Automation of fuzzy multi-criteria selection of robotic machine-assembly technologies using worst-case approach

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Abstract. In this paper a new method of selection of robotic machine-assembly technology is presented. The core of the technology suggested is the method of fuzzy multi-criteria alternatives selection using the worst-case approach. The automation of the proposed solution is based on the original WMS (Worst Method Solution) software, developed by authors. In the basis of this software are the ideas of robotic machine-assembly technology and its theoretical formalization.

1 Introduction

1.1 Relevance

Many branches of modern industry could be described as small series batch type production. The specifics of this type of production are the rapid change of nomenclature, frequent adjustments and flexibility to the market requirements. In these conditions, industrial robots (IR), which are considered to the base equipment for production automation, are widely used. According to the International Federation of Robotics [1], the annual output and implementation of IR in various industries is about 15%. In this context, studies of various solutions related to the use of IR in different technologies is important and relevant.

1.2 Problem statement

In engineering practice, when design or synthase robotic machine-assembly technologies (RMAT) for various of industries, many specific practical problems rise. Solutions of these problems could be solved by proper formulation of tasks and description of available technological, technical, and other limitations (input data). When we have input data formulated, a number of possible RMAT solutions appears and the problem of selection of the optimal one appears. According to the contents, this problem refers to multi-criteria (vector) optimization problems and the solution methods which are characterized by variability and ambiguity [2]. Each RMAT can be represented by a set of their (technologies) manifestations and this set can be described as a Discrete Set of Local Criteria (DSLC). The elements of the DSLC, which characterize each RMAT solution, consists of the following components [3]: Gm - geometric; Kn - kinematic; Dn - dynamic; Ct - control; En - energy; Tr - trajectory; τ (Q) - time (productivity); Fc -force; Fopt- a component that is defined by accepted types of criteria of optimality (economic, technical, etc.) in the design (analysis) of the RMAT; Rl - reliability; Ec - economic; Ac– accuracy.
The sequences of these criteria were analyzed in an expert questionnaire and the results were used in solving the optimization problem. A limited number of them have been analyzed in [4,5] for optimization of industrial robots' trajectory problems.
The desired solution to the task of selection of a RMAT is the simultaneous consideration of each of the discrete local criteria. However, in practice, this is not feasible, since the complexity of each of the manifestations of RMAT solutions does not given the opportunity to estimate precisely and in details one or another criterion, having determined the advantage of its manifestations for each component of the DSLC on a specific set of criteria under consideration. To solve such tasks, some indicators are converted into the rank of criteria, and others to a set of limitations, which in turn deter-mines the importance of studying the problem of the mutual relations of local discrete criteria on their discrete set and the influence of each criterion on the choice of a RMAT solution.
In order to develop a robotic technology, it is necessary to create a new and/or to use existing methods for solving a number of technological and other related problems. This will allow operators and designers to minimize resources for solving such tasks, time spent on designing/synthesizing of RMAT, making scientifically-based technological decisions of various content and others that increase the efficiency of robotic machine-assembly industries.
Thus, when choosing a RMAT solution, it is necessary to take into account the multi-criteria and un-certainty, as well as to make choices of solutions from the set of alternatives of a diverse nature if there are criteria having different types of measurement scales. In fact, the

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content of the task of the fuzzy multi-criteria selection of RMAT reduces to the formation of an ordered set of local criteria from the DSLC, which is performed on the set of alternatives, according to the data provided by the experts.

In [6] the effect of different normalization norms within multi-criteria decision making (MADM) models was assessed. Three well accepted MCDM tools, such as: preference ranking organization method for enrichment evaluation (PROMETHEE) [7]; grey relation analysis (GRA) [8]; technique for order preference by similarity to ideal solution (TOPSIS) methods [9] are applied for solving a flexible manufacturing system (FMS) selection problem in a discrete manufacturing environment.

Models described above, can't be used for solving our problem. PROMETHEE model is quite laborious because uses paired comparisons (as in Saati [10]). GRA model needs a complicated mathematical apparatus and corresponding complicated programming. TOPSIS model excludes positive-ideal and negative-ideal solutions and narrows the choice down.

We consider, that the use of fuzzy multi-criteria selection for choosing of a RMAT gives better results for practical implementations [11], [12].

1.3 Purpose of the paper

The purpose of this work is to increase the efficiency of technological preparation of robotic machine-assembly industries in selection of a robotic machine-assembly technology, due to the formation of an ordered set of discrete local criteria by the use of fuzzy multi-criteria alternative selection [4], [11], [12] and by applying the worst-case approach [5], [13].

2 Contents

2.1. The features of the method used

Based on the analysis of existing decision-making methods for solving multi-criteria problems in the conditions of primary uncertainty, the decision-making method is used for automated fuzzy multi-criteria selection of RMAT on the DSLC based on the ideas of Bellman-Zade and Saati [4,10]. The new model doesn't require any formation of matrix of paired comparisons. Instead, simple calculation ratios are used that include comparison with the worst alternative and the least important criterion (so called "Worst-case approach" [11,12]).

The peculiarity of using the worst-case approach for solving this problem is the lack of a 9-point scales for the alternatives rank relations [4]. The scale of the relevant assessments in our case is a 12-point scale, according to which each expert evaluates each local criterion (manifestation) of the DSLC without re-evaluations of different local criteria. In this case there is a lack of coherence of experts, which are determined by various known methods.

Another feature of using fuzzy multi-criteria choice of the alternatives for this task is the two-step solution. At the first stage there is the weight of each $E_{i_{E}dg}$ expert for each $S_{i_{S}dg}$ criterion (see below). This creates a set of potentially good solutions. At the second stage is the weight of each $S_{i_{S}dg}$ criterion for each $E_{i_{E}dg}$ expert. In this case, the final decision regarding the tuple of DSLC elements is formed.

A short description of the fuzzy multi-criteria selection of RMAT by the worst-case approach is as follows:

1.Identification of the expert alternatives as fuzzy sets. Every expert forms a set of $\mathrm{E} = (\mathrm{E}_{\mathrm{i}_{\mathrm{E}}\mathrm{dg}} \mid \mathrm{i}_{\mathrm{E}}\mathrm{dg} = \overline{1, \mathrm{n}_{\mathrm{E}}\mathrm{dg}})$ by presenting it as a fuzzy set of alternatives that givens an universal DSLC $\mathrm{S} = \left(\mathrm{S}_{\mathrm{i}_{\mathrm{S}}\mathrm{dg}} \mid \mathrm{i}_{\mathrm{S}}\mathrm{dg} = \overline{1, \mathrm{n}_{\mathrm{S}}\mathrm{dg}}\right)$ in the form:

$$\mathrm{E} = \left(\frac{\mathrm{w}_{1_{\mathrm{E}_{1w}}^{dg}}}{\mathrm{S}_{\mathrm{i}_1}^{dg}}, \dots, \frac{\mathrm{w}_{\mathrm{i}_{\mathrm{E}_{\mathrm{i}w}}^{dg}}}{\mathrm{S}_{\mathrm{i}_{\mathrm{S}_\mathrm{i}}^{dg}}}, \dots, \frac{\mathrm{w}_{\mathrm{n}_{\mathrm{E}_{\mathrm{n}w}}^{dg}}}{\mathrm{S}_{\mathrm{n}_{\mathrm{S}}dg}} \right). \quad (1)$$

The weights $\mathrm{w}_{\mathrm{n}_{\mathrm{E}_{\mathrm{i}w}}^{dg}}$ of the elements $\mathrm{S}_{\mathrm{i}_{\mathrm{S}_\mathrm{i}}^{dg}}$ is the weights of each local manifestation of RMAT from the DSLC to fuzzy sets as numbers in the interval [0,1]. This is taken into account as the criteria weights for the experts $\mathrm{E}_{\mathrm{i}_{\mathrm{E}}\mathrm{dg}}$. The following condition has to be satisfied:

$$\sum_{\mathrm{i}_{\mathrm{S}}\mathrm{dg}=1}^{\mathrm{n}_{\mathrm{S}}\mathrm{dg}} \mathrm{w}_{\mathrm{i}_{\mathrm{E}_{\mathrm{i}w}}^{dg}} = 1. \quad (2)$$

2. Determination of the best alternative $\left\langle \mathrm{S}_{\mathrm{i}_{\mathrm{S}}\mathrm{dg}} \right\rangle$, which is searched according to the Bellman-Zade [4] principle within the intersection of alternatives, that is a set $\mathrm{E} = (\mathrm{E}_{\mathrm{i}_{\mathrm{E}}\mathrm{dg}} \mid \mathrm{i}_{\mathrm{E}}\mathrm{dg} = \overline{1, \mathrm{n}_{\mathrm{E}}\mathrm{dg}})$. The alternative with the maximum weight $\left\langle \mathrm{S}_{\mathrm{i}_{\mathrm{S}}\mathrm{dg}\,\mathrm{max}} \right\rangle$ is chosen as the best one.

3. Alternative weights. The weights of alternatives included in the fuzzy sets are indicated at this step. In our case, the sum of weights, which is equal to one in expression (2) is distributed between the alternatives, that is, between all the experts, according to their ranks.

Let $\mathrm{R}_{\mathrm{S}_{\mathrm{i}_{\mathrm{S}}\mathrm{dg}}}$ be the rank of the criterion $\mathrm{S}_{\mathrm{i}_{\mathrm{S}}\mathrm{dg}} \in$ S with respect to the alternative $\mathrm{E}_{\mathrm{i}_{\mathrm{E}}\mathrm{dg}} \in$ E. It is assumed that the higher weight of an alternative, the higher is its rank.

Let $\mathrm{E}_{\mathrm{i}_{\mathrm{E}}\mathrm{dg}}\mathrm{S}_{\mathrm{i}_{\mathrm{S}_\mathrm{i}}^{dg}\mathrm{min}}$ be the worst alternative (by expert $\mathrm{E}_{\mathrm{i}_{\mathrm{E}}\mathrm{dg}} \in$ E) with weight $\mathrm{w}_{\mathrm{i}_{\mathrm{S}_{\mathrm{i}w}}^{dg}}$ and rank $\mathrm{R}_{\mathrm{S}_{\mathrm{i}_{\mathrm{S}}\mathrm{dg}}}$. The weights of all the alternatives are expressed by the weight of the worst alternative:

$$\left(\mathrm{w}_{\mathrm{i}_{\mathrm{S}_{\mathrm{i}w}}^{dg}} \mid \mathrm{i}_\mathrm{w} = \overline{1, \mathrm{n}_{\mathrm{E}}\mathrm{dg}} \right) = \frac{1}{\sum_{\mathrm{i}_{\mathrm{E}}\mathrm{dg}=1}^{\mathrm{n}_{\mathrm{E}}\mathrm{dg}} \frac{\mathrm{E}_{\mathrm{i}_{\mathrm{E}}\mathrm{dg}}\mathrm{S}_{\mathrm{i}_{\mathrm{S}_\mathrm{i}}^{dg}}}{\mathrm{E}_{\mathrm{i}_{\mathrm{E}}\mathrm{dg}}\mathrm{S}_{\mathrm{i}_{\mathrm{S}_\mathrm{i}}^{dg}}^{\mathrm{min}}}} \mid \sum_{\mathrm{i}_{\mathrm{E}}\mathrm{dg}}^{\mathrm{n}_{\mathrm{E}}\mathrm{dg}} \mathrm{w}_{\mathrm{i}_{\mathrm{S}_{\mathrm{i}w}}^{dg}} = 1 \quad (3)$$

For each criterion $\mathrm{S}_{\mathrm{i}_{\mathrm{S}}\mathrm{dg}} \in$ S we give the ratio of the ranks of alternatives using a constant amount scale.

4. Taking into account the importance of the experts' judgments. Let $\alpha_{\mathrm{i}_{\mathrm{S}}\mathrm{dg}}$ be the expert weight $\mathrm{E}_{\mathrm{i}_{\mathrm{E}}\mathrm{dg}} \in$ E, which

characterizes the relative importance of his judgment. Taking into consideration the weights of the experts, the fuzzy set of solutions $\langle D_{II}\rangle$ (for this task, this is an ordered set of manifestations of RMAT with DSLC) is formulated as follows:

$$\langle D_{II}\rangle = \langle \max\left(w_{i_{E^{dg}_{i_w}}} \mid i_w == \overline{1, n_{S^{dg}}}\right)^{E_{i_{E^{dg}}} W_{i_{S^{dg}} \min}^{\left(\alpha_{i_{S^{dg}}}\right)}} |A\rangle$$

Here the expression A is deciphered in 2.2.

2.2 Formalization of the task

The solution of this task is possible due to the use of experience, knowledge and intuition of the specialists by conducting an expert survey on the method of questioning. It is obvious that an expert assessment carries the subjective factors that may have a negative impact on the end result. This is due to the incompleteness of knowledge or the lack of necessary information; unreliability of knowledge, the presence of which is characterized by subjective and objective uncertainties, etc. Moreover, when solving the problem, the complexity of each of the manifestations of the RMAT, that is, in fact, every element of the DSLC, does not allow the expert to assess one or another criterion in absolute details and accurately, identifying the advantage of its manifestations in a specific set of criteria.

Thus, the unreliability of knowledge and of the existing factors forms a kind of obscurity during the assessment, which greatly affects the end result. The above mentioned should also is taken into account when solving such problems.

The foregoing allows us to make the general statement of the problem in the following interpretation: according to the known manifestations of RMAT in the manufacturing of the *g* product from the *d* group $S_{n_{S^{dg}}}$, forming the DSLC $S = \left(S_{i_{S^{dg}}} \mid i_{S^{dg}} = \overline{1, n_{S^{dg}}}\right)$, and the matrix *M*, which contains the data of the expert questionnaire conducted by a certain number of experts and relates to the input data (*Input*), it is necessary to select such RMAT from their final regenerated set on the results of a finite set of computational procedures $\left(\varphi_{i_{\varphi^{dg}}} \mid i_{\varphi^{dg}} = \overline{1, n_{\varphi^{dg}}}\right)$. The process of selection is determined by the formed ordered DSLC, which characteristically reflects the priority of each $S_{i_{S^{dg}}}$ local discrete criterion according to the judgments of all experts and accordingly is the final result (*Output*).

In this regard, the formalized statement of the problem is as follows:

Input:

$S = \left(S_{i_{S^{dg}}} \mid i_{S^{dg}} = \overline{1, n_{S^{dg}}}\right); E = (E_{i_{E^{dg}}} | i_{E^{dg}} = \overline{1, n_{E^{dg}}});$

$$M[n_{E^{dg}}\ x\ n_{S^{dg}}] = \begin{bmatrix} E_1 S_{i_1}^{dg} & \cdots & E_1 S_{i_{S^{dg}}} & \cdots & E_1 S_{n_{S^{dg}}} \\ \vdots & & \vdots & & \vdots \\ E_{i_{E^{dg}}} S_{i_1}^{dg} & \cdots & E_{i_{E^{dg}}} S_{i_{S^{dg}}} & \cdots & E_{i_{E^{dg}}} S_{n_{S^{dg}}} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ E_{n_{E^{dg}}} S_{i_1}^{dg} & \cdots & E_{n_{E^{dg}}} S_{i_{S^{dg}}} & \cdots & E_{n_{E^{dg}}} S_{n_{S^{dg}}} \end{bmatrix}$$

Output:

$$\left(\varphi = \left(\varphi_{i_{\varphi^{dg}}} | i_{\varphi^{dg}} = \overline{1, n_{\varphi^{dg}}}\right)\right):$$

$$:\left(\left(E = \left(E_{i_{E^{dg}}} | i_{E^{dg}} = \overline{1, n_{E^{dg}}}\right)\right) \times \left(S = \left(S_{i_{S^{dg}}} | i_{S^{dg}} = \overline{1, n_{S^{dg}}}\right)\right) \times M\left[n_{E^{dg}} \times n_{S^{dg}}\right]\right) \rightarrow$$

$$\rightarrow \frac{\langle max\left(w_{i_{E^{dg}i_W}} min \mid i_W = \overline{1, n_{S^{dg}}}\right)^{\left(E_{i_{E^{dg}}} W_{i_{S^{dg}}}^{\left(\alpha_{i_{E^{dg}}}\right)} min\right)} |A\rangle}{\left]\left(\forall S_{i_{S^{dg}}} \mid i_{S^{dg}} = 1, n_{S^{dg}}\right) \in S\right[}.$$

Where: ($A = \forall E_{i_{E^{dg}}} \subset E$; $\forall W_{i_{E^{dg}} i_W} min > W_{i_{E^{dg}} j_W} min$; $i_W \neq j_W$; $(i_W, j_W) = \overline{1, n_{S^{dg}}}$) is an expression that formalizes the ordering of the parameter $w_{i_{E^{dg}_{i_w}}}$ from *max* to *min*;

S – discrete set of local criteria, $S = (S_{i_{S^{dg}}} | \overline{1, n_{S^{dg}}})$;

$S_{i_{S^{dg}}} \in (Gm; Kn; Dn; Ct; En; Tr; (Q); Fc; F_{opt}; Rl; Ec; Ac)$ – components of DSLC;

$n_{S^{dg}}$ – number of local manifestations of RMAT that form the set S;

E – set of experts $\left(E = (E_{i_{E^{dg}}} | i_{E^{dg}} = \overline{1, n_{E^{dg}}})\right)$ whose judgments are used to form an ordered ranked DSLC;

$n_{E^{dg}}$ – number of experts who took part in decision-making process;

M – matrix containing quantitative estimates $S = \left(S_{i_{S^{dg}}} \mid i_{S^{dg}} = \overline{1, n_{S^{dg}}}\right)$, that reflects judgments $E_{i_{E^{dg}}}$ of the expert as for the advantage of $S_{i_{S^{dg}}}$ local criterion in questioning;

$w_{i_{S^{dg}_{i_w}}}$ – the weight value of $E_{i_{E^{dg}}}$ expert, $E_{i_{E^{dg}}} \in E$, with respect to $S_{i_{S^{dg}}}$ criterion, $S_{i_{S^{dg}}} \in S$;

$w_{i_{S^{dg}_{i_v}}}$ – the weight value of $S_{i_{S^{dg}}}$ criterion, $S_{i_{S^{dg}}} \in S$ in the judgments of $E_{i_{E^{dg}}}$ expert, $E_{i_{E^{dg}}} \in E$;

$\alpha_{i_{S^{dg}}}$ – weight value that characterizes the importance of $E_{i_{E^{dg}}}$ expert $E_{i_{E^{dg}}} \in E$ in determining the weight $S_{i_{S^{dg}}}$ criterion, $S_{i_{S^{dg}}} \in S$;

]... [– the data in these brackets is the reference data that is not used in the calculations.

2.3 The developed expert system for solving similar tasks

Described in 2.1. method takes into account recommendations given in [11]. It is implemented programmatically and it is in the basis of the developed by authors software product WMS (Worth Method Solution). WMS is a software developed expert system for automated solutions of the tasks of similar content (see Fig. 1). Its components are as follows:

– block of input and processing of primary information intended for users to enter the name, the number of criteria, the number of experts and the data of the expert survey, thus forming the matrix $M[n_{E^{dg}} \times n_{S^{dg}}]$. Its content reproduces a set of local criteria ordered by each $E_{i_{E^{dg}}}$ expert $S = \left(S_{i_{S^{dg}}} \mid i_{S^{dg}} = \overline{1, n_{S^{dg}}}\right)$. It is also possible to download the specified matrix from the database in WMS;

– the block of formation of fuzzy criteria from the weight of alternatives on a universal set of alternatives. For each of the local criteria, the worst alternative $({}_{E_{i_{E^{dg}}}} S_{i_{S^{dg}}} min$ chosen among all the experts (the minimum sum in the columns of the matrix $M[n_{E^{dg}} \times n_{S^{dg}}]$) and by comparing with it the weights of all the alternatives $w_{i_{S^{dg}_{i_w}}}$, from which fuzzy set with values of local criteria is formed.The obtained weights of all alternatives allow to write down the criteria as fuzzy sets, which are given on the universal sets of the alternatives;

– the block for forming the fuzzy criteria takes into account the relative importance of the criteria. Here, with the help of ranks, the weight of each criterion ${}_{E_{i_{E^{dg}}}} \alpha_{i_{S^{dg}}}$ that characterizes its importance is determined. By comparing the weight of each criterion with the least important $\alpha_{i_{S^{dg}} min}$, the weights of all the criteria are determined;

– the block for formation of fuzzy alternatives as a set with values of local criteria. It takes into account their relative importance and there is an operation of intersection of the latter with the obtaining of fuzzy set of alternatives with values of coefficients of their relative importance $W_{i_{S^{dg}_{i_w}}}^{(\alpha_{i_{S^{dg}}})}$. Then the weights of the criteria are determined $w_{i_{E^{dg}_{i_w}}}$. The worst alternative ${}_{E_{i_{S^{dg}}}} E_{i_{E^{dg}_i}} min$ is selected among the criteria and by comparing it with all the others. Then fuzzy sets with values of expert alternatives are formed;

– the block of making the final decision on the determining of the ordered sequence of local discrete criteria $\left\langle {}^{*}S_{i_{S^{dg}}} \right\rangle$, which is systematically considered when choosing RMAT.

– Fig.2 illustrates some screen forms of functioning of the developed software WMS product. Fig. 2,a - when entering the matrix and processing the initial data; Fig. 2,b - when initiating a program for calculations; Fig.2,c - a table of digital values of the relative importance of experts and their graphical interpretation in the form of a pie color chart is given; Fig.2,d is a table representation of the digital values of the coefficients of the relative importance of local criteria for the DSLC and their graphical interpretation in the form of a column diagram, which is a fuzzy set of the final solution of this problem.

Thus, based on the results of an automated RMAT selection for the number of experts $n_{E^{dg}}$=10, the number of criteria $n_{S^{dg}} = 12$ and correspondingly with the matrix *M[10 x 12]* (the results of the expert questionnaire are not given here), the disordered set of local criteria had such a composition:
S = $(Gm; Kn; Dn; Ct; En; Tr; \tau(Q); Fc; F_{opt};\ Rl; Ec; Ac;)$.
After automated solution of this task by the specified by us method by using the developed software product WMS, the set of local criteria has become well-organized and has the following composition:
S=$\langle Kn; En; Gm; Dn; \tau(Q);\ Ct;\ Ac; Rl; Tr; Ec; F_{opt};\ Fc\rangle$.
This means that when applying the fuzzy multi-criteria choice of RMAT for the specified input data, it is necessary to make a decision taking into account precisely this ordered sequence of elements of the DSLC.

3 Conclusion

When choosing RMAT from their synthesized final sets, the method of fuzzy multi-criteria selection of alternatives using the worst-case approach is used. It reduces the complexity of the calculations in the implementation of the selection process and thereby increases the efficiency of the technological preparation of machine-assemblies.

The Worst Method Solution software product is developed on the basis of the proposed expert system. It helps to choose a robotic machine-assembly technology and automates the fuzzy multi-criteria selection of alternatives by the worst-case approach. The Worst Method Solution software product is in fact invariant as for the nature and dimension of the tasks to solve and can be used to streamline the "internal" components of virtually every element of the discrete set of local criteria that has its own internal structure, such as reliability, dynamics, etc. This indicates the versatility of the developed software product.

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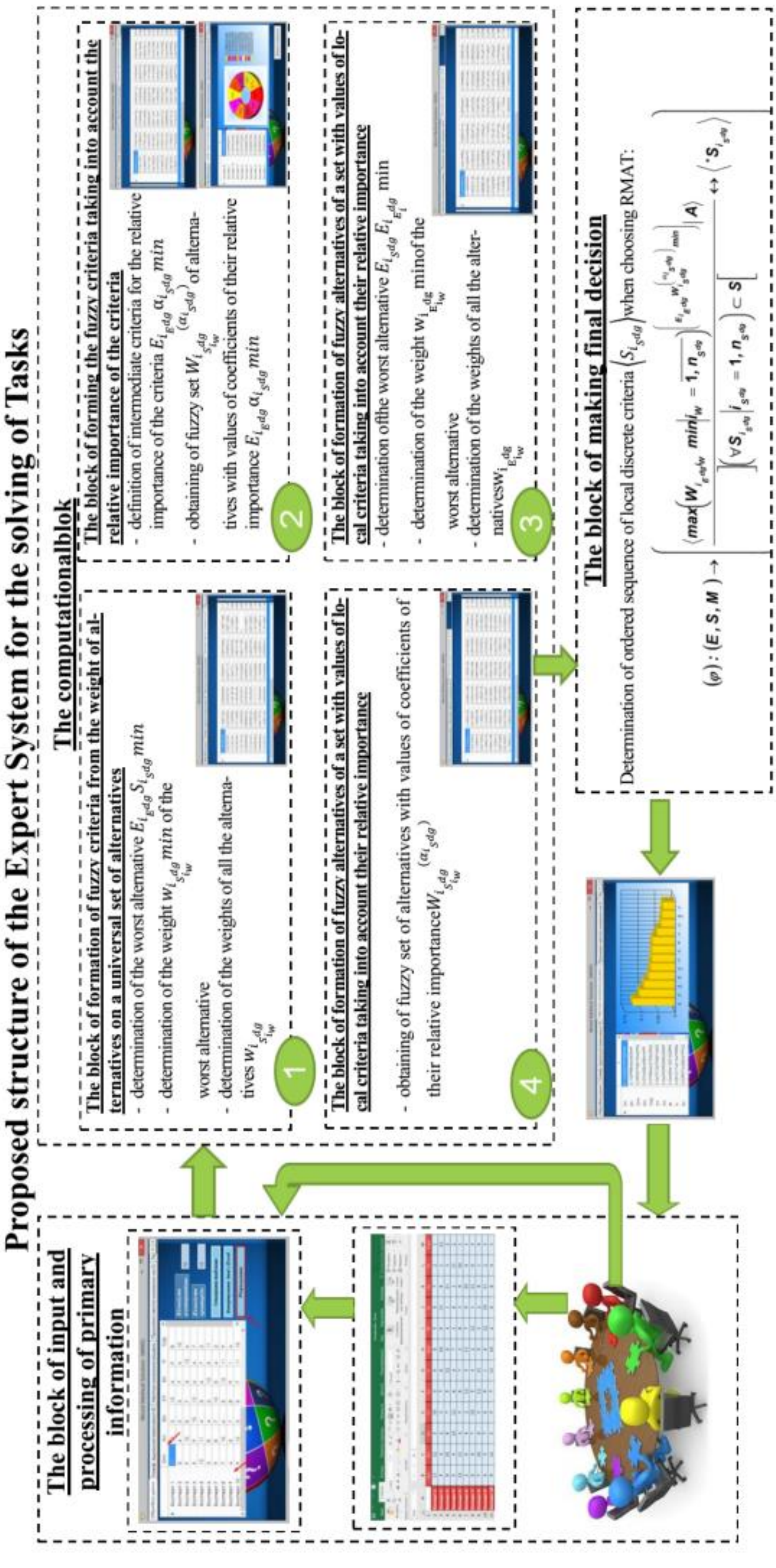
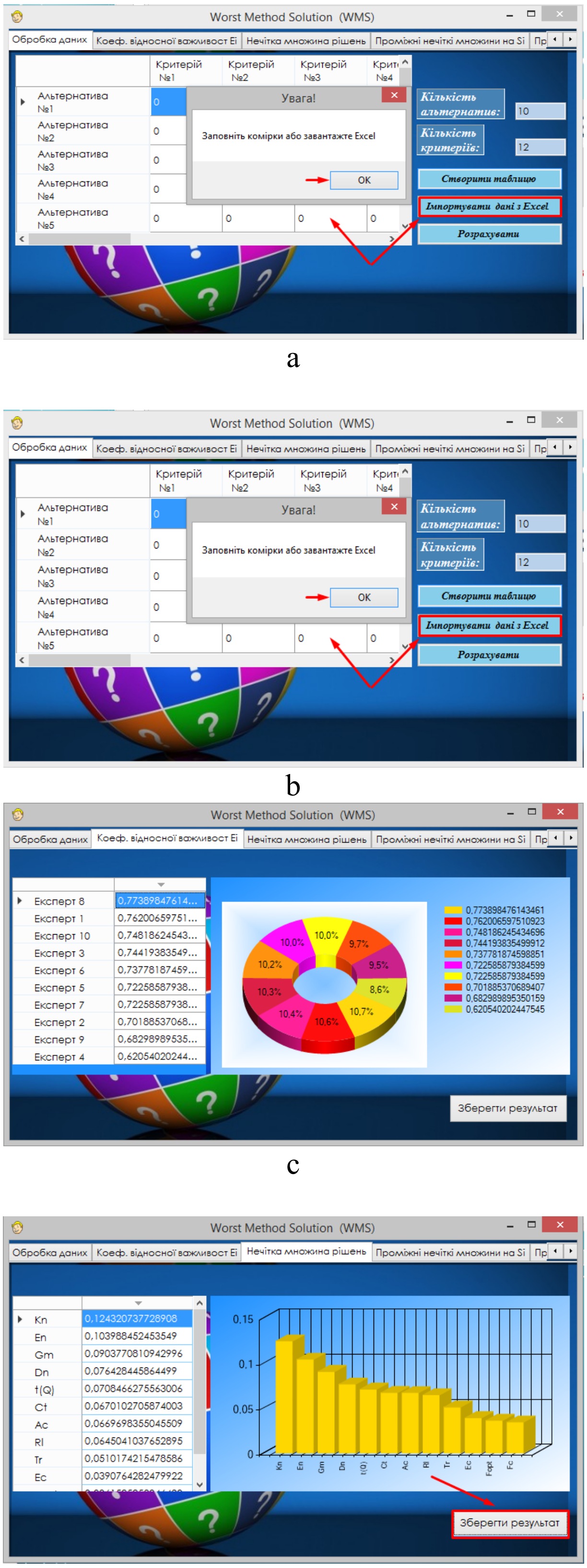


Fig. 1. Organizational structure of the proposed Expert System for automation of the selection process of the RMAT



a

b

c

d

Fig. 2. Screen shot views of the developed software product WMS for n_{Edg}=10 (the number of experts) and n_{Sdg} = 12 (the number of criteria).

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