\}$, (k = 1, 2, ..., c), k – the number of the stage, c – the quantity of stages;

2) The quantity of decision tree nodes – m_k (k = 1, 2, ..., c) at each stage are determined depending on the number of decision tables;
3) The quantity of the paths of the model decision tree connecting the root node with the terminal node (called *leaf*): $z = m_c$, where m_c is the quantity of nodes at the final decision tree stage. The quantity of paths in the tree is the number of alternative combinations.

Once the decision analysis model and the data described according to tree notation are available, the rational decision must be sought, i.e. by selecting an appropriate algorithm, the alternatives can be ranked by rationality. The authors propose the synthesis method of multi-stage and multiple attribute decisions applying three decisions – SyMAD-3. The algorithm of the proposed method consists of two stages:

Decision stage 1 (Fig. 1) is intended for the formulation of the problem, the preparation of evaluation data and performing preliminary alternative evaluation. The stage consists of the following six steps:

1) The identification of the quantity of decision stages and the formulation of an attribute system for each stage k (k = 1, 2, ..., c) of the decision tree. Filling decision tables $(A_t, t = \overline{1, m_k})$;

2) By using these data tables, decision matrixes are subsequently formed:

$$X_t = \left[x_{ij}^t \right], \left(t = \overline{1, m_k}; i = \overline{1, a_t}, \; j = \overline{1, n_k} \right), \qquad (1)$$

where: t is the number of a decision table, a_t is the quantity of alternatives in t-th decision table, n_k is the quantity of alternatives at the k-th stage;

3) Filling (expert) pair wise comparison matrixes used for identifying the significance of attributes. $E = \{p\}$, p = 1, 2, ..., e_p, E – expert set, p – the number of an expert, e_p – the quantity of experts;

4) The identification of the consistency of pair wise comparison matrixes. For this purpose, the consistency degree S of each matrix is calculated:

$$S = \frac{S_I}{S_A}, \qquad (2)$$

where: S_I is the matrix consistency index, S_A is the average random index. If $S < 0.1$, matrix consistency is sufficient and the matrix is used for identifying the subjective significance of attributes; in case it is not, matrix data is not used for further calculations (Saaty 1990);

5) The identification of the significance of attributes for the k-th stage applying pair wise attribute comparison matrixes completed by experts and the method of least squares for identifying the subjective significance of attributes:

$$\overline{q}_{kj}, \left(j = \overline{1, n}, k = \overline{1, c} \right). \qquad (3)$$

Using the subjective significance of attributes, the degree of an agreement of expert estimates can be determined applying W. Kendall's concordance coefficient (Ustinovichius *et al.* 2007). If the agreement of expert estimates are sufficient, the integrated significances of attributes

$$q_{kj}^*, (j = \overline{1, n_k}, k = \overline{1, c}) \qquad (4)$$

are calculated, otherwise the group of experts is reconsidered;

6) Using decision matrixes (1) and integrated significances of attributes (4), the rationality of alternatives is identified employing three methods: TOPSIS, SAW and COPRAS;

7) Once calculations are completed using all three methods, the results are provided in the form of relative significance criteria according to TOPSIS, SAW and COPRAS methods without adding them up:

$$\left(A_k^i \left(Topsis, Saw, Copras \right) \right) = \left(R_{kT}^i, R_{kS}^i, R_{kC}^i \right), \qquad (5)$$

where: $\left(k = \overline{1, c}, i = \overline{1, m_k} \right)$.

Decision stage 2 (Fig. 2) is intended for the formulation of alternative combinations and evaluation of their rationality. Using the alternatives produced at Decision stage 1 and described in decision tables A_t as well as rationality evaluation results and the decision tree model provided in the previous research of the authors, alternative combinations

$$B_s, \left(s = \overline{1, z} \right) \qquad (6)$$

are completed.

The following actions are carried out at Decision stage 2:

1) Data on alternative combinations are provided in the form of vectors:

$$B_s = \left[\left(R_{1,T}^i, R_{1,S}^i, R_{1,C}^i \right), \ldots, \left(R_{c,T}^i, R_{c,S}^i, R_{c,C}^i \right) \right], \qquad (7)$$

where: $\left(i = \overline{1, m_k}, \quad s = \overline{1, z} \right)$;

2) The obtained alternative combinations are entered into the decision table (Table 1) the data of which will be used for further calculations;

Table 1. A decision table of alternative combinations

Stages:	stage 1			...	C-th stage		
Attributes / Alternatives	$\boldsymbol{R_{[1]}}$	$\boldsymbol{R_{[2]}}$	$\boldsymbol{R_{[3]}}$	...	$\boldsymbol{R_{[7]}}$	$\boldsymbol{R_{[8]}}$	$\boldsymbol{R_{[9]}}$
$\boldsymbol{B_1}$	$R^1_{c,T}$	$R^1_{c,S}$	$R^1_{c,C}$	...	$R^1_{s,T}$	$R^1_{s,S}$	$R^1_{s,C}$
$\boldsymbol{B_2}$	$R^1_{c,T}$	$R^1_{c,S}$	$R^1_{c,C}$	...	$R^2_{s,T}$	$R^2_{s,S}$	$R^2_{s,C}$
...	...	...	...	...	...	...	...
$\boldsymbol{B_z}$	$R^{n1}_{c,T}$	$R^{n1}_{c,S}$	$R^{n1}_{c,C}$	...	$R^{n3}_{s,T}$	$R^{n3}_{s,S}$	$R^{n3}_{s,C}$
Min/max	*Max*	*Max*	*Max*		*Max*	*Max*	*Max*

3) When using TOPSIS, SAW and COPRAS methods, the evaluation of the table of alternative combinations (Table 1) is made:

1. Using data on made decisions (Table 1), the decision matrix is completed:

$$Y = [y_{sl}], \left(s = \overline{1,z}, l = \overline{1,k \times mt}\right), \quad (8)$$

where: mt is the number of the methods applied (in our case mt = 3), k is the number of the stage (k = 1, 2, .., c). In this case, s is the quantity of rows in matrix Y and l is the quantity of columns in matrix Y.

$$(y_{sl}) = (R^i_{k,M}), \left(s = \overline{1,z}, l = \overline{1,k \times mt}, M = \overline{1,mt}\right), \quad (9)$$

where: $(i = \overline{1,m_k}, k = \overline{1,c}, M = \overline{1,mt})$, M is the number of the method, mt – the quantity of methods;

2. A set of attributes required for evaluating the alternatives provided in matrix Y is provided:

R = $\{R_1\}$, (l = 1, 2, ..., k×mt). These attributes are maximised, whereas their significance values are the same because they are not affected either by subjective or objective factors. The significance values of the attributes must satisfy the equation:

$$\sum_{j=1}^{k+mt} w_j = 1, \quad (10)$$

where: k is the quantity of stages, mt is the quantity of methods;

3. The performed evaluation of alternative combinations using the above methods, rationality evaluation and ranking alternative combinations are given in a form of a table.

The algorithm for the synthesis method of multi-stage and multiple attribute decisions is provided in two flow charts below (Fig. 1 and Fig. 2). The proposed method may be used for solving various multi-stage and multiple attribute decision-making problems when information about the attributes is provided in a quantitative form.

3. Methods applied for calculations

Based on the judgement of each expert, the subjective, objective and integrated values of the significances of the attributes are determined.

The subjective values of criteria significance are determined based on expert pair wise comparison. The values of $\overline{q_j}(j = \overline{1,n})$ are found by solving the optimization problem:

$$\min\left\{\sum_{i=1}^{n}\sum_{j=1}^{n}\left(b_{ij}\overline{q_j} - \overline{q_i}\right)\right\}, \quad (11)$$

when, the unknown values of $\overline{q_j}\left(j = \overline{1,n}\right)$ satisfy constraints:

$$\sum_{j=1}^{n}\overline{q_j} = 1, \quad \overline{q_i} > 0, \left(j = \overline{1,n}\right). \quad (12)$$

Group evaluation may be considered to be reliable only if the estimates elicited from various experts or the members of a cooperative decision making group are consistent. The level of the agreement of expert estimates can be determined using W. Kendall's concordance coefficient (Saaty 1990).

The next step is the calculation of the objective significance values of the criteria using the Entropy method (Ustinovichius 2007).

Values q^*_j (the significance of integrated attributes) are determined according to the formula:

$$\overline{q_j}\sum_{j=1}^{n} q^*_j q_j - q^*_j q_j = 0, \quad (j = 1, 2, ..., n), \quad (13)$$

when $\overline{q_j}$ (the significance of subjective attributes found making a pair wise comparison) and q_j (objective significance found employing the Entropy method) are known (Ustinovichius 2007).

To identify the rationality of alternatives, three multiple attribute decision-making methods – TOPSIS, SAW and COPRAS – are applied based on quantitative calculations.

Mathematically, *Simple Additive Weighting* (SAW) method can be stated as follows: suppose the decision maker assigns a set of importance weights to attributes $\overline{q} = \{\overline{q}_1, \overline{q}_2, \ldots, \overline{q}_n\}$. Then, the most preferred alternative A^* is selected such that:

$$A^* = \left\{ A_i \left| \max_i \sum_{j=1}^{n} \overline{q}_j \overline{x}_{ij} / \sum_{j=1}^{n} \overline{q}_j \right. \right\}, \quad (14)$$

where: x_{ij} is the outcome of the i^{th} alternative about the j^{th} attribute with a numerically comparable scale. The weights are usually normalized so that:

$$\sum_{j=1}^{n} q_j = 1. \quad (15)$$

Simple Additive Weighting method requires a comparable scale for all elements in the decision matrix. The comparable scale is obtained using equation:

$$\overline{x}_{ij} = \frac{x_{ij}}{x_j^{\max}} \quad (16)$$

for benefit criteria and equality:

$$\overline{x}_{ij} = \frac{x_j^{\min}}{x_{ij}} \quad (17)$$

for cost criteria.

Method TOPSIS was developed by Hwang and Yoon (1981). The technique is based on the idea that the optimal alternative is the most similar one to an ideal solution (being closest to it and at the longest distance from the negatively ideal solution). This method is known as TOPSIS – *Technique for Order Preference by Similarity to Ideal Solution*.

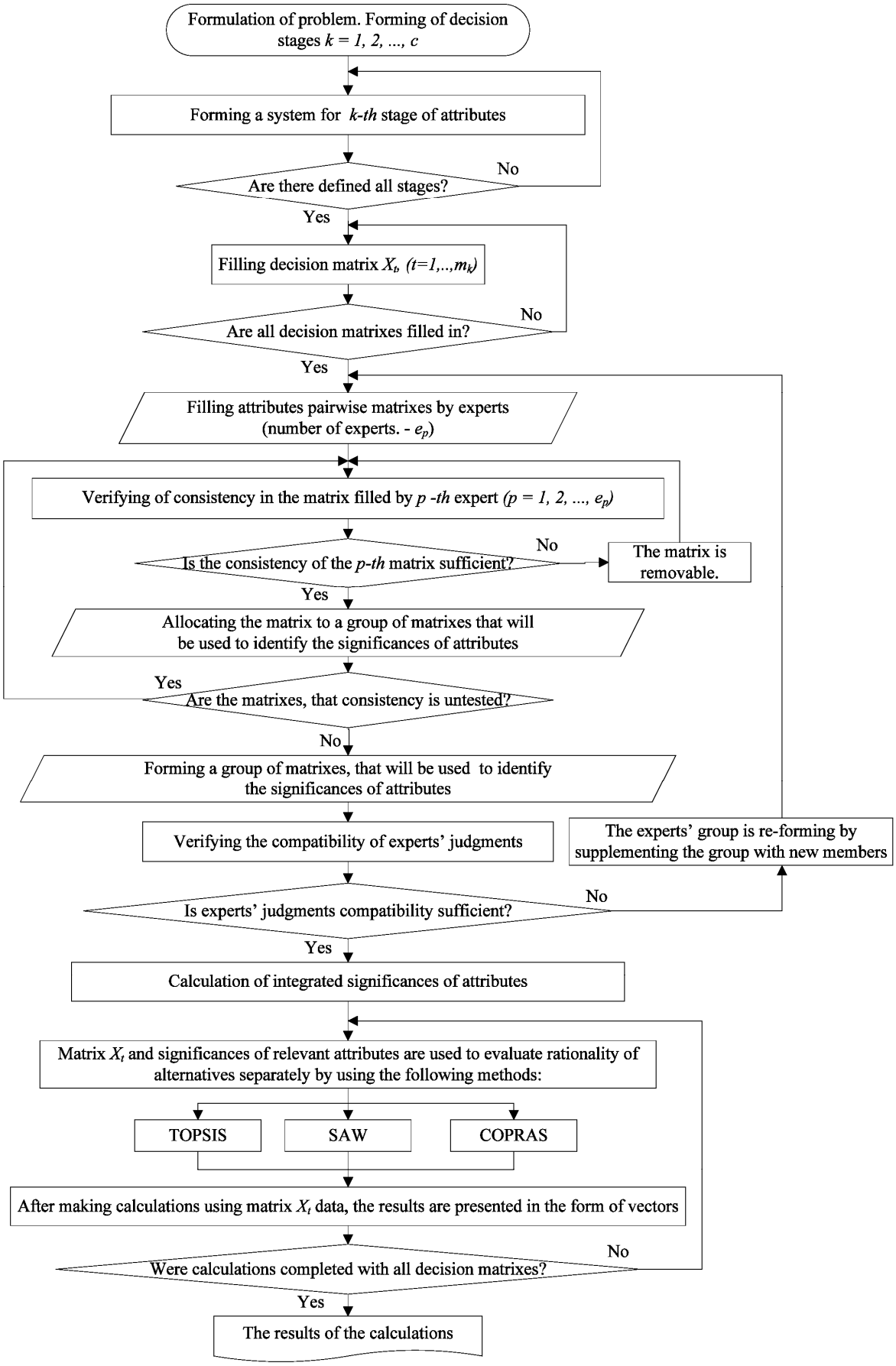

Fig. 1. Part 1 of the algorithm of the multi-stage decision synthesis method (SyMAD-3)

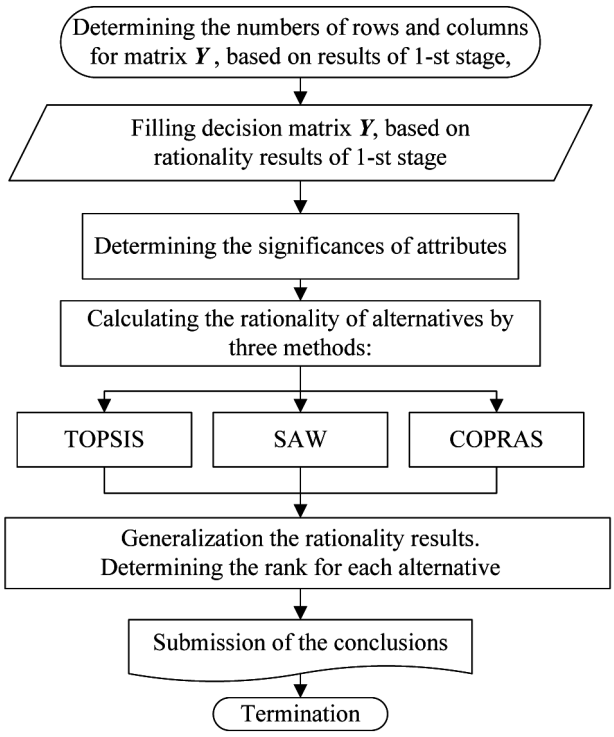

Fig. 2. Part 2 of the algorithm for the multi-stage decision synthesis method (SyMAD-3)

A relative distance of any i^{th} variant from the ideal one is obtained by the formula:

$$K_{BIT} = \frac{L_i^-}{L_i^+ + L_i^-}, i = \overline{1,m}, \quad (18)$$

where: K_{BIT} [0, 1], L_i^+ is the distance between the compared i-th variant and the ideal one; L_i^- is the distance between the compared i^{th} variant and the negatively ideal alternative. The nearer to one is K_{BIT} value, the closer is the i^{th} variant to $a+$, i.e. an optimal variant is the one that has the highest value of K_{BIT} .

Method COPRAS consists of several stages of calculation. At stage 1, the normalisation of the elements of the decision matrix is conducted using the formula:

$$d_{ij} = \frac{x_{ij} \cdot q_j^*}{\sum_{i=1}^{m} x_{ij}}, \quad i = \overline{1,m},\ j = \overline{1,n}, \quad (19)$$

where: x_{ij} is the value of the attribute j of alternative i; m is the number of alternatives; n is the number of attributes; q_j^* is the integrated significance value of the j^{th} attribute.

At stage 2, the sums of minimising S_{-i} and maximising S_{+i} evaluating the normalised attributes of each alternative are calculated. The following formulas are used:

$$S_{+i} = \sum_{j=1}^{n} d_{+ij}, \quad (20)$$

$$S_{-i} = \sum_{j=1}^{n} d_{-ij}, \quad i = \overline{1,m},\ j = \overline{1,n}. \quad (21)$$

At stage 3, the relative significance of comparable alternatives is identified on the basis of positive S_{-i} and negative S_{+i}, the characteristics that describe the alternatives. The relative significance (rationality) of each alternative Q_i is identified using the formula:

$$Q_i = S_{+i} + \frac{S_{-\min} \cdot \sum_{i=1}^{m} S_{-i}}{S_{-i} \cdot \sum_{i=1}^{m} \frac{S_{-\min}}{S_{-i}}}, \quad i = \overline{1,m}. \quad (22)$$

The higher is Q_i value, the more the alternative complies with the needs (preferences) of a decision-making person (Zavadskas *et al.* 2010; Tupenaite *et al.* 2010).

4. The synthesis of structural, technological and safety decisions using SyMAD-3

Construction work must be organised so that the safety of employees should be ensured during the entire construction process (construction of a building) to prevent/reduce the number of accidents and occupational diseases. In the course of construction, such technological procedures shall apply to ensure the quality of work and safety as well as to observe technology requirements set out in the technology project.

In order to improve working conditions and the quality of work, structural, technological and safety decisions of construction processes should be integrated into a whole. Then, the focus should be on one object, the elements of which would include three main areas, namely, structural elements, technology and safety decisions of construction processes.

The multi-stage decision tree model is used for the above purpose, with the help of which, the analysis of finding a solution to the problem is conducted and a set of possible alternatives is modelled. This model is used for analysing the possible construction variants of the wall by combining structural, technological and security decisions into a single object of a decision. The overall decision tree model using the synthesis method of multi-stage and multiple attribute decisions SyMAD-3 is shown in Fig. 3.

5. Case study

A multiple attribute decision problem the decision analysis model of which was described in the previous research done by the authors has been formulated. The overall decision tree model is made and presented in Fig. 3. The use of the SyMAD-3 method solves the multi-stage and multiple attribute decision problems.

In order to identify coherence among structural, technological and safety decisions, three types of external wall variants were selected: Masonry structure No. 1 *Arko* calcium silicate blocks; Masonry structure No. 2 Ventilated façade; Masonry structure No. 3 Insulated solid masonry wall.

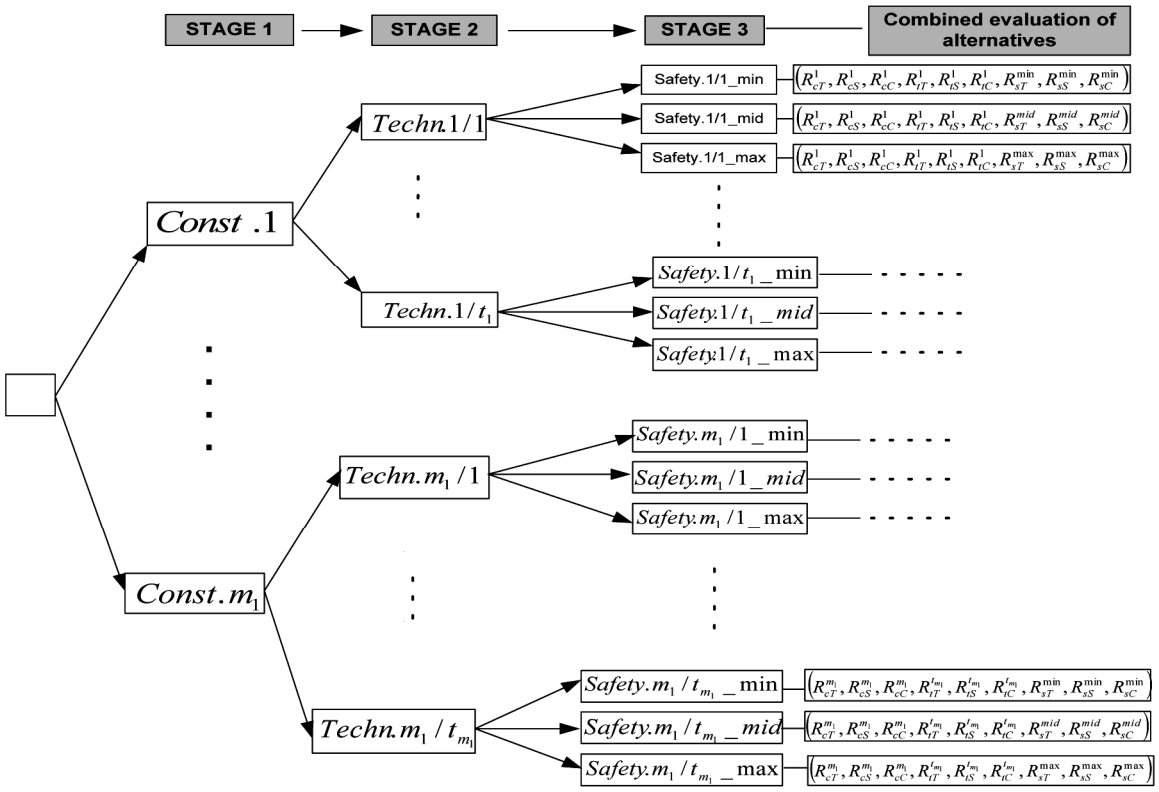

Fig. 3. The synthesis model of multiple attribute decisions

The variants of external wall structure are identified in this article as three alternatives: A_1, A_2 and A_3. The priority and significance of each variant directly and proportionally depend on the system of attributes characteristic to each alternative, their values and significance. For this reason, 12 attributes were selected: R_{C1}, R_{C2}, R_{C3}, R_{C4}, R_{T1}, R_{T2}, R_{T3}, R_{T4}, R_{S1}, R_{S2}, R_{S3} and R_{S4}. These attributes were divided into three separate groups: structure, technology and work safety. Four attributes were allocated to each structural group: *wall resistance to cold (wall longevity, years), wall heat transfer coefficient (W/m²K), the weight of external walls (m²kg) and material cost per 1 m² of wall installation (LTL/m²)*. The attributes of the technological group cover *labour cost (man-hour/m²), employee qualification category (score)*, *mechanism demand (mechanism-hour/m²)* and *construction process labour cost (LTL/m²)*. The attributes of the work safety group consist of *the level of risk at the work place (score), protective equipment cost (LTL/m²), labour cost to ensure safety (man-hour/m²)* and *mechanism demand to ensure safety (mechanism-hour/m²)*. The values of the alternative attributes are provided in Table 2. Steps 1 and 2 of the first decision stage have been completed.

To identify attribute significance, expert judgement is required (steps 3–4 of stage 1).

The survey involved 33 respondents. The evaluation of structural, technological and work safety decisions was provided by a group of people that involved construction company directors, construction technical supervisors, construction managers, occupational health and safety professionals, researchers, employees of the State Labour Inspectorate, engineers and construction workers.

Table 3 provides the subjective values of attribute significance on the basis of which the degree of the consistency of expert judgment and the coefficient of the pair wise matrix consistency are determined. Following the procedure of determining two kinds of consistency, the following findings were obtained:

1) To verify the consistency of expert judgement, the value of the significance of concordance coefficient χ^2 is calculated and compared with table distribution value $\chi^2_{(0.05;\ 32)}$. The made calculations showed that expert judgement on the significance values of structural and technological attributes were sufficiently consistent; however, judgement on the significance of work safety attributes is of insufficient consistency;

2) After verifying the consistency of pair wise comparison matrixes completed by experts, consistency coefficient S was calculated. 33 experts found that the consistency coefficient of the matrixes was greater than 0.1 in nearly 50%, which indicates that attribute ranking done by experts does not satisfy transitivity property;

3) Pair wise comparison matrixes, the consistency of which is sufficient ($S < 0.1$), were used for further calculations.

Four steps of stage 1 of the SyMAD-3 method were completed and 3 decision stages was identified; a set of attributes was formed and decision tables were completed – 3; finally, calculations were made to determine the significance of attributes. The subjective and integrated

Table 2. The values of the attributes of evaluated external wall construction variants

Attributes			Masonry structure No. 1 ***Arko* calcium silicate blocks**	Masonry structure No. 2 **Ventilated façade**	Masonry structure No. 3 **Insulated solid masonry wall**
Technology	Labour cost (man-hour/m^2)	*Min*	3.76	4.61	6.06
	Employee qualification category (score)	*Max*	4.17	4.0	4.17
	Mechanism demand (mechanism-hour/m^2)	*Min*	0.560	0.955	1.107
	Construction process labour cost (LTL/m^2)	*Min*	84	96	135
Structure	Wall resistance to cold (cycles)	*Max*	50	75	50
	Wall heat transfer coefficient (W/m^{2}K)	*Min*	0.223	0.217	0.222
	The weight of external walls (m^{2}kg)	*Min*	573	635	672
	Material cost per 1 m^2 of wall installation (LTL/m^2)	*Min*	181	269	193
Work safety	The level of risk at the work place (score)	*Min*	3	4	3
	Protective equipment cost (LTL/m^2)	*Min*	177	162	185
	Labour cost to ensure safety (man-hour/m^2)	*Min*	0.146	0.140	0.154
	Mechanism demand to ensure safety (mechanism-hour/m^2)	*Min*	0.021	0.021	0.022

Table 3. The subjective values of attribute significance using data obtained by 33 experts

Expert No.	R_{T1}	R_{T2}	R_{T3}	R_{T4}	R_{K1}	R_{K2}	R_{K3}	R_{K4}	R_{D1}	R_{D2}	R_{D3}	R_{D4}
Expert 1	0.1718	0.0685	0.1177	0.642	0.07	0.4368	0.0445	0.4487	0.4091	0.370	0.110	0.111
Expert 2	0.175	0.0752	0.1055	0.6443	0.0503	0.2625	0.0646	0.6226	0.2351	0.606	0.078	0.081
Expert 3	0.0674	0.0882	0.1045	0.74	0.0558	0.3486	0.0504	0.5451	0.633	0.252	0.057	0.059
Expert 4	0.4831	0.1311	0.2682	0.1176	0.2438	0.1371	0.4755	0.1437	0.178	0.058	0.139	0.626
Expert 5	0.0566	0.7582	0.1287	0.0566	0.7871	0.1039	0.0455	0.0636	0.7925	0.045	0.060	0.102
Expert 6	0.0939	0.1323	0.0881	0.6857	0.0831	0.2414	0.0694	0.6062	0.386	0.433	0.085	0.096
Expert 7	0.4151	0.1321	0.0853	0.3675	0.0513	0.3725	0.2069	0.3694	0.25	0.25	0.25	0.25
Expert 8	0.0765	0.1159	0.0703	0.7373	0.0528	0.6208	0.0541	0.2723	0.6454	0.216	0.071	0.068
Expert 9	0.0655	0.6766	0.1595	0.0984	0.5161	0.1225	0.2587	0.1028	0.0908	0.129	0.672	0.108
Expert 10	0.0899	0.1145	0.0682	0.7275	0.1031	0.7706	0.0546	0.0717	0.5586	0.303	0.075	0.063
Expert 11	0.0799	0.3647	0.3467	0.2086	0.1631	0.3846	0.0559	0.3965	0.5801	0.128	0.155	0.136
Expert 12	0.0722	0.6692	0.1608	0.0978	0.4784	0.1546	0.243	0.124	0.1015	0.149	0.634	0.116
Expert 13	0.0516	0.7033	0.1625	0.0827	0.5868	0.2233	0.1166	0.0733	0.0968	0.121	0.694	0.089
Expert 14	0.1	0.1087	0.0857	0.7056	0.1917	0.1583	0.0711	0.5789	0.5051	0.101	0.238	0.156
Expert 15	0.0832	0.6414	0.0552	0.2202	0.1317	0.0855	0.2668	0.516	0.1774	0.268	0.209	0.346
Expert 16	0.2375	0.2966	0.3593	0.1067	0.043	0.1337	0.0649	0.7584	0.0394	0.061	0.117	0.783
Expert 17	0.5673	0.0827	0.2196	0.1305	0.4228	0.3091	0.1828	0.0853	0.4257	0.312	0.166	0.097
Expert 18	0.5807	0.0678	0.22	0.1315	0.4396	0.3074	0.1834	0.0696	0.4257	0.312	0.166	0.097
Expert 19	0.0374	0.2171	0.0874	0.658	0.1021	0.6828	0.0663	0.1488	0.1393	0.064	0.076	0.721
Expert 20	0.0785	0.2452	0.0612	0.6151	0.0711	0.6035	0.0525	0.2729	0.5188	0.296	0.093	0.093
Expert 21	0.1676	0.4326	0.063	0.3368	0.0608	0.6709	0.0514	0.217	0.4475	0.448	0.050	0.055
Expert 22	0.1201	0.3587	0.0643	0.4569	0.0953	0.2088	0.27	0.4259	0.2603	0.157	0.322	0.260
Expert 23	0.0959	0.443	0.1907	0.2704	0.126	0.3956	0.1627	0.3156	0.0681	0.406	0.381	0.145
Expert 24	0.1746	0.1213	0.5828	0.1213	0.1461	0.1066	0.0623	0.685	0.6608	0.068	0.136	0.136
Expert 25	0.2104	0.379	0.1778	0.2328	0.0899	0.7089	0.098	0.1032	0.0773	0.719	0.148	0.056
Expert 26	0.098	0.1049	0.1823	0.6148	0.148	0.6418	0.1155	0.0947	0.6288	0.071	0.086	0.215
Expert 27	0.5995	0.0849	0.1515	0.1641	0.1827	0.066	0.6536	0.0977	0.2231	0.104	0.289	0.384
Expert 28	0.1803	0.0477	0.0572	0.7147	0.343	0.1997	0.0621	0.3952	0.6527	0.086	0.108	0.153
Expert 29	0.2441	0.3258	0.1131	0.3169	0.4468	0.276	0.0919	0.1853	0.4	0.2	0.2	0.2
Expert 30	0.3115	0.1202	0.3115	0.2568	0.5128	0.1923	0.1026	0.1923	0.5102	0.125	0.172	0.193
Expert 31	0.3051	0.4382	0.0362	0.2204	0.4346	0.302	0.0946	0.1688	0.4206	0.096	0.285	0.199
Expert 32	0.3328	0.144	0.1195	0.4037	0.1522	0.1535	0.1214	0.573	0.1183	0.29	0.504	0.089
Expert 33	0.1123	0.0637	0.0838	0.7402	0.0869	0.1052	0.0681	0.7397	0.1972	0.557	0.183	0.064
Expert judgement	*Consistent*				*Consistent*				*Inconsistent*			

values of significance at all stages are provided in Table 4. To evaluate the rationality of alternatives, the integrated values of attribute significance will be used.

In step 5 of stage 1, the evaluation of the rationality of all alternatives at all stages is carried out applying three methods: TOPSIS, SAW and COPRAS. Calculation results are provided in Table 5.

After evaluation using three methods, the following results were obtained:

1. $T_1 \succ T_3 \succ T_2$. It can be maintained that the rationality value of alternative T_1 is the highest;
2. $K_2 \succ K_3 \succ K_1$. It can be maintained that the rationality value of alternative K_2 is the highest;
3. $D_2 \succ D_1 \succ D_3$. It can be maintained that the rationality value of alternative D_2 is the highest.

On the basis of the conclusions provided above, we cannot establish which alternative is the most rational one with respect to structural, technological and safety decisions.

The data displayed in Table 5 are used for completing alternative combinations (see Table 6).

The data set in Table 6 will be used for calculations, whereas the values of attribute significance are equal to $w_j = 0.111$, ($w_j = 1, 2, ..., 9$). All attributes are maximised.

Having applied the algorithm of the synthesis method SyMAD-3, the following calculation results were obtained (Table 7).

The calculated results presented above show that alternative B^2 – *ventilated façade* is the most rational alternative in light of structural, technological and work safety aspects.

It order to compare calculation results obtained by applying the new method SyMAD-3 when alternatives are separately evaluated from the point of view of structural, technological and work safety requirements with the results using the method when these groups of attributes are not segregated, the authors selected the expert method identifying the significance of attributes (Zavadskas1991).

Table 4. The values of attribute significance

Structural attributes	R_{C1}	R_{C2}	R_{C3}	R_{C4}
Subjective values of significance	0.2129	0.3144	0.0965	0.3763
Integrated values of attribute significance	0.0024	0.9817	0.0098	0.0061
Ranking significance	4	1	2	3
Technological attributes	R_{T1}	R_{T2}	R_{T3}	R_{T4}
Subjective values of significance	0.3745	0.1051	0.2628	0.2576
Integrated values of attribute significance	0.0344	0.9323	0.0097	0.0236
Ranking significance	2	1	4	3
Work safety attributes	R_{S1}	R_{S2}	R_{S3}	R_{S4}
Subjective values of significance	0.4559	0.2603	0.1463	0.1376
Integrated values of attribute significance	0.0537	0.1698	0.1944	0.5821
Ranking significance	4	3	2	1

Table 5. Rationality indicators of structural, technological and safety decisions

	Alternatives	T_1	T_2	T_3
Technology	Rationality value acc. to TOPSIS	1	0.2546	0.6525
	Ranking acc. to TOPSIS	**1**	**3**	**2**
	Rationality value acc. to SAW	1	0.949	0.973
	Ranking acc. to SAW	**1**	**3**	**2**
	Rationality values acc. to COPRAS	0.3432	0.3247	0.33209
	Ranking acc. COPRAS	**1**	**3**	**2**
	Alternatives	K_1	K_2	K_3
Structure	Rationality value acc. to TOPSIS	0.0981	0.91	0.1809
	Ranking acc. to TOPSIS	**3**	**1**	**2**
	Rationality value acc. to SAW	0.973	0.997	0.975
	Ranking acc. SAW	**3**	**1**	**2**
	Rationality values acc. to COPRAS	0.3303	0.3385	0.3312
	Ranking acc. COPRAS	**3**	**1**	**1**
	Alternatives	D_1	D_2	D_3
Safety	Rationality value acc. to TOPSIS	0.6735	0.7142	0.2858
	Ranking acc. to TOPSIS	**2**	**1**	**3**
	Rationality value acc. to SAW	0.978	0.987	0.935
	Ranking acc. SAW	**2**	**1**	**3**
	Rationality values acc. to COPRAS	0.3376	0.3398	0.3226
	Ranking acc. COPRAS	**2**	**1**	**3**

The significance of twelve attributes obtained using the expert method is provided in Table 8. The verification of expert judgement consistency finds it sufficient. The values of attribute significance were calculated using the dataset of 33 experts.

The values of attribute significance, including structural (R_{Cj}, $j = 1, 2, 3, 4$), technological (R_{Tj}, $j = 1, 2, 3, 4$) and work safety (R_{Sj}, $j = 1, 2, 3, 4$) aspects are provided in Table 8.

Using the significance (Table 8) and values of the attributes (Table 2), the rationality of alternatives A_1, A_2 and A_3 using three methods TOPSIS, SAW and COPRAS can be calculated. The results of calculation present the most rational alternative A_1 which is *Arko calcium silicate blocks*. Calculation results $A_1 \succ A_2 \succ A_3$ are provided in Table 9.

A comparison of these two methods shows the existing difference. Multiple attribute decision problems are solved by identifying the stages of the problem and by carrying out calculations at each stage. Finally, the results of the made calculations are summarized, which allows the analysis and assessment of a more detailed multiple attribute decision making problem than in the case where the decision making problem does not fall into smaller segments.

Table 6. A dataset of alternative combinations

Types of attributes	Structure			Technology			Safety		
Attributes / Alternative	$R^T_{[1]}$	$R^S_{[2]}$	$R^C_{[3]}$	$R^T_{[4]}$	$R^S_{[5]}$	$R^C_{[6]}$	$R^T_{[7]}$	$R^S_{[8]}$	$R^C_{[9]}$
B^1	0.0981	0.973	0.33034	1	1	0.3432	0.6735	0.978	0.3375
B^2	0.91	0.997	0.33847	0.2546	0.949	0.3247	0.7142	0.987	0.3397
B^3	0.1809	0.975	0.33118	0.6525	0.973	0.3321	0.2858	0.935	0.3226
max/min	*Max*	*Max*	*Max*	*Max*	*Max*	*Max*	*Max*	*Max*	*Max*

Table 7. The rationality and ranking of alternative combinations

	Rationality			Ranking		
Combinations of alternatives / Method	B_1	B_2	B_3	B_1	B_2	B_3
TOPSIS	0.4528	0.6124	0.2662	2	**1**	3
SAW	0.887	0.906	0.783	2	**1**	3
COPRAS	0.3367	0.37025	0.29305	2	**1**	3

Table 8. The significance of attributes applying the expert method

Types of the attributes	Structure				Technology				Safety			
Attribute	R_{c1}	R_{c2}	R_{c3}	R_{c4}	R_{f1}	R_{f2}	R_{f3}	R_{f4}	R_{s1}	R_{s2}	R_{s3}	R_{s4}
Significance of the attribute	0.080	0.083	0.079	0.083	0.085	0.086	0.084	0.086	0.085	0.083	0.082	0.083
max/min	min	max	min	min	max	min	min	min	min	min	min	min

Table 9. The rationality of the external wall alternatives according to technological, structural and work safety attributes using the significance of attributes determined by the expert method

	Rationality			Ranking		
Alternatives / Method	A_1	A_2	A_3	A_1	A_2	A_3
TOPSIS	0.7185	0.4877	0.3098	1	2	3
SAW	0.961	0.879	0.826	1	2	3
COPRAS	0.36296	0.3306	0.30646	1	2	3

6. Conclusions

The analysis of related work demonstrates that multiple attribute decision analysis and synthesis allow a more detailed approach to decision making in terms of which the authors of the previous research provided a multi-stage decision model. Then, the problems of a multi-stage and multiple attribute decision-making were provided in the form of this model. However, the authors of the current article present a new multi-stage and multiple attribute decision synthesis method – SyMAD-3 for solving multiple attribute decision-making problems. If qualitative input data for a decision-making problem are provided for solving the problem, it is more convenient to use such multiple attribute qualitative methods as TOPSIS, SAW and COPRAS. Since each method has its own premises, the authors suggested that these three methods for decision-making should be combined into a single method. Combining methods increases decision reliability, because a decision-maker has an opportunity to see the results of rationality evaluation considering each alternative to all three methods.

The new synthesis method of multiple attribute and multi-stage decisions using three methods (SyMAD-3) complies with the following main requirements imposed in this paper:

- completing all possible alternative combinations increases the level of result details;
- exists a possibility of noting the impact of individual decision stages on the rationality of alternative combinations in the course of calculations;
- considering different sensitivity of multiple attribute decision-making methods with respect to input data, using the synthesis method of multiple attribute decisions, three multiple attribute decision-making methods are combined into a single system thus increasing the reliability of the made decision.

This method allows combining such elements of the construction process as structural, technological and work safety decisions into a single complex decision.

The authors have evaluated the complexity of the algorithm of the proposed synthesis decision method (SyMAD-3) and compared it with the complexities of the algorithms of multi-stage synthesis methods proposed by other authors. As a result, they make an assumption that the method described in the article is more efficient time-wise. The complexity of the algorithms used in the method take linear time $O(n.)$, because the basis of this method is vector algebra for arrays.

Apart from construction projects, the proposed method can also be applied to other problems related to decision making. In the future, the authors are planning to

apply the SyMAD-3 method to solve multiple attribute decision-making problems encountered in other areas where input data rely on quantitative estimates.

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NAUJAS KONSTRUKCINIŲ, TECHNOLOGINIŲ IR SAUGOS SPRENDIMŲ SINTEZĖS METODAS (SYMAD-3)

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S a n t r a u k a

Šiame darbe autoriai pateikia naują daugiakriterinių sprendimų sintezės metodą (*SyMAD-3 – Synthesis of Multiple Attribute Decisions using three methods*), skirtą daugiapakopiams, daugiatiksliams sprendimams apjungti į vieną bendrą įvertį. Metodas taikomas statybos projektui parinkti atsižvelgiant į konstrukcinius, technologinius ir saugos sprendimus. Sprendimo patikimumui padidinti taikomi trys kiekybiniais matavimais pagrįsti daugiatiksliai sprendimo priėmimo metodai, kuriais remdamasis sprendimą priimantis asmuo gali stebėti jam aktualaus sprendimo rezultatus, gautus trimis metodais, priklausančiais tai pačiai klasei. Pateikto metodo algoritme taikomi efektyvumo rodiklių integruoto reikšmingumo nustatymo ir daugiatiksliai sprendimo priėmimo (*SAW – Simple Additive Weighting, TOPSIS – Technique for Order Preference by Similarity to Ideal Solution, COPRAS – COmplex PRoportional ASsessment*) metodai, pagrįsti kiekybiniais matavimais.

Reikšminiai žodžiai: daugiakriteriniai metodai, daugiatiksliai sprendimo priėmimo metodai, statyba, technologinis, architektūrinis, saugos, sprendimų sintezės metodai, patikimumas.

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