Запропоновано новий метод автоматизованого вибору роботизованих механоскладальних технологій за техніко-економічними критеріями. Вибір виконується на відомій множині роботизованих механоскладальних технологій, складових системи техніко-економічних критеріїв, аналізованих методах амортизаційних відрахувань залишкової вартості промислових роботів та інших організаційно-технологічних вхідних даних. Змістом останніх є: період експлуатації промислових роботів в гнучких виробничих комірках, період та обсяг випуску продукції, кількість та обсяг партій запуску виробів у виробництво.

Процес вибору роботизованих механоскладальних технологій виконується за мінімальним значенням одного з вибраних користувачем техніко-економічних критеріїв із їх попередньо розробленої системи. Кожен із критеріїв з різним ступенем деталізації змістовно відтворює «роботизовану» складову собівартості випуску одиниці продукції і обумовлений використанням лише промислових роботів.

Виконана формалізація процесу вибору дала можливість розробити алгоритмічне забезпечення, що покладено в основу функціонування розробленої комп'ютерної програми в програмному середовищі MS Excel. Працездатність комп'ютерної програми протестовано на прикладах, що на множині синтезованих роботизованих механоскладальних технологій відрізняються тільки варійованими даними щодо організаційно-технологічних особливостей використання промислових роботів в механоскладальних гнучких виробничих комірках.

Аналіз отриманих результатів показав, що для розглянутих прикладів за інших рівних умов найменшим є критерій вибору, обумовлений використанням прямолінійного методу амортизації вартості промислових роботів незалежно від кількості років їх експлуатації.

Сформовані математичні узагальнення та надані рекомендації щодо використання методів амортизаційних відрахувань вартості промислових роботів, що визначають їх залишкову вартість при розрахунку критеріїв вибору.

Розроблений метод вибору роботизованих механоскладальних технологій є інваріантним в контексті можливості його використання в різних країнах з різною нормативною базою щодо існуючих методів амортизаційних відрахувань при визначенні залишкової вартості промислових роботів

Ключові слова: промисловий робот, роботизована механоскладальна технологія, техніко-економічний критерій, амортизація

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DEVELOPMENT OF A NEW METHOD FOR AUTOMATED SELECTION OF ROBOTIC MECHANIC-ASSEMBLY TECHNOLOGIES BASED ON THE TECHNICAL AND ECONOMIC CRITERIA

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1. Introduction

Technical and economic criteria occupy an important place in the analysis and selection of objects and processes of different origin and nature, including the selection of robotic mechanic-assembly technologies (RMAT) on their pre-synthesized non-empty finite set [1]. This is an integral part of technological training of robotic mechanic-assembly productions (RMAP) [1]. The variability of the final set of the considered factors and their content indicates the need to perform such calculations in the automated form on the methodically and scientifically grounded basis by one of the proposed criteria. This clearly affects the final cost of manufactured products, for example, in the mechanic-assembly flexible production cells (FPC) of machine and tool building. Naturally, the RMATs are implemented using industrial robots (IR).

In order to enhance the efficiency of the RMAP, the selection of the RMAT, the finite set of which is generated during designing the FPC, and the synthesis of the RMAT in them provides a scientifically grounded approach in terms of implementation of the selection process. This is one of the ways to protect possible capital and other losses during operation and/or designing the FPS, and thus is one of the ways to increase the efficiency of the RMAP in general.

The mentioned tasks are the components of the technological preparation of the RMAP [1].

The importance of conducting research related to the use of IR is particularly evident against the background of their (IR) annual production and introduction in various branches of modern automated productions with a wide range of their [IR] design and technological solutions [2].

According to the data of the International Federation of Robotics (IFR) over the last 8–10 years, the growth of the IR production is on average 15 % per year [3], which is considerable in monetary terms. Therefore, diverse studies that involve the use of the IR, including the selection of the RMAT, are essential.

The relevance of the studies in this area is determined, on the one hand, by the lack of a uniform methodological approach to the selection of the RMAT, which is determined by the specific feature of setting the selection problem, and on the other hand, by the need for effective use of IR, realizing the RMAT.

2. Literature review and problem statement

The subject-matter of the RMAT selection is one of the least explored in information sources.

A widespread use of relatively new scientific and methodological approaches for the design/synthesis/selection of flexible production systems, including the FPC employing various methodical and mathematical bases is widely known [4–8]. The focus is on a wide range of decision-making methods. It is organization of ranking in making decisions for profit estimation (PROMETHEE) [4], gray relational analysis based on partially known, incomplete information (GRA) [5], the method for evaluating the dynamic and fuzzy environment as for stationary and/or movable obstacles in the projected robotic structure [6, 7], etc. Paper [8] represents an attempt to assess systematically the methods mentioned in [4–7] and other procedures using different methods for normalization of the obtained results.

The logical continuation of the listed significant studies [4–8] would be the generation/design/synthesis of the finite set of the RMAT on the selected structures of flexible production systems and their (technologies) choice. However, these studies do not contain this component as one of the possible research results.

It is known about a relatively small number of commonly available papers, the content of which reproduces primarily generation (design/synthesis) of certain technologies [9–13]. Thus, in paper [9], the problem of the technologies of multi-nomenclature tool productions is solved on a powerful methodical-scientific base with the use of weighted blurred attributes. Their characteristic feature is that the problem of selection of a particular technology itself is not solved. Paper [9] uses the specific TOPSIS technique for the selection in the context of design/synthesis of the computer integrated production technologies. This requires a powerful mathematical apparatus for making a meta-model. However, the paper is research by nature and is not suitable for a wide range of manufacturers.

The key points of the content of paper [10] are to highlight the issues related to use of the IR in metalwork technologies. Technological functions performed by the IT are considered, the necessity to perform certain optimization calculations of IR functioning is emphasized, etc. That is, some requirements for design/synthesis namely of robotic metalwork technologies are generalized, but their selection according to certain criteria is not performed.

In was established in paper [11] that combining useful components from each standard analyzed in the paper, it is possible to form the estimates of productivity of robotized machines, on which the technology for mass production can be developed. That is the content of this paper is the development of the organizational and technical basis for robotics of machining technology. At the same time, the technologies are not selected by certain criterion, but only designed/synthesized.

Article [12] is close to the explored problem of the selection of the RMAT. A developed and quantitatively defined hierarchical model of decision making regarding including corporate priorities to the assessment of robotics technologies in power engineering is proposed. However, the specificity of this subject area makes it impossible to use the obtained results, primarily in terms of the lack of a set of generated technologies. And therefore, the process of selection itself in the accepted here sense, that is, by the technical-economic criterion, is impossible.

There is a known work [13], which introduces a profound analytical review on the selection and substantiation of the most appropriate method for the selection of technologies. The fact of increasing the use of methods of Multi-Attribute Decision Making (MADM) to solve the problem of selection of technologies under production conditions is emphasized. That is, such methods for choosing technologies are analyzed, but the selection of technologies themselves by certain criteria is not performed.

As a fact, in problem-oriented papers [4–13], the choice of technologies, including the RMAT, remains beyond the attention of researchers. Thus, all the analyzed information sources have unresolved problems concerning efficiency of using the IR under modern automated industries of machine- and tool building. One of such indicators of IR efficiency is the part of production cost under certain robotic technological structures, determined by the application of only IR («robotic component» of cost).

This makes it possible to argue that it is advisable to conduct research devoted to the development of a new method of automated selection of the RMAT by technical and economic criteria. This is the content of this study.

The content, composition, and specifics of calculation of technical, economic and combined, that is, technic-economic criteria of the RMAT selection, were considered in papers [1, 14].

Criteria of technic-economic content as such and as a system of technical and economic criteria (STEC) are represented in paper [14]. Their mutual hierarchy is shown, the possibility of using each criterion as a criterion for the selection of the RMAT is highlighted. In this case, the general analysis of the set of local criteria, which are the content of the RMAT manifestation, as a result of a systemic approach to the RMAT synthesis is performed. This in turn is a result of a multi-theoretical systemic approach to the design/synthesis of the RMAT [1].

In general, there remained the unresolved issues regarding the impact of different types of depreciation expense of the IR costs on the magnitudes of the STEC criteria and their influence on the selection of the RMAT from their pre-synthesized set. The issues of automated calculation of selection criteria remained outside consideration.

The structural components of STEC are the elements of this system, that is, the criteria marked in this paper as $F1$, $F2.1$ and $F2.2$ [14]. Analytical expressions (1) to (3) for calculation of each of these criteria and represented explanations of their content were determined based on the analysis of papers [1, 14]. In expressions (1) to (3), in order to generalize understanding of each of the corresponding criteria, the main factors that first of all determine the content of the specified criterion in the generalized and informative way are indicated in brackets after abstract function $f(...)$. Thus:

– $F1=F_{opt\,N_{\ln}}$ (1) is the part of the technological cost of manufacturing of d-th products of their g-th group in the volume $N_{pr}^{d_g}$, which is determined by general financial expenses Z. The latter, in turn, are related with such data about the IR as balance cost C^{IR} (taking into account coefficient 1.15 for transportation, mounting and installment of the IR), accumulated time term of (using) operation T_{pr}^{IR}, power P^{IR} used in manufacturing product O^{dg} of volume $N_{pr}^{d_g}$ and duration of its (IR) operation in days T_{pr}^{IR} and in actual hours A_{nh}^{IR} (the basis for determining the costs of electric power C^E); basic $S_b=(M/T_w)\cdot t$ and additional $S_{ex}=S_b/10$ salary (with 22 % addition to it) of an adjuster during manufacturing products at the expense of his monthly salary rate M and the number of working shifts t, which is determined taking into account the number of working days in a month T_w (21–22 days by the norms acting in Ukraine), depreciation norm H_a and the magnitude of every i^{d_g} batch of product launch in manufacturing $N_{\ln_{i^{d_g}}}^{d_g}$, as well as K_p^{IR} – coefficient that determines the use of the IR by the capacity at manufacturing the produce of the assigned volume $N_{pr}^{d_g}$:

$$\left(\begin{array}{l} F1=F_{opt_{N_{\ln}}}=\dfrac{Z}{N_{pr}^{d_g}}= \\ =\dfrac{S_b+S_{ex}+\left(S_b+S_{ex}\right)\cdot 22\,\%+1.15\cdot C^{IR}+\dfrac{C^{IR}\cdot H_a}{100}\cdot\dfrac{T_{pr}^{IR}}{365}+C^E\cdot P^{IR}\cdot A_{nh}^{IR}\cdot K_p^{IR}}{N_{pr}^{d_g}}=f\left(N_{pr}^{d_g}\right)\end{array}\right)\rightarrow\min; \quad (1)$$

– $F2.1=F_{opt_{N^{d_g}_{\ln_{i^{d_g}}}T}}$ (2), implies determining criterion $F1$ for each i^{dg}-th launch batch of products in manufacturing $N_{\ln_{i^{dg}}}^{dg}$ taking into account the economic component of accumulated time resource of IR operation $T_{i^{d_g}}^{IR_S}$ until the moment of manufacturing the products of each i^{d_g} launched batch of volume $N_{\ln_{i^{d_g}}}^{d_g}$ with subsequent formation of criterion $F2.1$ as such, which is reduced to product unit O^{dg} taking into account the amount of produce in n^{d_g} launch batches $N_{\ln_{i^{d_g}}}^{d_g}$ within the planned reporting period $T_{pr}^{d_g}$:

$$\left(F2.1=F_{opt_{N^{d_g}_{\ln_{i^{d_g}}}T}}=\frac{\sum_{i^{d_g}=1}^{n^{d_g}}F_{opt_{N_{\ln_{i^{d_g}}}}}}{\sum_{i^{d_g}=1}^{n^{d_g}}N_{\ln_{i^{d_g}}}^{d_g}}=f\left(F1,T_{i^{d_g}}^{IR_S}\right)\right)\rightarrow\min; \quad (2)$$

– $F2.2=F_{opt_{N^{d_g}_{\ln_{i^{d_g}}}T_r}}$ (3) takes into account the sum of criteria $F2.1$ related to the economic component of all the produce amount in n^{d_g} product launching batches and determined by accumulated time resource of the IR operation prior to beginning each i^{d_g} batch of volume $N_{\ln_{i^{dg}}}^{dg}$ launched in production (that is $T_{i^{d_g}}^{IR_S}$), and by the duration of the IR re-adjustment T_r^{IR} between i^{d_g} and $(i+1)^{d_g}$ launch batches of volumes $N_{\ln_{i^{dg}}}^{dg}$ and $N_{\ln_{(i+1)^{dg}}}^{dg}$, respectively, which took place within the planned period of product manufacturing $T_{pr}^{d_g}$, with subsequent recalculation of the generalized criterion per conditional unit of produce of general volume $N_{pr}^{d_g}$ in n^{d_g} launch batches within the planned period $T_{pr}^{d_g}$:

$$\left(F2.2=F_{opt_{N^{d_g}_{\ln_{i^{d_g}}}T_r}}=\frac{\sum_{i^{d_g}=1}^{n^{d_g}}F_{opt_{N_{\ln_{i^{d_g}}}T_r}}}{\sum_{i^{d_g}=1}^{n^{d_g}}N_{\ln_{i^{d_g}}}^{d_g}}=f\left(F2.1,T_r^{IR}\right)\right)\rightarrow\min. \quad (3)$$

Thus, each of the proposed technical and economic criteria provides for its calculation during manufacturing a certain number of units of products in the production batch $N_{pr}^{d_g}$. The latter, in turn, depends on the requirements for operative planning at a particular enterprise and can be produced by several launch batches $N_{\ln_{i^{dg}}}^{dg}$, which is necessary to take into consideration when choosing RMAT according to $F2.1$ and $F2.2$ criteria. At each subsequent $(i+1)^{d_g}$ launch batch $N_{\ln_{(i+1)^{dg}}}^{dg}$ the time of starting the operation of IR $T_{(i+1)^{dg}}^{IRs}$ may not correspond to the time of completion of the operation of IR $T_{i^{d_g}}^{IR_F}$ during the production of the previous i^{d_g} launch batch, i. e. $T_{(i+1)^{dg}}^{IRs}\neq T_{i^{dg}}^{IR_F}$. This is due to the fact that between the launch batches of one type of the product, other types of products can be produced, which is characteristic flexible production in their various industries.

It is obvious that during the automatic calculation of the criteria of the RMAT selection, their following features are taken into consideration:

– the system of technical and economic criteria previously offered by one of the co-authors is used [14];

– the components of the STEC are calculated on the finite set of the STEC elements;

– depreciation expense of the IR cost is determined on the finite set of DM of the most common and known methods for their calculations [15], which appropriately correspond to the set tasks of the considered domain;

– in general, the content of the STEC components as criteria for automated choice of the RMAT and performed calculations in content reproduce the specific features of the RMAT in the part of formation of the «robotic» component of the technological cost of manufacturing products on the mechanical assembly FPC of machine and tool building [1].

At present, the analyzed information sources superficially explore the tasks of this problem area in the part of automation of calculations, analysis of obtained results and their practical use as criteria for the automated selection of the RMAT. It is characteristic that the completeness of the factors influencing the calculated values of selection criteria and, therefore, the result of the automated choice of the RMAT, are not taken into account.

At the same time, the content of such problems is an integral part of the technological preparation of the RMAP [1]. Therefore, the methodically substantiated solution of the above-mentioned tasks is one of the ways to improve the efficiency of design/operation of the RMAP and their technological preparation.

This requires more in-depth research, especially in the part of automated calculation, the use of components of STEC as criteria for choosing the RMAT and taking into consideration the completeness of selection factors, which is performed in the given work.

The content and use of the results will enable the producers and designers to minimize consumption of time, intellectual, production and other resources that influence the production cost. Minimization of the part of cost, determined by IR («robotic» component) in various robotic technological structures, including mechanic assembly FPC of machine and tool building is one of the sources of increasing the efficiency of the RMAP in general.

3. The aim and objectives of the study

The aim of this research is to increase the efficiency of technological preparation of the RMAP during the automated choice of the RMAT on their set with consideration of the STEC, the methods for determining depreciation expense of the IR cost, duration of the IR operation and manufacturing the produce in the FPC of machine and tool building.

To achieve the set goal, the following tasks were to be solved in this paper:

– to develop a new method of automated choice of the RMAT according to technical and economic criteria;

– to propose an extended set of factors that systematically determine the results of the RMAT choice;

– to develop the algorithm of the automated choice of the RMAT according to the developed method and to implement it in software;

– to demonstrate the serviceability of the developed method for the automated choice of the RMAT by technical and economic criteria;

– to provide generalized recommendations on the use of the developed method for the automated selection of the RMAT based on its informative features.

4. Summary of the proposed method and its formalization

Based on the above, we proposed the graphic representation of the STEC components, which determine the specific features of their manifestation and indicate the peculiarities of the calculation of the proposed criteria *F*1, *F*2.1 and *F*2.2 (Fig. 1). Here, apart from the mentioned above, designate: $N^{dg}_{\ln_1},...,N^{dg}_{\ln_{i^{dg}}},...,N^{dg}_{\ln_{n^{dg}}}$ are the volumes of batches launched in manufacturing of the product of total volume $N^{d_g}_{pr}$; $T^{IRs}_1,...,T^{IRs}_{i^{dg}},...,T^{IRs}_{n^{dg}}$ is the accumulated time of IR operation before the start of launch in production of the 1st,..., i^{d_g}, ..., n^{d_g} product launch batch, respectively; $T^{IR_F}_1,...,T^{IR_F}_{i^{dg}},...,T^{IR_F}_{n^{dg}}$ is the accumulated time of IR operation after finishing the production of the 1st, ..., i^{d_g},..., n^{d_g} launch batches of product, respectively.

During the graphic representation of criterion *F*2.2, which among other parameters takes into account time for IR readjustment, for example, between i^{d_g} and n^{d_g} launch batches of the analyzed products $T^{IR}_{r(i^{dg}-n^{dg})}$, we separated the batches of launching in production of other kinds of products, for example, of the (d_g+1)-th name, by the launch batches of volume $N^{d_g+1}_{\ln},...,N^{d_g+i}_{\ln},...,N^{d_g+n}_{\ln}$, which do not belong to the current d_g-th (analyzed) launch batch of products. In Fig. 1 for criterion *F*2.2 these parameters are marked by grey fill of smaller-size rectangles.

Analysis of the essence of the graphical representation of the STEC components identified the specific features of calculation of technical and economic criteria for the selection of the RMAT, which made it possible to propose a new method for the automated selection of the RMAT by the technical and economic criteria. Its content is based on decision making based on the calculated optimality criterion F_{opt} as the STEC element. This includes: pre-synthesized RMAT set ${}_{RMA}T^{d_g}=\left({}_{RMA}T^{d_g}_{i_T}\middle|i_T=\overline{1,n_T}\right)$, the data of organizational-technological content (*In*) and finite set (*DM*) of the methods of depreciation expenses of the IR cost selected for further use. They are also attributed to organizational and technological input data.

That is why the process of choosing the RMAT by the specified criteria can be formalized as the ultimate set of calculations $\varphi=\left(\varphi_{i_\varphi}\middle|i_\varphi=\overline{1,n_\varphi}\right)$ for certain content and of the total amount n_φ, which provides the minimum value of the selected optimization criteria F_{opt}, which is the criterion for the RMAT selection:

$$\varphi:\left(In\times MA\times {}_{RMA}T^{d_g}_{i_T}\right)\rightarrow$$
$$\rightarrow\left(\left(F_{opt}=\{F1,F2.1,F2.2\}\right)\rightarrow\min\right), \qquad (4)$$

where × is the Cartesian product of the set of input data *In* of organizational and technological content, *MA* are the sets of methods of IR depreciation, which are taken into account in calculations, that is *MA*=(*SM*, *MADRV*, *CM*) and the set of preliminarily generated RMAT ${}_{RMA}T^{d_g}=\left({}_{RMA}T^{d_g}_{i_T}\middle|i_T=\overline{1,n_T}\right)$ of total amount n_T; → is the symbol of suractive reflection of input data, united by Cartesian product ×, on the set of selection criteria [16], which is implemented by the set of calculation φ from the expression (4); brackets {...} mean that only one of the criteria: either *F*1, or *F*2.1, or *F*2.2, taking into account their hierarchy, is selected by a user as optimization criterion when choosing the RMAT [14].

Thus, the final decision in the automated choice of the RMAT by the technical and economic criteria means the choice of such RMAT, for which there is a minimum value of the criterion, pre-selected by a user from the STEC. The calculation of the selection criterion is performed on the sets of *DM* depreciation methods, pre-synthesized by the RMAT ${}_{RMA}T^{d_g}_{i_T}$, organizational and technological input data In and taking into consideration the cost of the IR depending on its operation period.

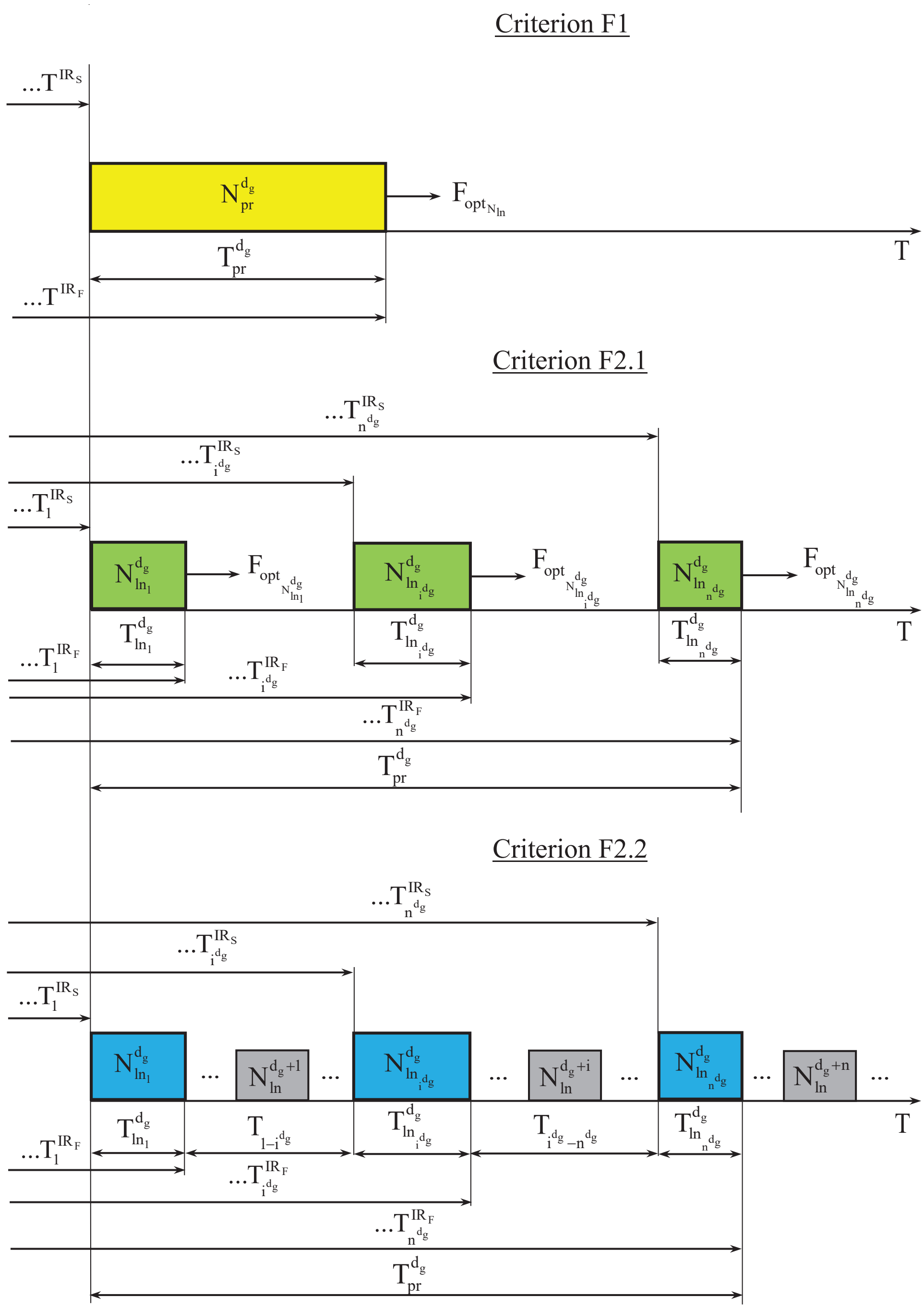

Fig. 1. Graphical representation of STEC components, which determine the specifics of technical and economic criteria for choosing RMAT

In general, the problem of choosing RMAT is the one-criterial optimization problem by its content. However, it has not been solved before in the statement that is explored here.

Thus, the solution of the problem regarding the development of the method for the automated choice of RMAT for technical and economic criteria was reproduced.

5. Analysis of the methods for depreciation expense of the cost of industrial robots

One of the key factors in calculating the STEC components is the methods of depreciation expenses of fixed assets, which include the IR. The following is a brief analysis of the most common methods of depreciation expenses of the cost of fixed assets, including the IR [15], the life period of which is not less than 5 years according to the recommendations given in [17]. In subsequent calculations, we will accept the IR operation period equal to 5 years. The methods of depreciation expenses of IR, selected by the results of analysis, actually form their *DM* set, which is also used in subsequent calculations. Their substantial content features are graphically illustrated in Fig. 2–5, where the abscises axis mean the years of IR depreciation, and the ordinate axis indicates a percentage, %, of depreciation cost of the IR over years. The constructed diagrams are subsequently used to discuss the obtained results. The analysis results are as follows:

1. In the straight-line method (*SM*), the annual amount of depreciation (*D*) is calculated by expression (5) as dividing the difference of the original cost (*OC*) of the depreciated IR and its residual value (*RV*) for the term of its useful life (*TUL*) in years:

$$D = \frac{OC - RV}{TUL}. \qquad (5)$$

Here and in the future, to simplify the calculations, we accept the *RV*=0 as such, which is not mandatory, that is, the company expects (or does no expect) to obtain from the implementation (liquidation) of the IR after the end of term of their useful years (operation) [18].

In fact, in the *SM*, the cost of the object of fixed assets, that is, of the depreciated IR, is evenly debited (distributed) during its useful years, by the constructed diagram in Fig. 2. Here, for each useful year, the residual value of the IR decreases by 20 % of its original cost. That is why the balance value of the IR after 5 useful years is 0 conditional units.

This method is adopted as the element of the *DM* set that is a*ccepted* for the use in subsequent research as the one, the parameters of which can be calculated and used to solve the tasks set here.

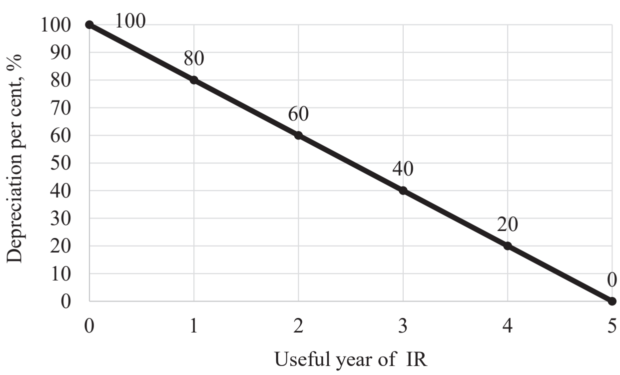

Fig. 2. Graphic illustration of the straight-line depreciation method

2. The annual amount of depreciation by the method of accelerated decrease in residual value (*MADRV*) is determined as the product of the residual value (*RV*) of the IR at the beginning of the reporting year or the original cost OC on the date of the beginning the depreciation calculation (6) and the doubled annual depreciation norm (N_d). The latter is calculated based on useful years of the object (*n*) (7). This method belongs to the group of accelerated depreciation methods. All the principal features of this group are similar and imply that a significant proportion of depreciation expenses is accumulated during the first useful year years.

This method is used if it is planned that the efficiency of the fixed assets object will be much higher at the beginning of operation than at the end of operation, and if the service costs in the process of operation significantly increase.

Corresponding analytic expressions for the *MADRV* take the form:

$$D = RV \cdot N_d \cdot 2; \qquad (6)$$

$$N_d = \frac{100\,\%}{n}. \qquad (7)$$

This method *is accepted* for research. Its graphical illustration is shown in Fig. 3. The specific feature of using this method is that within 4 useful years, the annual value of the IR decreases evenly by 40 % with respect to the value of the previous year. And within the last, 5th year, the cost of IR is completely «nullified» at the end of the year, that is, decreases by 100 % in respect to the residual value of the IR at the end of the 4th year, taking into consideration the previously accepted *RV*=0.

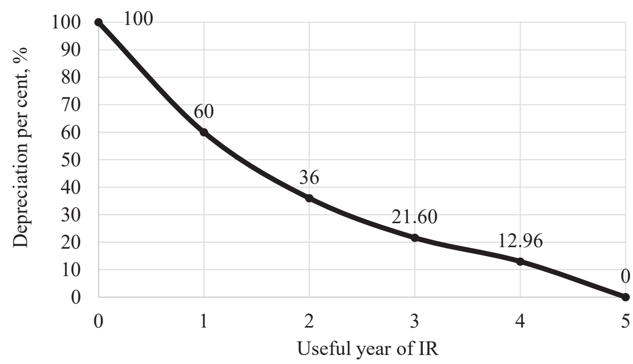

Fig. 3. Graphic illustration of the method of accelerated decrease of residual cost of MADRV

3. The use of the cumulative method (*CM*), the graphic illustration of which is shown in Fig. 4, implies the calculation of the annual amount of depreciation *D* as the product of depreciated value, that is (*OC*–*RV*) (earlier accepted *RV*=0), and the cumulative coefficient *CC*.

The latter is calculated by dividing the number of years, remaining until the end of useful years (*NYtillEUY*) of the IR, by sum of the number of useful life years (*NULY*):

$$D = RV \cdot N_d \cdot 2; \qquad (8)$$

$$CC = \frac{NYtillEUY}{NULY}. \qquad (9)$$

Fig. 4 shows that the characteristic feature of this method is an uneven decrease in the cost of the IR for each year, calculated according to expressions (8) and (9), with respect to the initial cost of the IR.

This method *is accepted* for research as the one, the parameters of which can be calculated by the data of the problems that are solved here.

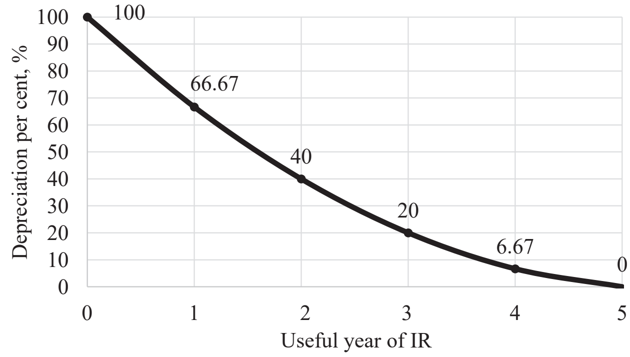

Fig. 4. Graphic illustration of cumulative method CM

4. Using the method of a decrease in residual cost (*MDRV*) (Fig. 5), the annual amount of depreciation *D* is calculated as

the product of residual value RV of the IR at the beginning of the reporting year or the initial cost of PC on the date of the beginning to calculate depreciation and the annual depreciation norm H_a from expressions (10), (11).

The latter (that is, H_a, %) is calculated as the difference between the unity and the result of the root of the n-th degree of the number of useful years of the IR from the result from division of residual value (RV) of the IR on its original cost OC:

$$D = OC(RV)\cdot N_d; \quad (10)$$

$$N_d = \left(1 - \sqrt[n]{\frac{RV}{OC}}\right)\cdot 100\,\%. \quad (11)$$

This method *is rejected* for research at the presence in the calculations of the LV, without which calculation from expressions (10), (11) is impossible. This method is illustrated the Fig. 5 on condition that the RV is equal to 1 % of the OC and N_a of depreciation is determined as 60.19 %.

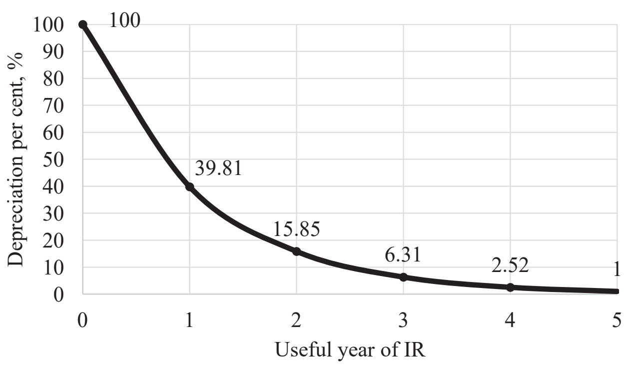

Fig. 5. Graphic illustration of the method for decreasing residual value MDRC

5. When using the production method (PM), the sum of depreciation is determined as product of number of unit produced (NUP) and the production depreciation rate (PDR). The latter is calculated by division of the depreciated value that is (OC–RV), by the total estimated production volume ($TEPV$), which a company expects to produce using the object of fixed assets, in this case the IR:

$$D = NUP \cdot PDR; \quad (12)$$

$$PDR = \frac{OC - RV}{TEPV}. \quad (13)$$

This method *was rejected* for research due to the fundamental impossibility to predict the number of products (parts or goods) that is planned to be produced during the period of useful life of the IR. That is why it is impossible to construct the graphic illustration of the method with the use of dependences (12), (13) under these conditions. This depreciation method is used mainly for the depreciation of vehicles, where it is possible, for example, to «tie up» clearly to the speedometer and to easily calculate the planned operation of the vehicle.

According to the results of the conducted analysis of the methods of depreciation expenses of the IR cost, the DM set included the following methods MA=(SM, $MADRV$, CM), which is mentioned above in the comments to expression (4).

An extended set of factors that systematically influence and therefore determine the results of the RMAT selection included DM, STEC, the set of the analyzed RMAT (regarding their choice) that is evident by the content of the solved problems and input data of organizational-technological content – set In in expression (4).

6. Algorithm for the automated selection of robotic mechanic-assembly technologies

Based on substantive essence, graphical representation of the specific features of the STEC manifestation, the content of analyzed and accepted to calculations methods of the IR cost depreciation and with consideration [19], the generalized block-diagram of the algorithm of automated selection of RMAT by technical and economic criteria $F1$, $F2.1$, $F2.2$ was designed (Fig. 6).

The structure and composition of the algorithm involves the execution of five methodically conditioned and sequentially executed stages $E1$–$E5$.

$E1$ is the stage of preparation of input data In. In this case, the content of unit 2 is preparation and collection of input date In for the analyzed set RMAT and their introduction in the computer program in unit 3 by a user, which is necessary for subsequent calculations. In units 4 and 5, a user chooses, respectively, one of the selection criteria (or their any number), which is the STEC element, that is, from set ($F1$, $F2.1$, $F2.2$), and depreciation method or methods, which are accepted for application, from their finite set DM.

$E2$ is the stage of calculation in unit 6 of the set of criteria $F1$ for the accepted depreciation methods during determining residual value of the IR from expression (1) and depending on the selected depreciation methods, which determine residual value of the IR, from expressions (5) to (9). If only criterion $F1$, checked in unit 7, is chosen as selection criterion in unit 4, one proceeds to the performance of unit 14 – displaying the results of the calculated magnitudes of criterion (criteria) $F1$ on the screen and the obtained results are graphically illustrated in unit 15 in the form of column charts. The final decision on the selection of the RMAT by criterion $F1$ and depreciation methods that determine residual value of the IR and estimated values of criterion $F1$ is made in unit 16.

If other criteria, that is, $F2.1$ or $F2.2$, were selected by a user in unit 4, then taking into account the hierarchy of the specified criteria [14], stage $E3$ is realized. Its content is the calculation of the finite set of values of criteria $F2.1$ performed on the finite set of the RMAT and adopted methods for depreciation expenses from the DM set to determine the residual value of the IR. For this purpose, one preliminarily calculates number of useful life of the IR $T^{d_g}_{\ln_i dg}$ when manufacturing the products of each i^{d_g} launch batch of volume $N^{d_g}_{\ln_i dg}$ (unit 8) and the actual set of criteria $F2.1$from expressions (2) and (5)–(9) (unit 9). If in unit 4 a user chooses only criterion $F2.1$ that is checked in unit 10, the actions, described above in calculation of $F1$, are performed for criterion $F2.1$ in units 14–16.

In case a user chooses criterion $F2.2$ in unit 4, stage $E4$ is performed. Its work begins with determining in unit 11 of durations of readjusting the IR T_r^{IR} between certain launch batches of products considering their number for the period $T_{pr}^{d_g}$ of the IR useful life. In unit 12, the values of criteria $F2.2$ criteria are calculated on the sets synthesized by the PMAT and the DM depreciation methods of the IR value, selected in unit 5.

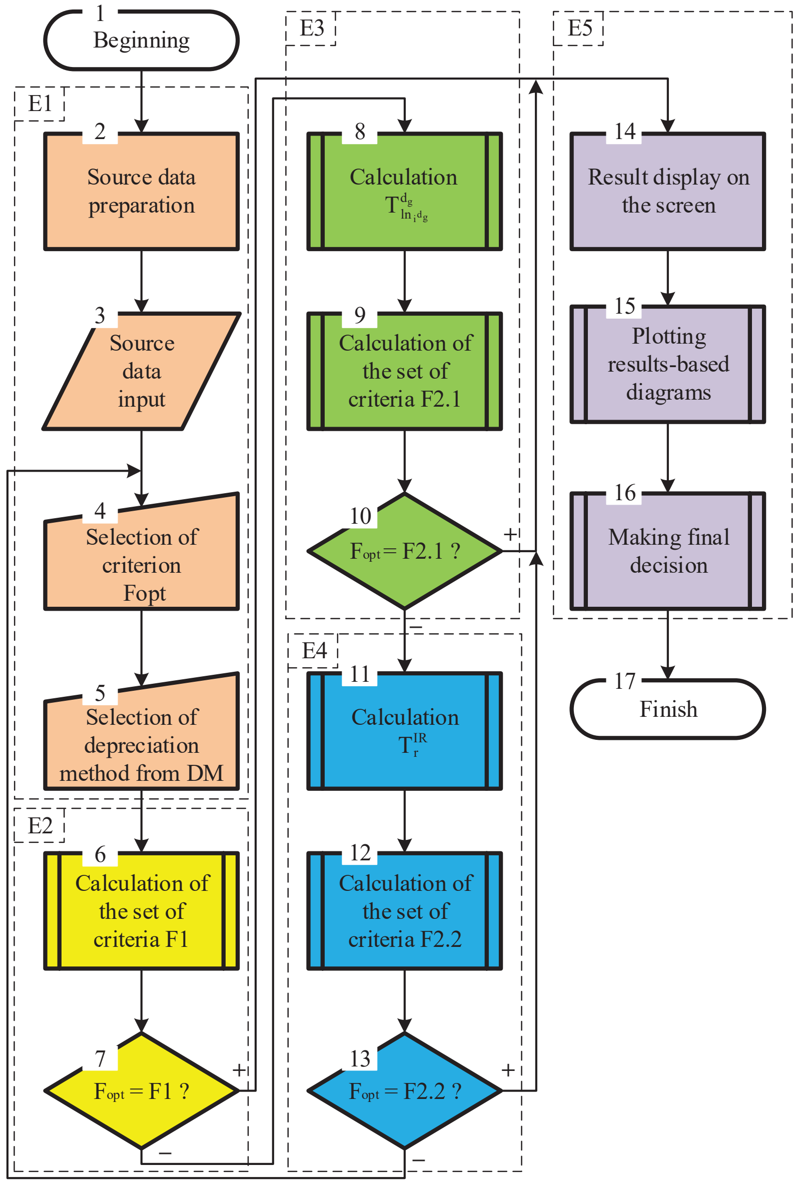

Fig. 6. Block-diagram of the algorithm of the process of RMAT selection by STEC criteria

which is the criteria of the RMAT selection by technical and economic criteria.

Initial data of the organizational and technological content, which are the elements of set *In* (1) for calculation of criteria *F*1, *F*2.1, *F*2.2 in the choice of RMAT, are the following (here the bottom-right indices indicate conditional numbers of the RMAT that identify ordinal numbers of the elements of the finite set of pre-synthesized RMAT, in this case two of them):

– balance value of the IR:
$C_1^{IR} = 370\ 000$ c. u.;
$C_2^{IR} = 420\ 000$ c. u.;

– salary rate of adjuster:
$M = 8\ 000$ c. u./month;

– number of working days of adjuster: $t_1 = 20$ days and $t_2 = 18$ days for criterion *F*1; $t_1 = 50$ days and $t_2 = 45$ days for criteria *F*2.1 and *F*2.2, respectively;

– volume of production batch:
$N_{pr}^{d_g} = 500$ products;

– number of days of IR operation during realization of the production batch $N_{pr}^{d_g}$: $T_1 = 60$ days; $T_2 = 57$ days;

– actual number of working hours of IR during manufacturing the produce batch: $A_{nh_1}^{IR} = 960$ hours; $A_{nh_2}^{IR} = 930$ hours;

– cost of 1 kW-h of electric power: $C^E = 2$ c. u./kWh.;

– capacity of IR: $P_1^{IR} = P_2^{IR} = 4\,kW$;

– coefficient of using IR by capacity: $K_{p_1}^{IR} = 0.650$; $K_{p_2}^{IR} = 0.875$;

– volume of launch batches (only for criteria F2.1, F2.2): $N_{\ln_1}^{d_g} = 75$ products (10 and 9 days, respectively); $N_{\ln_2}^{d_g} = 275$ products (30 days for two examples); $N_{\ln_3}^{d_g} = 150$ products (20 and 18 days, respectively).

The criteria of RMAT selection, respectively, *F*1, *F*2.1 and *F*2.2 as components of the STEC were calculated from expressions (1) to (3) taking into consideration each of 5 years of IR useful life and by each of the accepted methods for depreciation expenses, specifically: SM, MADRV and CM.

The resulting deliverables are displayed on the screen, analyzed in content (unit 14), graphically illustrated (unit 15) and evaluated with making final decision in unit 16.

Thus, the actions performed in units 14–16, are the content of execution of stage *E*5.

By the structure and content of computational actions of each unit, the described algorithm of the RMAT choice for the technical and economic criteria does not contradict the possibility of its automated implementation, which was performed in the software environment MS Excel.

7. Conditions and results of selection of robotic mechanic-assembly technologies according to the technical and economic criteria

To check the operability of the developed algorithm, Fig. 6 illustrated the choice of the RMAT by the STEC components calculated in the software environment MS Excel,

Generalized graphic illustrations of calculated values of each of criteria *F*1, *F*2.1, *F*2.2 by different depreciation methods are shown in Fig. 7–9 by column charts. Here, the selection criteria with corresponding informative indices are marked on the abscises axis: left bottom index indicates the year of IR useful life, and the right bottom index indicates the sequence number of the analyzed RMAT, and the calculated magnitudes of criteria, that is costs of the product unit in conditional monetary units, in this case in UAH, are marked on ordinate axis. Thus, the identifier of each criterion, the value of which is illustrated by the separate column of the chart, is presented by a description of the following structure: ${}_{i_y}F1_{i_T}$, ${}_{i_y}F2.1_{i_T}$ and ${}_{i_y}F2.2_{i_T}$, where $(i_y = (\overline{1, n_y}))$ year of the IR useful life, $n_y = 5$ years $(i_T = (\overline{1, n_T}))$ – designations of the i_T RMAT of their total number n_T.

This visualization makes it possible to assess visually the change of the total «robotic» cost of manufacturing the unit of product for the planned period, which can be considered as an illustrative basis that contributes to making final decisions in the automated selection of the RMAT.

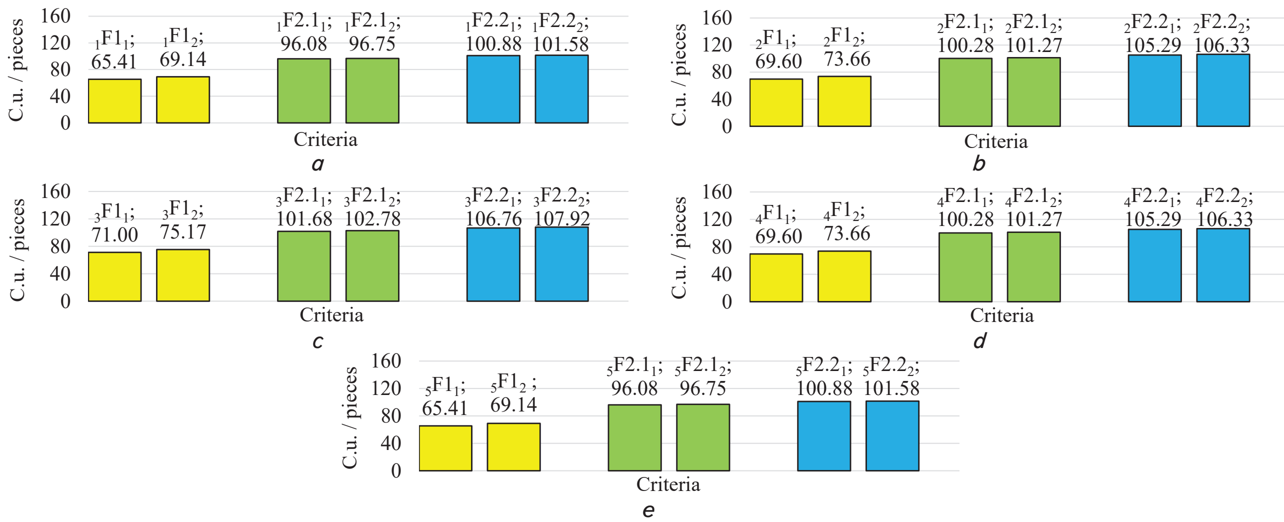

Fig. 7. Generalized graphic illustration of values of criteria *F*1, *F*2.1, *F*2.2 calculated by the Straight-line method (SM) for depreciation expenses of the IR for different years of its operation: *a* – for the 1st year; *b* – for the 2nd year; *c* – for the 3rd year; *d* – for the 4th year; *e* – for the 5th year

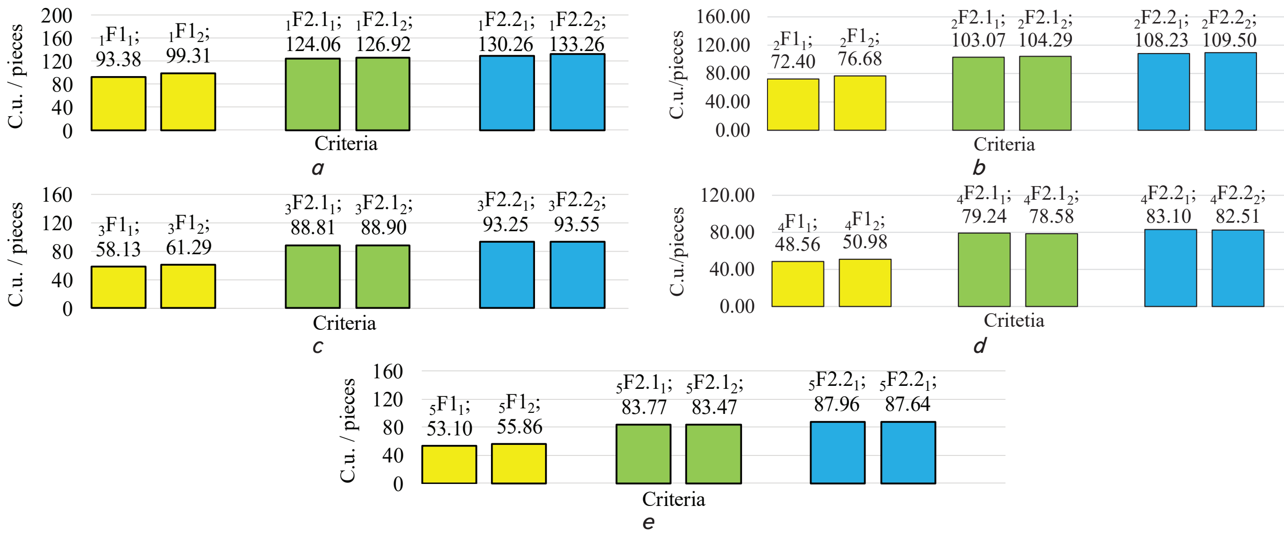

Fig. 8. Generalized graphic illustration of values of criteria *F*1, *F*2.1, *F*2.2 calculated by the method of accelerated decrease of residual value (MADRV) for depreciation expense of the IR for different years of operation: *a* – for the 1st year; *b* – for the 2nd year; *c* – for the 3rd year; *d* – for the 4th year; *e* – for the 5th year

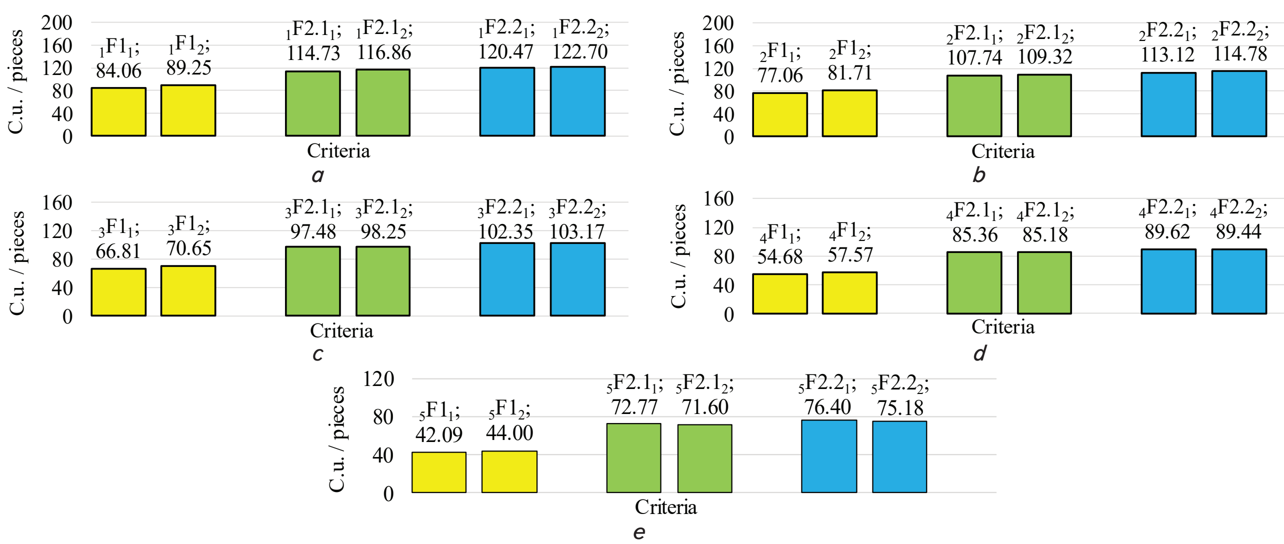

Fig. 9. Generalized graphic illustration of calculated values of criteria *F*1, *F*2.1, *F*2.2 by the cumulative method (CM) for depreciation expenses of the IR for different years of its operation: *a* – for the 1st year; *b* – for the 2nd year; *c* – for the 3rd year; *d* – for the 4th year; *e* – for the 5th year

Thus, the method for automated selection of the RMAT by the technical and economic criteria, its algorithmic and programmatic realization, as well as graphical representation of results were developed.

8. Discussion of results of using the developed method for selecting robotic mechanic-assembly technologies

Analysis of Fig. 7–9 indicates that, the RMAT, the selection criteria for which are designated by bottom lower index 1 is in fact optimal in most cases by all criteria, except conditioned separately, and for each of the 5 years of the IR. That is, the first of the analyzed RMAT is optimal by criterion $F1_1$.

It is characteristic that actually the magnitudes of criteria $F1$ for different RMAT are the lowest in comparison with the values of the other criteria within the analysis of every depreciation, irrespective of the number of useful years of IR. In this case, the smallest value of criterion $F1$ (Fig. 9) was obtained for the CM of the IR depreciation for the 5th year of the IR useful life: ${}_5F1_1$=42.09 c. u./pieces, which is 0.45 of the maximal value ${}_1F1_1$=93.38 c. u./pieces for MADRV (Fig. 8) for the first year of the IR operation. The ration of the minimal and maximum values of criterion, $F2.2$ is 0.76, which was obtained taking into consideration its minimal value ${}_1F2.2_2$=101.58 c. u./pieces for the SM (Fig. 7) and maximum value ${}_1F2.2_2$=133.26 c. u./pieces for MADRV (Fig. 8).

Thus, for the conditions of the examined test sample of the RMAT, criteria $F1$ have the lowest values and criteria $F2.2$ have the highest values in most cases. This is explained by substantive features of calculating these criteria and specific initial data of their calculation when choosing the RMAT.

According to the data of Fig. 7–9, the magnitudes of all examined criteria decrease in each useful year of the IR. This is explained by the progressive annual decrease in the residual value of the IR (Fig. 2–4), the share of which is decisive in calculation of each criterion. At this, there is a different intensity of values for annual change of each criterion. This is also explained by substantive features of the analyzed depreciation methods and the condition of not taking into account the IR residual value for the full useful time period.

When using MADRV, there are somewhat lower values of criteria ${}_4F2.1_1$ and ${}_5F2.1_1$, which characterize $(i_T=1)$ RMAT in comparison with the corresponding values of criteria ${}_4F2.1_2$ and ${}_5F2.1_2$, which characterize the $(i_T=2)$ RMAT (Fig. 8). The same was true for the CM: the corresponding pairs of values of criteria ${}_4F2.2_1$ and ${}_5F2.2_1$ are lower compared to ${}_4F2.2_2$ and ${}_5F2.2_2$ (Fig. 9). This is explained by substantial features of implementation of depreciation expenses of the IR values for the 4th and the 5th useful years for the MADRV and CM, respectively.

The calculated values of the criteria of the RMAT selection are shown in Table 1 for the convenience of further analysis. The methods for depreciation expenses of the IR values (SM, MADRV and CM) are the columns, which also include the ratings (places) for each of the calculated criteria ${}_{i_y}F1_{i_T}$, ${}_{i_y}F2.1_{i_T}$ and ${}_{i_y}F2.2_{i_T}$, which in turn are the rows in Table 1.

The data shown in Fig. 7–9 and in Table 1 do not indicate the need to give categorical recommendations on unambiguous choice of one or another examined criteria or prioritize them on their set.

Analysis of data from Table 1 reveals the following:

1. Analysis of the total cost of manufacturing one item of product for 5 years by different methods for depreciation expenses DM and criteria $F1$, $F2.1$, $F2.2$ indicates the priority of these methods in the following sequence: $CM \rightarrow MADRV \rightarrow SM$. This statement is caused by the data of the specific example and requires a separate more detailed analysis and interpretation and may be the subject of further research.

2. Analysis of the obtained ratings of various methods for annual depreciation expenses of the IR value by criteria $F1$, $F2.1$, $F2.2$ indicates the following:

– the best (has the lowest rating) is the method of accelerated decrease of residual value (MADRV) with the total of points in the rating equal to 9;

– the cumulative method (CM) ranks second with the total of points in the rating equal to 10;

– the straight-line method (SM) under these conditions occupies the last place with total of point in the rating equal to 11.

That is why the priorities of ratings of these methods DM from the best to the worst are represented by the following sequence of elements of the DM set: $MADRV \rightarrow CM \rightarrow SM$.

It is advisable to emphasize that the calculation results shown in Fig. 7–9 and in Table 1 are determined exclusively by input data of specific test examples that were explored.

When it comes to the use of the DM elements, the situation is rather ambiguous, because none of the methods takes into consideration moral and physical depreciation of the IR simultaneously with the volume of executed work and the transfer of these costs to the production costs. However, these costs are partially transferred to the cost of production facilities, which is taken into account in STEC by percentage for the annual repairs of the IR. Enterprises have their arguments in favor of those methods, which are chosen during accounting, but they must not forget about the economic expediency of the made choice, not only about the simplification of accounting.

Generalization on the conducted research can be outlined as follows:

– selection of the method of depreciation expense of the IR value is caused by the normative base of a particular country, the priority of a company-manufacturer of products and specific organization and technology of manufacturing products on it;

– on condition of a high original cost of the IR, it is advisable to use the Straight-line method, because other methods from the proposed list refer to accelerated depreciation methods, which can significantly affect the magnitude of the accepted selection criterion;

– it is worthwhile for enterprises to invent the mechanisms of the combined approach regarding the determined methods for annual depreciation expense of the IR value, which determined the «robotic» component of the cost of manufacturing the unit of produce as an inseparable component of the total cost of products. The mentioned above will require more detailed research into feasibility, possibility of forming and using other technical and economic criteria for choosing the RMAT;

– analysis of the process of choosing RMAT in the above statement, that is, according to the accepted selection criteria $F1$, $F2.1$, $F2.2$ indicates that today there is no optimal method with DM. Each of the examined methods, which has a series of advantages and disadvantages, can be used to select the RMAT and be selected only by a user considering the organizational and technological features of a particular enterprise.

Table 1

Calculated values of «robotic» component of the cost of manufacturing one item of produce by each of criteria $F1$, $F2.1$, $F2.2$ for each of 5 years of useful application of the IR (according to the test examples and Fig. 7–9)

Criterion \ Method	Straight-line method (SM)		Method for accelerated decrease of residual value (MADRV)		Cumulative method (CM)	
	Cost of a piece of produce	Place in the rating	Cost of a piece of produce	Place in the rating	Cost of a piece of produce	Place in the rating
For criteria $F1_1$ and $F1_2$						
${}_1F1_1$	65.41	1	93.38	3	84.06	2
${}_1F1_2$	69.14	1	99.31	3	89.25	2
${}_2F1_1$	69.60	1	72.40	2	77.06	3
${}_2F1_2$	73.66	1	76.68	2	81.71	3
${}_3F1_1$	71.00	3	58.13	1	66.81	2
${}_3F1_2$	75.17	3	61.29	1	70.65	2
${}_4F1_1$	69.60	3	48.56	1	54.68	2
${}_4F1_2$	73.66	3	50.98	1	57.57	2
${}_5F1_1$	65.41	3	53.10	2	42.09	1
${}_5F1_2$	69.14	3	55.86	2	44.00	1
$Sum_1/place_1$	341.02/3	11/3	325.57/2	9/1	324.7/1	10/2
$Sum_2/place_2$	360.77/3	11/3	344.12/2	9/1	343.18/1	10/2
For criteria $F2.1_1$ and $F2.1_2$						
${}_1F2.1_1$	96.08	1	124.06	3	114.73	2
${}_1F2.1_2$	96.75	1	126.92	3	116.86	2
${}_2F2.1_1$	100.28	1	103.07	2	107.74	3
${}_2F2.1_2$	101.27	1	104.29	2	109.32	3
${}_3F2.1_1$	101.68	3	88.81	1	97.48	2
${}_3F2.1_2$	102.78	3	88.90	1	98.25	2
${}_4F2.1_1$	100.28	3	79.24	1	85.36	2
${}_4F2.1_2$	101.27	3	78.58	1	85.18	2
${}_5F2.1_1$	96.08	3	83.77	2	72.77	1
${}_5F2.1_2$	96.75	3	83.47	2	71.60	1
$Sum_1/place_1$	494.4/3	11/3	478.95/2 482.16	9/1	478.08/1 481.21	10/2
$Sum_2/place_2$	498.82/3	11/3	2	9/1	1	10/2
For criteria $F2.2_1$ and $F2.2_2$						
${}_1F2.2_1$	100.88	1	130.26	3	120.47	2
${}_1F2.2_2$	101.58	1	133.26	3	122.70	2
${}_2F2.2_1$	105.29	1	108.23	2	113.12	3
${}_2F2.2_2$	106.33	1	109.50	2	114.78	3
${}_3F2.2_1$	106.76	3	93.25	1	102.35	2
${}_3F2.2_2$	107.92	3	93.55	1	103.17	2
${}_4F2.2_1$	105.29	3	83.10	1	89.62	2
${}_4F2.2_2$	106.33	3	82.51	1	89.44	2
${}_5F2.2_1$	100.88	3	87.96	2	76.40	1
${}_5F2.2_2$	101.58	3	87.64	2	75.18	1
$Sum_1/place_1$	519.1/3	11/3	502.8/2	9/1	501.96/1	10/2
$Sum_2/place_2$	523.74/3	11/3	506.46/2	9/1	505.27/1	10/2

In general, the obvious advantages of the designed method for automated choice of the RMAT by technical and economic criteria are its systemic consistency and the automation of the criteria calculation. Systemic consistency is determined using a set of factors affecting the magnitude of the selection criteria. The latter, in turn, are also the elements of the system – STEC. Automation of calculations carried out on the set of the considered factors increases the performance of calculations and determines practical value of the study. The combined influence of systemic consistency and automation in an obvious way increases the efficiency of operation/design of the RMAP and their technological preparation.

The results are useful for specialists-practitioners and organizations involved in various areas of industrial robotics and can be used in scientific research in the area of robotics.

At the same time, the developed method has a number of limitations, such as: orientation in this version of its implementation to the Ukrainian normative base regarding the methods of depreciation expense of the fixed assets, which include the IR; the need for clear determining initial data of organizational and technological content, which are necessary for implementation of the developed method.

However, these limitations do not fundamentally contradict to practical value of this method (it is actually effective in terms of problem statement and its automated implementation) and its scientific component (systematic consistency of decision making on extended set of factors).

The authors believe that the promising directions of this research is the development of the original software of the automated choice of RMAT, the functioning of which involves taking into consideration other components of the factors determining the criteria of the RMAT selection. In this case, there is obvious expediency of integrating software for implementation of the developed method into the general automated system of technological training of the RMAP (provided its full version is available). This will make it possible to get all the components of the source data of set I in the automatic mode, and thus to increase the level of automation of the process of the RMAT selection and to execute it automatically.

9. Conclusions

1. Based on the analysis and generalizations of the groundwork regarding the problem of choosing the RMAT by certain criteria, we developed the new method for automated choice of the RMAT by technical and economic criteria, which systematically consider the set of factors influencing and determining the selection result. The distinctive feature of the new method is the expanded set of factors, on which the choice is made. The problem of the selection of the RMAT in this statement and in this way has never been solved before. The result of selection is the smallest calculated value of the criterion of the STEC, previously chosen by a user, which is performed on the set of the analyzed RMAT, DM and the previous period of the IR operation. The use of the proposed method increases the efficiency of technological training of the RMAP due to the automation of calculations of selection criteria and extension of the set of factors determining the result of the choice.

2. The used set of factors systematically determines the magnitude only of «robotic» component of the technological cost of manufacturing products as criteria for choosing the RMAT, which (cost) is regarded as a variable component of the total cost of manufacturing the product. The factors included: the STEC, the formed set of the methods of the IR value depreciation and other components of organizational and technological content. Their use generally extends the possibility of reasonable systemic technological decisions in the selection of the RMAT in such a statement.

3. The substantive essence of the developed method and the determined set of factors are the basis of the developed algorithm of the RMAT choice, which provides its automated realization. This made it possible to develop on its basis the software for the automated calculation of the STEC components. The specific features of its functioning are based on the features of statement of solving the problems of the RMAT, which primarily implies the use of an extended set of factors of the automated calculation of the STEC components. Their calculated values by the user's choice are the criteria for choosing the RMAT.

4. The developed algorithm of automated calculation of the STEC components was implemented in software in the MS Excel environment. The results of conducted testing of the developed software for specific conditions of the testing problem proved its working capacity and showed that according to the indicator of total cost of manufacturing one item of products during 5 years of the IR useful life by the sum of the criteria designed for STEC (324.7 c. u./pieces), it is advisable to use the CM of depreciation expenses of residual value of the IR. In this case criterion $F1$ in the first two years of useful life in the SM has the lowest values (for example, for the first year of useful life for the first RMAT ${}_1F1_1=65.41$ c. u./pieces), criterion $F2.2$ for the MADRV (for example, for the first year of useful life for the first RMAT ${}_1F2.2_1=120.46$ c. u./pieces) has the highest values in most cases. At the same time, for the last fifth year of the IR useful life, the values of criterion ${}_5F1_1=42.09$ c. u./pieces for the CM are the lowest and ${}_5F2.4_1=76.40$ c. u./pieces are the highest under the same conditions. The MADRV is the best by the total indicator that is equal to 9.

5. Analysis and discussion of the results of the used method for the RMAT choice by the technical and economic criteria made it possible to form generalizations about the usage of factors and their components. In this case, the specific values of each selection criteria are determined only by the specific calculation parameters regardless of the number of years of the IR useful life, the used depreciation methods (DM) and the data of organizational and technological content for each analyzed RMAT.

The conducted analysis of the results of test examples and the provided generalizations indicate the feasibility of development of the combined approach regarding the use of certain methods for depreciation expenses during the IR useful life. For example, during the 1–2 years of useful life, it is effective to use the SM, and during the last fifth year – the CM. At the same time, the MADRV has the advantage during 3–4 years of the IR useful life.

Taking into consideration these generalizations, a user can make decisions about both the choice of selection criteria and make final decisions on the results of the RMAT selection.

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