UDC 681.5.004
DOI: 10.15587/1729-4061.2024.306516

DESIGN OF AN INFORMATION-COMPUTER SYSTEM FOR THE AUTOMATED MODELING OF SYSTEMS FOR AUTOMATIC ORIENTATION OF PRODUCTION OBJECTS IN THE MACHINE AND INSTRUMENT INDUSTRIES

An information-computer system has been developed for the automated modeling of systems for automatic orientation of production objects, which is one of the most important and complex creative flexible production systems of machine and instrument engineering. The proposed information-computer system for automated modeling of systems of automatic orientation of production objects is an effective tool for solving an important task of a scientific and applied nature. Its use makes it possible to increase the speed and efficiency of information processing and to make correct and well-founded decisions when determining the composition and method of organization of systems of automatic orientation of production objects. The structure of this information-computer system is a specific set of software and hardware and information and telecommunication tools and interactive functional modules. This structure reproduces a certain paradigm that conditions the integrity and integration of the information-computer system for automated modeling of systems for automatic orientation of production objects in flexible production systems. In addition, uniformity, extensibility, the possibility of modernization and changeability of software components, protection of information from unauthorized access and preservation of commercial secrets are ensured according to international criteria for evaluating the protection of the computer system. Neuro-fuzzy network information processing and computer vision algorithms have been implemented for automatic identification of production objects and orientation devices, which are components of automatic orientation systems of production objects. The developed information-computer system processes information in real time with high accuracy and speed

Keywords: information-computer system, automatic orientation, technological preparation of production, decision support

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Received date 09.04.2024
Accepted date 17.06.2024
Published date 28.06.2024

How to Cite: *Cherepanska, I., Sazonov, A., Melnychuk, P., Melnychuk, D., Kalchuk, S., Pryadko, V., Yanovsky, V. (2024). Design of an information-computer system for the automated modeling of systems for automatic orientation of production objects in the machine and instrument industries. Eastern-European Journal of Enterprise Technologies, 3 (2 (129)), 6–19. https://doi.org/10.15587/1729-4061.2024.306516*

1. Introduction

Activation and globalization of production processes, including in machine and instrument building, increased competition in industrial markets, constant growth in requirements for product quality and safety lead to constant flexible changes in the structure of production. This is achieved through their organization according to the principles of flexible computer-integrated systems (FCIS), construction of new or modernization of existing flexible production systems (FPS), as components of FCIS, including systems for automatic orientation of production objects (SAOPO). The latter is one of the most important and complex creative FPS. It is obvious that in order to increase the speed, reasonableness, correctness, and efficiency of decisions made at the stage of technological preparation of production, there is a need to conduct research and design convenient and functional information-computer systems (ICS) for automated modeling of SAOPO. That is, automating the processes of selecting technological equipment, in particular automatic orientation devices (OD) and creating SAOPO on their basis.

In general, SAOPO is a specific production environment of a functionally interacting set of OD with a set of production objects (PO) for their automatic orientation and a set of other technological equipment (TE) functioning in FPS. SAOPO modeling involves the determination of optimal OD models from the point of view of the balance between the likely effects and costs of their use for automatic orientation of PO, and the functional compatibility/coupling of the OD with other maintenance in FPS. It is obvious that this is a rather complex, multi-stage, time-consuming, financially and intellectually expensive process. After all, SAOPO is designed to solve one of the most important and difficult tasks of organizing robotic production in the mechanical engineering and instrument engineering industry – this is the automatic orientation of PO.

Therefore, for the effective work of specialists at machine- and instrument-building enterprises, at the stage of technological preparation of production, in particular, at the stage of choosing technological equipment, including OD and creating SAOPO based on them, an appropriate toolkit is necessary. An example can be ICS, which is built according to the principles of modularity, aggregation, systematicity, and effectiveness, on the basis of modern software and hardware and information and telecommunication tools. This will ensure both the development and use of information models for solving practical engineering tasks, as well as the protection of information from unauthorized access and the preservation of commercial secrets.

The purpose of the operation of ICS for the automated modeling of SAOPO is to provide specialists with the necessary data to quickly make a well-founded, correct and effective decision regarding the composition and method of organization of SAOPO. This decision is based on the use of reliable information about the structural features and physical and mechanical properties of PO, technical and economic characteristics and functional capabilities of the set of ODs. At the same time, the functional compatibility of SO and PO is taken into account in order to ensure the automatic orientation of the latter and their functional coordination/coupling with other maintenance in FPS.

Correctly making effective decisions at the stage of technological preparation of production when choosing technological equipment, including OD, is extremely important. After all, this ensures the technically efficient and economically profitable functioning of not only SAOPO as it is but also takes into account its interaction with other components of FPS and FCIS as a whole.

2. Literature review and problem statement

Review of studies [1–4] shows that the tasks that are solved at the stage of technological preparation of production, including the task of modeling SAOPO, are one of the most difficult and important tasks in the design of FPS. They affect the quality and competitiveness of products. After all, the optimal orientation of PO is of crucial importance for improving the quality of production [2]. But the issues related to the automated modeling of SAOPO in flexible production remained unresolved. The results of studies given in the literature [3, 5] indicate a significant influence of the orientation of PO on the accuracy of dimensions, strength, overall cost, and quality. Many approaches are discussed in the literature, but no attention is paid to the problem of automating the making of correct, justified, and effective decisions when choosing components of SAOPO. Its successful solution requires the use of effective, universal, and high-performance means, technologies, methods, and mathematical apparatuses to support the rapid adoption of well-founded, correct, and effective decisions [1], in particular, when determining the composition and method of organization of SAOPO. That is why this question arouses considerable interest in the world scientific community.

In [4], the research results of three methods of decision-making in the selection of basic technological equipment with multiple attributes are reported, namely orthographic and matrix approaches, analytical hierarchical process (AHP) and analytical network process (ANP). It is shown that the methods provide indices of choice of various analyzed alternatives. But the issues related to taking into account all stages of technological preparation of production remained unresolved. A number of criteria have not been defined that allow one to assess future effects and costs from the use of this or that technological equipment, in particular OD. Also, the problem of creating appropriate software and computer tools for increasing the speed and efficiency of information processing and making correct and well-founded decisions when determining the composition and method of organization of SAOPO has not been solved.

In [6], the results of the development of a functional model of the process of technological preparation of production are reported. It is shown that it can become the basis of informational support for projects to create new equipment. But the questions related to the detailing of the stages of technological preparation of production and the tasks to be solved at the same time, in particular, the task of modeling SAOPO, remained unresolved. Also, the problem of creating appropriate software and computer tools for increasing the speed and efficiency of information processing and making correct and well-founded decisions when determining the composition and method of organization of SAOPO has not been solved.

In work [7], the results of the study of only five technical and economic indicators for the design and selection of equipment at the regional level are given. But the criteria that allow us to assess future effects and costs from the use of this or that technological equipment, in particular OD, have not been taken into account. Also, the problem of creating appropriate software and computer tools for increasing the speed and efficiency of information processing and making correct and well-founded decisions when determining the composition and method of organization of SAOPO has not been solved.

Work [8] shows the concept of developing an integrated system for designing production technological processes in mechanical engineering. The algorithm of the automated analysis of the three-dimensional model of PO is presented. The general functional structure of ICS for the automated detection and formalization of significant parameters of PO is described. The choice of technology and the formation of the route for the production of PO, taking into account the data of the production process, are described. But the problem of creating appropriate software and computer tools for increasing the speed and efficiency of information processing and making correct and well-founded decisions when determining the composition and method of organization of SAOPO remained unsolved.

Work [9] considers the selection of means for organizing the robotic environment, in particular loading and unloading equipment, for manufacturing enterprises. A list of equipment selection criteria and a selection methodology based on a multi-criteria decision-making method based on an analytical hierarchical process are provided. However, the development data is focused on the modeling of the loading and unloading process and the selection of loading and unloading equipment, which is used for the partial arrangement of the robotic production environment, which is a simpler task compared to the task of modeling SAOPO and the selection of software. The problem of creating appropriate software and computer tools for increasing the speed and efficiency of information processing and making correct and well-founded decisions when determining the composition and method of organization of SAOPO has not been solved.

Paper [10] provides an approach to the selection of equipment for flexible assembly production in mechanical engineering and presents the structure of the procedure for determining a different sequence of tasks depending on alternative assembly modes. This procedure makes it possible to evaluate the respective performance of each alternative with requests for capabilities expressed in terms of volume and product range. However, the problem of creating appropriate software and computer tools for increasing the speed and efficiency of information processing and making correct and well-founded decisions when determining the composition and method of organization of SAOPO has not been solved.

Paper [11] shows the possibility of automating the formalized selection of technological operations by establishing relationships between all components of the technological process. It is shown that, depending on the specifics of the company's work, the selection of equipment is a complex process. The study demonstrates the nuances that interfere with production and affect the approach to the selection of equipment for one or more technological operations. However, the information in the paper is of a somewhat declarative nature and is presented fragmentarily. In this regard, the problem of creating appropriate software and computer tools for increasing the speed and efficiency of information processing and making correct and well-founded decisions when determining the composition and method of organization of SAOPO has not been solved.

Works [12, 13] provide a comprehensive approach based on conceptual matrix models and a software tool for automated decision-making in the development of product production processes at the design stage of FPS. However, this software product is aimed at small business enterprises and does not take into account the specificity of machine and instrument manufacturing industries. Therefore, the problem of creating appropriate software and computer tools for increasing the speed and efficiency of information processing and making correct and well-founded decisions when determining the composition and method of organization of SAOPO has not been solved.

In [14], a method for automatically determining the orientation of PO during laser welding of a powder layer is given. This method contains two stages. First, an existing approach based on face clustering is used to automatically create alternative orientations of PO deposited in a layer of laser powder. Secondly, the amount of support, volumetric error, surface roughness, time and cost of assembly are taken into account. The value of each alternative orientation of PO is estimated using certain evaluation models. The weight of these indicators is determined by pairwise comparison. A weighted sum model is used to calculate the total value of the factors of each alternative orientation. According to the calculated total values, the optimal orientation of PO is determined. The given material is definitely a valuable basic study, but it needs to be refined in terms of the selection of OD for the implementation of the optimal orientation of PO. Therefore, the problem of creating appropriate software and computer tools for increasing the speed and efficiency of information processing and making correct and well-founded decisions when determining the composition and method of organization of SAOPO has not been solved.

Work [15] reports the results of research into the approach to the automated selection of optimal robotic trajectories in FPS. It is shown that the result of the functioning of this approach is its optimal trajectory according to the chosen criterion. But the problem of creating appropriate software and computer tools for increasing the speed and efficiency of information processing and making correct and well-founded decisions when determining the composition and technique of SAOPO organization remained unsolved.

Thus, all this gives reason to assert that the important scientific and technical problem related to the development of original and modern tools for the automated modeling of the components of FPS, including SAOPO, has not been resolved. After all, such a system is being developed in order to increase the speed and efficiency of information processing and make correct and well-founded decisions when determining the composition and technique of SAOPO organization, at the stage of technological preparation of production. It should be able to enable automated adoption of correct and effective decisions at high speed in real time. That is why it is expedient to carry out a study on the development of an information-computer system for automated modeling of systems for automatic orientation of production objects in machine and instrument engineering.

3. The aim and objectives of the study

The purpose of our research is the development of an information-computer system for automated modeling of systems for automatic orientation of production objects (ICS for automated modeling of SAOPO). This will make it possible:

1) to increase the speed and efficiency of processing information about structural features and physical and mechanical properties of PO, technological characteristics, and functional capabilities of OD;

2) to make correct and well-founded decisions when determining the composition and technique of SAOPO organization at the stage of technological preparation of production.

To achieve the goal, it is necessary to solve the following tasks:

– to formalize the process of determining the composition and technique of SAOPO organization;

– to develop a structural diagram of ICS for automated modeling of SAOPO, to determine the structure of its functional modules, information flows, methods and means of automated data processing;

– to develop a structural diagram of the network integration of ICS for the automated modeling of SAOPO in FCIS in the machine- and instrument-making industries.

– to conduct experimental studies of the performance of ICS for automated modeling of SAOPO.

4. The study materials and methods

The object of research is the process of determining the composition and technique of SAOPO organization.

The subject of our study is the ICS for automated modeling of SAOPO.

The hypothesis of the study is based on the assumption that the implementation of the tasks of development of ICS for automated modeling of SAOPO could increase the speed and efficiency of information processing and making informed engineering decisions regarding the selection of equipment. It could also provide a social and economic effect, which would consist in reducing intellectual and time costs.

Research methods are based on the application of computer vision algorithms, artificial intelligence technologies, in particular, the original neuro-fuzzy network that we developed earlier, a detailed description of which is given in [16]. In addition, publicly available tools of database management systems (DBMS) are used. Research methods are also based on the application of some methods of system analysis, in particular, the method of normalization, correlation analysis, and the heuristic method.

The results, confirming the feasibility of our technological advancements, were obtained during experimental studies by simulation methods with the use of special software, including neurosimulators. A modern basic personal computer with an Intel(R) Core(TM) i3-7020U CPU @ 2.30 GHz and 4.00 GB of RAM was used. The methods of graphic representation and statistical processing were applied to treat the experimental data.

5. Results of investigating the information-computer system for automated modeling of systems for automatic orientation of production objects

5. 1. Formalizing the process of determining the composition and technique for organizing automatic orientation systems of production objects

The development of ICS for the automated modeling of SAOPO involves a preliminary analysis and formalization of the process of determining the composition and technique of SAOPO organization. It functions as a part of FPS and is the environment for the interaction of a number of ODs and POs. The latter are characterized by a variety of functional capabilities, structural features, and physical and mechanical properties. In general, the orientation of PO is one of the most complex auxiliary operations performed when organizing a robotic production environment. It consists in the automatic transfer of a set of POs from an initial non-oriented position (INP) to a predetermined final oriented position (FOP) [1]. FOP is determined by technological equipment that interacts with PO. For automatic orientation, various software is used, capable of technically realizing the necessary composition of orienting movements (COM), in particular, a set of circular movements and linear movements of PO in three-dimensional space during their automatic orientation [1]. At the same time, the results from many studies [1, 16, 17] show that it is not enough to determine only COM since the properties of PO material also have a significant impact on the process of automatic orientation. Therefore, in addition to the analysis of the structural features of PO, it is necessary to analyze their physical and mechanical properties and determine the types of force effects (TFE) that can be applied to ensure the necessary COM. In other words, the function of SAOPO consists in feeding FPS with material objects of production in the required quantity, at a given speed, and in a position convenient for their coupling with the technological equipment of this FPS.

It should be noted that modeling the composition and technique of SAOPO organization is a rather complex and not always obvious process. After all, there is no unequivocal functional correspondence between PO and OD, which make up the composition of SAOPO and determine the way of its organization. There is always a set of alternative solutions from which one must find the optimal one. Visualization of this process is carried out using the Euler-Venn model (Fig. 1), and its formalization is given by expressions (1) to (3).

The functional interaction of the set of ODs with the set of POs for their transfer from INP to FOP by performing the necessary COM makes it possible to form a set of alternatives $SOOV_n^f$, which is formalized by expression (1):

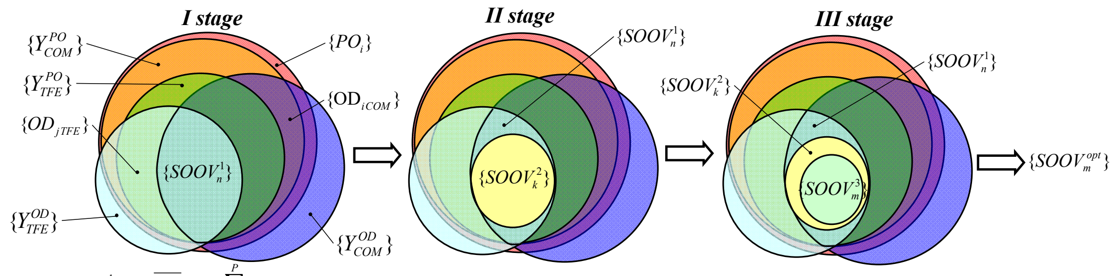
$$\left\{SOOV_n^f \mid n=\overline{1,N}\right\}=\left\{\left\{\mathrm{OD}_{\mathrm{COM}}\right\}\cap\left\{\mathrm{OD}_{\mathrm{TFE}}\right\}\right\}\cap\left\{\left\{\mathrm{PO}\right\}\right\}, \quad (1)$$

where $SOOV_n^f$ is a set of alternatives of functionally agreed POs and ODs; n – alternative number; N is the number of alternatives; $\mathrm{OD}_{\mathrm{COM}}$ – a set of OD that ensure the implementation of the necessary COM for automatic orientation of PO; $\mathrm{OD}_{\mathrm{TFE}}$ – a set of ODs that ensure the implementation of the force effects of ODs on PO, which are different in terms of physical content, in order to ensure the implementation of COM; PO is a set of oriented ODs.

The choice of the most expedient in terms of practical implementation of alternatives is made from a set $SOOV_n^f$ of criteria. These criteria make it possible to assess the probable future effects (for example, increasing the accuracy and speed of orientation, the reliability of the operation of SAOPO, etc.). In addition, they allow one to estimate costs (for example, for modernization, acquisition, maintenance and repair of equipment, training of service personnel, etc.). A formalized description of this process is given by expression (2):

$$\left\{SOOV_k^d\right\}= \\ =\begin{cases}\left\{\left\{SOOV_k^d \mid k=\overline{1,K}\right\}=\sum\limits_{g=1}^{g}\mathrm{OD}_g\right\}\supset\left\{SOOV_n^f\right\}, \\ \text{if } \left|SOOV_n\right|\neq\varnothing; \\ \varnothing, \text{if } \left|SOOV_n^f\right|=\varnothing,\end{cases} \quad (2)$$

where $SOOV_k^d$ – a set of alternatives appropriate for their practical implementation; k – alternative number; K is the number of alternatives; OD_g – OD in the composition of alternatives that are expedient in terms of their practical implementation; g – OD number in the alternative; G is the number of ODs in the alternative.



$\{SOOV_n^1 \mid n=\overline{1,N};\ N=\sum_{p=1}^{P} OD_p\} = \{OD_{iCOM}\} \cap \{OD_{jTFE}\} \geq 1$

$SOOV_n^f$ is a set of alternatives of functionally agreed POs and ODs;
n – alternative number;
N is the number of alternatives;
OD_{COM} – a set of OD that ensure the implementation of the necessary COM for automatic orientation of PO;
OD_{TFE} – a set of ODs that ensure the implementation of the force effects of ODs on PO, which are different in terms of physical content, in order to ensure the implementation of COM;
PO is a set of oriented ODs.

$\{SOOV_k^2 \mid k=\overline{1,K};\ K=\sum_{g=1}^{G} OD_g\} \supset \{SOOV_n^1\}$

$SOOV_k^d$ – a set of alternatives appropriate for their practical implementation;
k – alternative number;
K is the number of alternatives;
OD_g – OD in the composition of alternatives that are expedient in terms of their practical implementation;
g – OD number in the alternative;
G is the number of ODs in the alternative.

$\{SOOV_m^3 \mid m=\overline{1,M};\ M=\sum_{t=1}^{T} OD_t\} \supset \{SOOV_k^2\}$

$SOOV_m^{opt}$ is a set of optimal alternatives that reflect the optimal, in the accepted sense, qualitative and quantitative composition of SAOPO;
m is the number of the optimal alternative;
M is the number of optimal alternatives;
OD_t – OD in the composition of optimal alternatives of SAOPO;
t is the OD number in the set of optimal alternatives; T is the number of ODs in the set of optimal alternatives.

Fig. 1. The Euler-Venn model of modeling the composition and technique of organizing automatic orientation systems of production objects

Making the final decision, i.e., choosing the optimal composition and technique of SAOPO organization from a set $SOOV_k^d$ of alternatives appropriate for their practical implementation should be based on mathematical calculations of probabilistic effects and costs. That is, one optimal alternative $SOOV_m^{opt}$, is determined that reflects the optimal qualitative and quantitative composition of SAOPO from the set $SOOV_k^d$ according to expression (3). At the same time, it is taken into account that the costs should in no case exceed the effects obtained from the application of this SAOPO:

$$\left|\left\langle SOOV_m^{opt} \mid m=\overline{1,M}\right\rangle\right| = \begin{cases} \left\{\left\{SOOV_m^{opt} \mid m=\overline{1,M}\right\} = \sum_{t=1}^{T} \mathrm{OD}_t\right\} \supset \left\{SOOV_k^d\right\}, \\ \text{if } \left|SOOV_k^d\right| \neq \varnothing; \\ \varnothing, \text{if } \left|SOOV_k^d\right| = \varnothing, \end{cases} \quad (3)$$

where $SOOV_m^{opt}$ is a set of optimal alternatives that reflect the optimal, in the accepted sense, qualitative and quantitative composition of SAOPO; m is the number of the optimal alternative; M is the number of optimal alternatives; OD_t – OD in the composition of optimal alternatives of SAOPO; t is the OD number in the set of optimal alternatives; T is the number of ODs in the set of optimal alternatives.

The search for the final solution is the search for some balance between the expected effects and possible costs. This search can be implemented using methods of system analysis. In particular, the heuristic method, the method of normalization and correlation analysis, which allow us to quantitatively substantiate the importance of the indicators of the assessment of the received probabilistic effects and costs from the use of the optimal alternative $SOOV_m^{opt}$. This alternative reflects the optimal qualitative and quantitative composition of SAOPO. The simplest way is a comparative analysis of the correlation coefficients of OD indicators as components of SAOPO. These indicators form the parameters of its effectiveness, provided that the pre-formed set $SOOV_k^d$ of suitable alternatives for the qualitative and quantitative composition of SAOPO is not empty, i. e., $\left|SOOV_k^d\right| \neq \varnothing$.

To convert the correlation coefficients into weighting coefficients, formula (4) known from [18] can be used:

$$\omega_j = \frac{r_j}{\sum_{j=1}^{n} r_j}, \quad (4)$$

where ω_j is the weighting coefficient of the jth indicator of OD as a component of SAOPO, which forms the parameters of its effectiveness; r_j is the correlation coefficient and index of the jth indicator of OD as a component of SAOPO, and the resulting indicator of the efficiency of SAOPO application in FPS; n is the number of OD indicators as components of SAOPO.

5. 2. Structural diagram of the information-computer system for automated modeling of systems for automatic orientation of production objects

Taking into account the above, ICS for the automated simulation of SAOPO is a specific set of software-hardware and information-telecommunication tools and interactive functional modules. The processes of automated preparation and processing of technical and economic information are distributed between these interactive functional modules. This information is necessary for the automated adoption of a reasoned, correct, and effective decision regarding the composition and technique of SAOPO organization. The development of the ICS structure for the automated modeling of SAOPO and its components was carried out on the basis of the principles of modularity, aggregation, systematicity, effectiveness, and security.

The principles of modularity and systematicity make it possible to consider each component of the newly created ICS for the automated simulation of SAOPO as a separate interactive functional module that is autonomously used to solve a specific local task at a separate stage of SAOPO modeling. And the integration of modules in the general structure of ICS for the automated simulation of SAOPO ensures its integrity. Circulation of information flows and data exchange between functional modules in the ICS for the automated simulation of SAOPO is carried out using unified technical means according to the principles of aggregation. This is due to the fact that the output information flows of some modules are input for others.

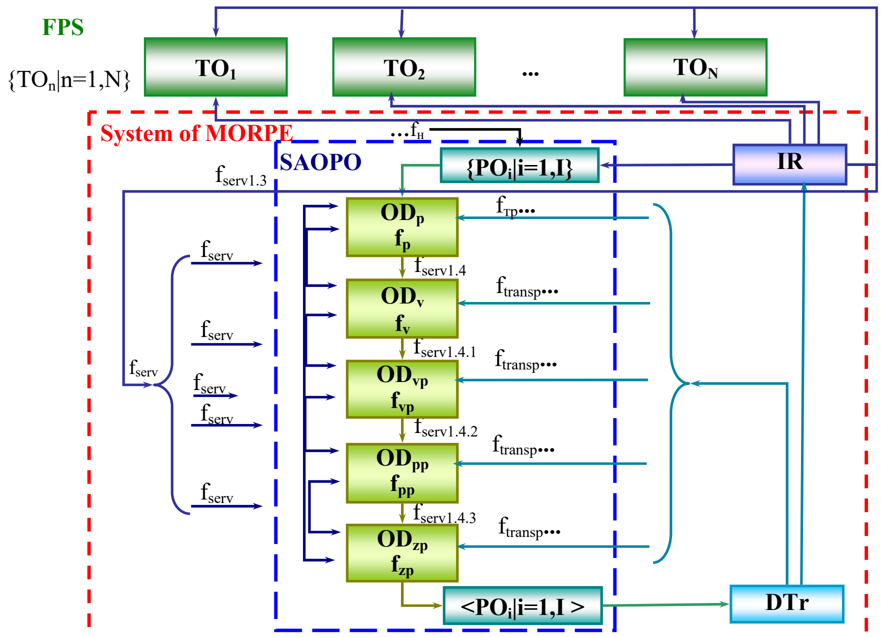


Fig. 2. IDEF0-model of the functioning of the system for the automatic orientation of production objects as part of a flexible production system

The principle of integration and integrity of the system provides the possibility of collective access of individual functional modules of ICS for automated simulation of SAOPO to industrial database management systems (DBMS) of FCIS. For example, DBMS PO and DBMS OD, etc. Integration of the entire ICS for automated simulation of SAOPO into the unified information space of FCIS is also carried out. In addition, this allows us to ensure the flexibility, extensibility, and changeability of the software components of the proposed ICS.

The principle of the effectiveness of ICS work for the automated simulation of SAOPO is understood as its focus on finding the best ODs from the set of known ones that provide a balance between expected effects and possible costs. These ODs form the composition of SAOPO. And their functional coordination with PO and conjugation with other technological equipment of FPS determines the technique of SAOPO organization. For this purpose, the methods of system analysis and fuzzy logic, mathematical tools, and neural network technologies are used in the corresponding modules of the ICS for the automated modeling of SAOPO.

Comprehensive protection of information from unauthorized access and preservation of commercial secrets according to the international standard TCSEC [8] in ICS for the automated simulation of SAOPO is organized according to the principle of security.

The functioning of SAOPO as part of FPS is visualized by the IDEF0 model (Fig. 2). The IDEF0 model shown in Fig. 2 gives an idea of the physical composition of FPS and SAOPO as a component of FPS. In addition, the IDEF0 model reflects the interrelationships, directions, and hierarchy of material flows circulating in FPS related to the production process and the arrangement of the robotic production environment formed by a set of POs. In Fig. 2, the following designations accepted in [16] are used: a system of MORPE – a system of means of organizing the robotic production environment; SAOPO – system of automatic orientation of PO; DTr – transport device; IR – industrial robot; TO is the basic technological equipment, OD is an orientation device.

Taking into account the above, the newly designed ICS for the automated simulation of SAOPO contains a certain set of components and functional modules. These modules and components are used to solve certain local tasks and manage relevant information flows. For this, certain methods and means of automated data processing are used, including our original developments, such as neuro-fuzzy networks and computer vision algorithms [16]. The structural diagram of the newly designed ICS for the automated simulation of SAOPO is shown in Fig. 3.

The composition of the functional modules of the proposed ICS for the automated simulation of SAOPO and the used methods and means of automated data processing are as follows:

1) data storage (SD) organized by DBMS. SD is used to accumulate and store information necessary to solve local tasks of determining the composition and technique of SAOPO organization (not shown in Fig. 3). In particular, information about:

– structural features and physical and mechanical properties of PO;

– technological characteristics and OD functionality;

– COM is necessary for automatic orientation of PO;

– the composition of other technological equipment in FPS with which the operation of SAOPO is coordinated.

2) a module for automated collection and loading of data in SD with the possibility of working under manual mode (not shown in Fig. 3);

3) module of automated identification, systematization, and grouping of ODs. In this module, automated identification, systematization, and grouping of ODs are carried out according to:

– structural features and physical and mechanical properties of PO;

– COM necessary for automatic orientation;

– possible types of force influences (TFE) to enable COM.

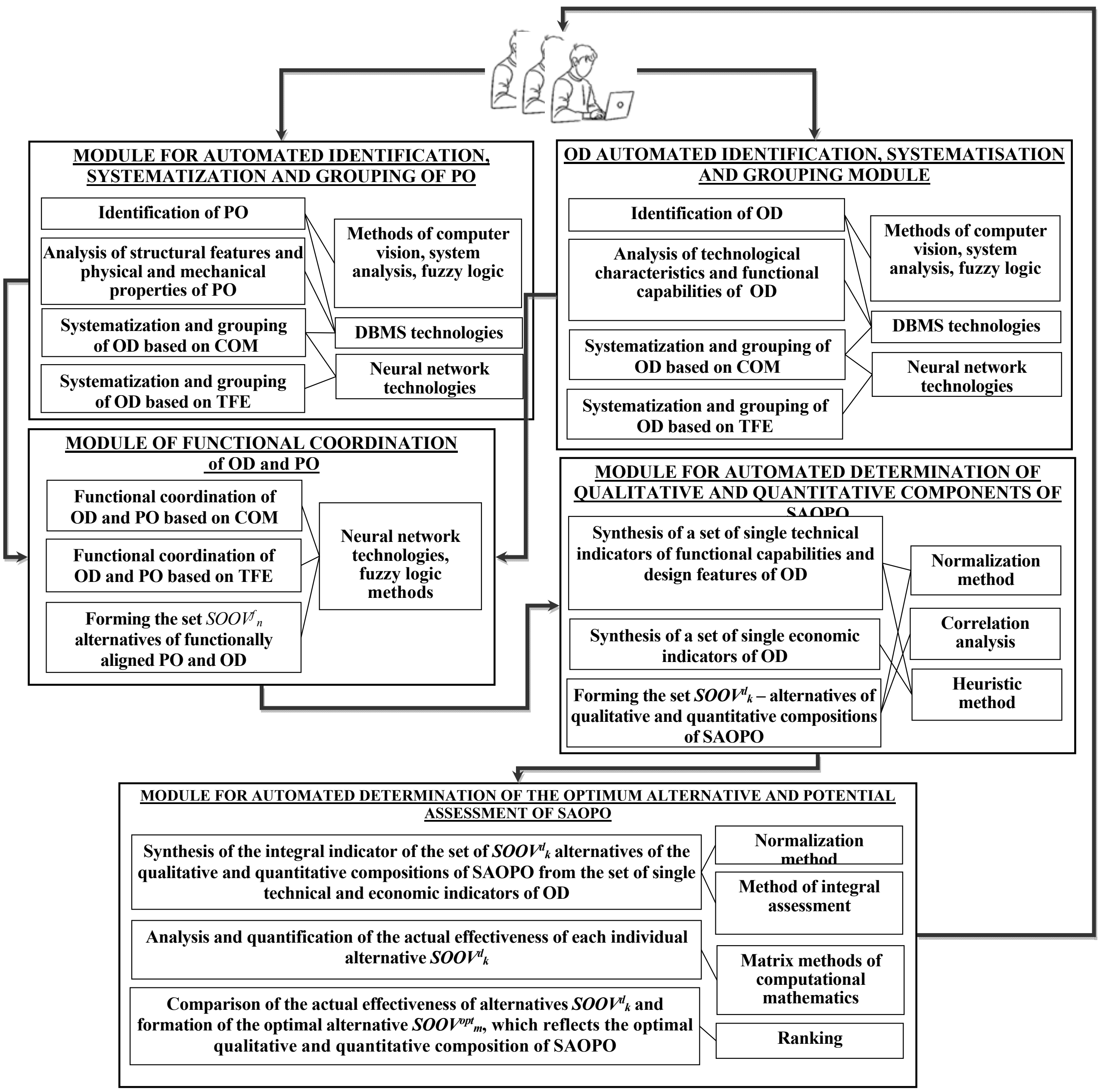


Fig. 3. Structure of the information-computer system for automated modeling of the system of automatic orientation of production objects

In this module, methods of computer vision, system analysis, fuzzy logic, neural network technologies, and DBMS tools are used to solve the specified tasks;

4) the module of automated identification, systematization, and grouping of OD, in which automated identification, systematization, and grouping of ODs is carried out according to their technical characteristics, functional capabilities, COM and TFE, which they can implement for automatic orientation of PO. The module uses methods of computer vision, system analysis, fuzzy logic, neural network technologies, and DBMS tools to solve these tasks;

5) the module of functional alignment of OD and PO. In the module, OD and PO are automatically aligned according to the necessary COM and TFE, which can be applied to PO for their automatic orientation. Also, in this module, the formation of a set $SOOV_n^f$ of functionally coordinated PO and OD alternatives is performed. The module uses neural network technologies and methods of fuzzy logic to solve the specified tasks;

6) a module for automated determination of qualitative and quantitative components of SAOPO. In this module, an automated selection of the most appropriate for the practical implementation of OD and a set of criteria is carried out. These criteria make it possible to estimate the likely future effects and costs of using the formed variants of the qualitative and quantitative composition of SAOPO. To solve the specified tasks in the module, such methods of system analysis as the normalization method, correlation analysis, heuristic method are used;

7) a module for automated determination of the optimal alternative and assessment of the potential of SAOPO. In this module, the integral indicator of the quanti-

tative assessment of each individual alternative solution is formed, regarding the composition and technique of SAOPO organization. Also, this module searches for the optimal solution from a set $SOOV_m^{opt}$ of alternatives obtained at the previous stages. Mathematical methods and methods of systemic and economic analysis are used in the module to solve the specified tasks, in particular, matrix methods, methods of normalization, integral evaluation, and ranking.

5. 3. Structural diagram of the network integration of the proposed information-computer system

In addition to the main task, ICS for the automated modeling of SAOPO must provide access to all the necessary information to every specialist of the enterprise and at the same time comply with the principles of information protection and preservation of commercial secrets. From these positions, certain levels of access to the processes of accumulation, storage, processing, and transmission of data in ICS for the automated modeling of SAOPO are established. Such data, for example, can be data on the features of the automatic orientation process and other technological processes, design features or physical properties of new POs, their cost price, information about counterparties, etc. Therefore, in accordance with international standards ISO 27005 and ISO 27001, ICS for the automated modeling of SAOPO must meet the basic requirements of information security control. As well as the international criteria for Trusted Computer System Evaluation Criteria (TCSEC)) [19]. Fig. 4 shows the general scheme of information network integration of ICS for the automated modeling of SAOPO into the general industrial information network of FCIS in the machine- and instrument-making industries.

The general scheme of information network integration of ICS for the automated modeling of SAOPO into the general industrial information network FCIS ensures collective access of the company's specialists to the necessary information. The proposed system has four levels of protection (D, C, B, and A) in accordance with the TCSEC international standard and provides reliable preservation of confidential information.

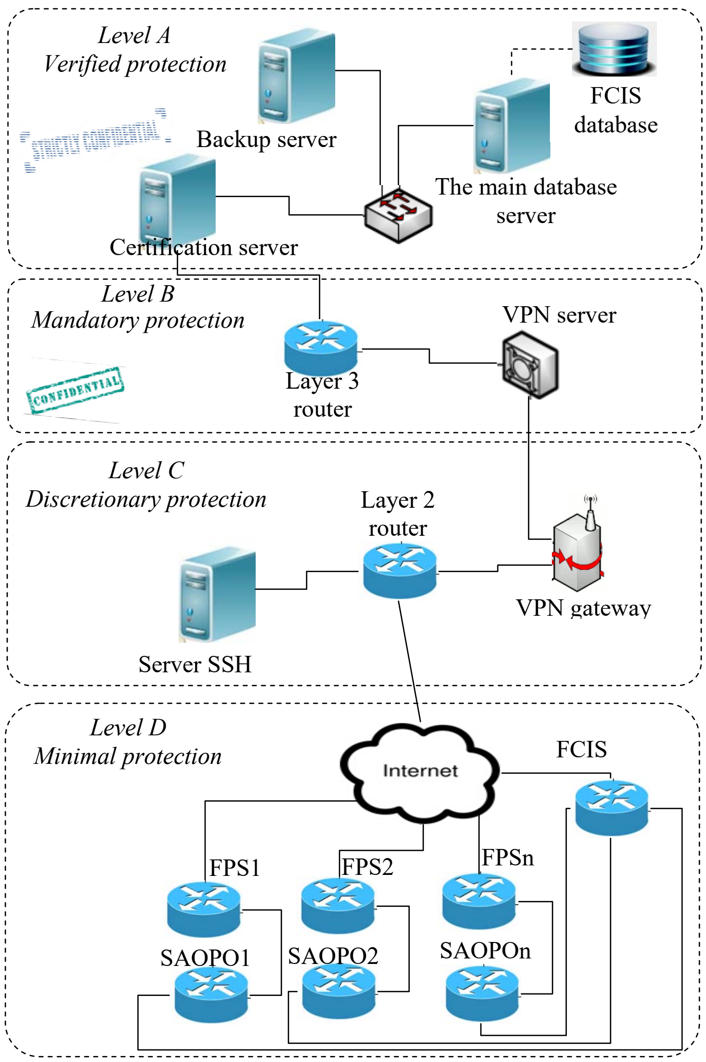


Fig. 4. General scheme of the information network integration of the information-computer system for the automated modeling of systems of automatic orientation of production objects into the general industrial information network FCIS with four levels of protection in accordance with TCSEC criteria

5. 4. Experimental studies on the performance of an information-computer system for the automated modeling of systems of automatic orientation of production objects

Experimental studies on the performance of the proposed ICS for the automated modeling of SAOPO were carried out by computer simulation methods using the software that we developed and specialized software for the synthesis of artificial neural networks. After all, as you know, computer simulation, including in the creation and research of artificial neural networks, is less expensive but no less effective than a natural experiment. At the same time, the results are more visible and convenient, easily interpreted and understood by specialists. Screenshots of the dialog windows of some modules of our software are shown in Fig. 5, 7–9.

Verification of the proposed ICS for the automated modeling of SAOPO was carried out for an abstract PO, the type of conical roller made of St20kp steel according to DSTU 7809 and DSTU 7808 with different ends, a blind hole on one of them, and a weight of 5.5 kg (Fig. 5).

In order to carry out automatic orientation of this PO, it is necessary to determine COM, TFE to transfer it from INP to FOP, which is determined, for example, by the characteristics of the gripping device of an industrial robot (IR). Schematically, an example of the process of transferring PO from INP to FOP by performing COM is shown in Fig. 6.

It is also necessary to choose such OD models, from some previously known set, which will form such a composition of SAOPO, which will ensure an optimal balance between the effects and costs of their use. In addition, it is necessary to comply with the condition of functional consistency of the determined composition of SAOPO (i.e., the set of ODs) with other technological equipment of FPS. This determines the technique of SAOPO organization.

PO, considered as an example in the module of automated identification, systematization, and grouping of POs (Fig. 7), the necessary COM and TVS for its orientation were automatically identified and determined. Owing to the use of neuro-fuzzy networks and computer vision algorithms, the information processing time did not exceed three seconds, which corresponds to the real-time mode, and the maximum relative error did not exceed 5 %, which meets the requirements of modern production.

In the OD and PO functional coordination module (Fig. 8), eleven OD models are automatically defined under the conditional names Model OD1, Model OD2, etc. These OD models form such a composition of SAOPO that provides an optimal balance between the effects and costs of their application (Fig. 8). Information processing time did not exceed two seconds.

In the module for the automated determination of the optimal alternative and the assessment of the potential of SAOPO, two OD models were finally selected on the basis of automatically performed ICS calculations – Model OD2 and Model OD9. The application of these OD models determines the technique of SAOPO organization. The technique of SAOPO organization automatically defined in this module meets the condition of its functional consistency with other technological equipment of FPS, for example, IR (Fig. 9).

The obtained result is final and can be proposed for practical application as having the greatest efficiency.

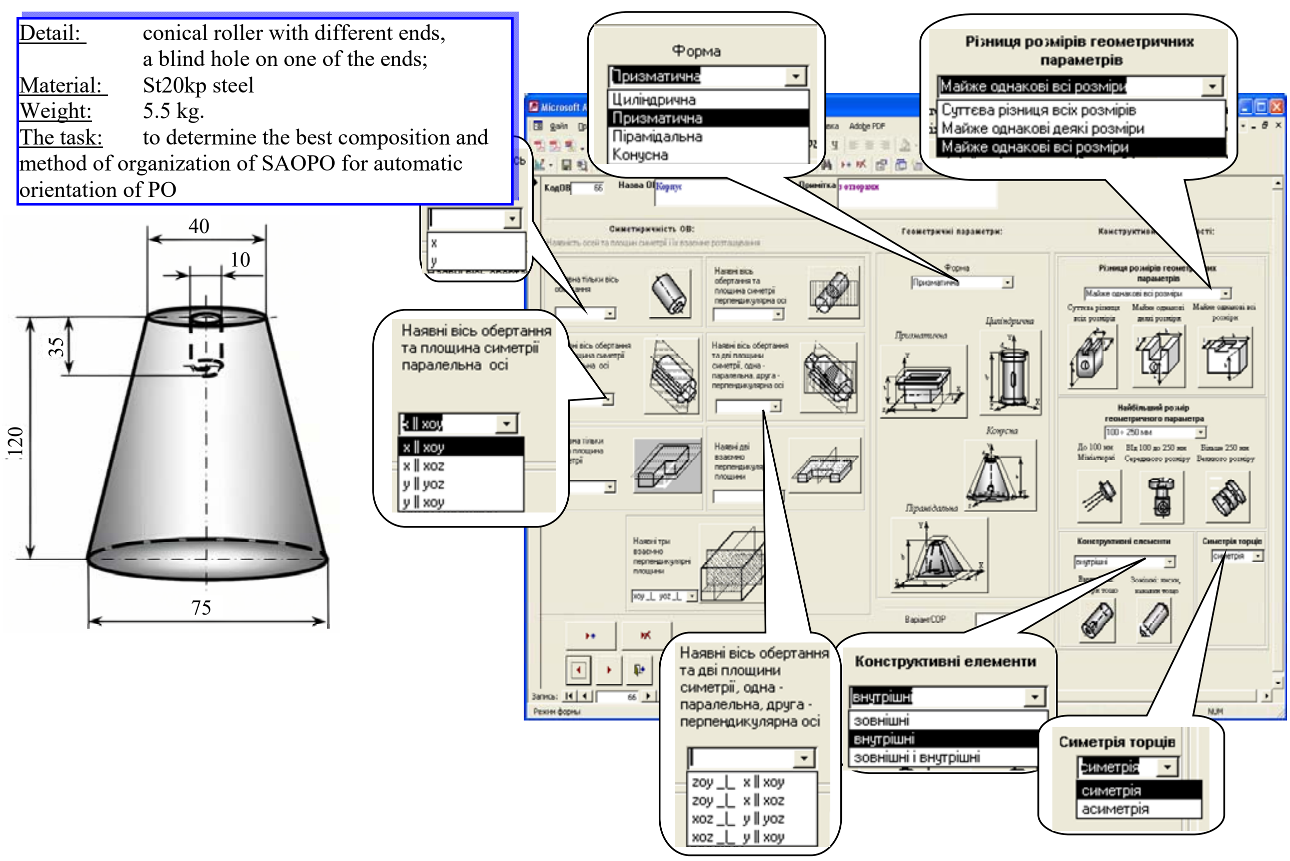


Fig. 5. Screenshot of the production object data store dialog

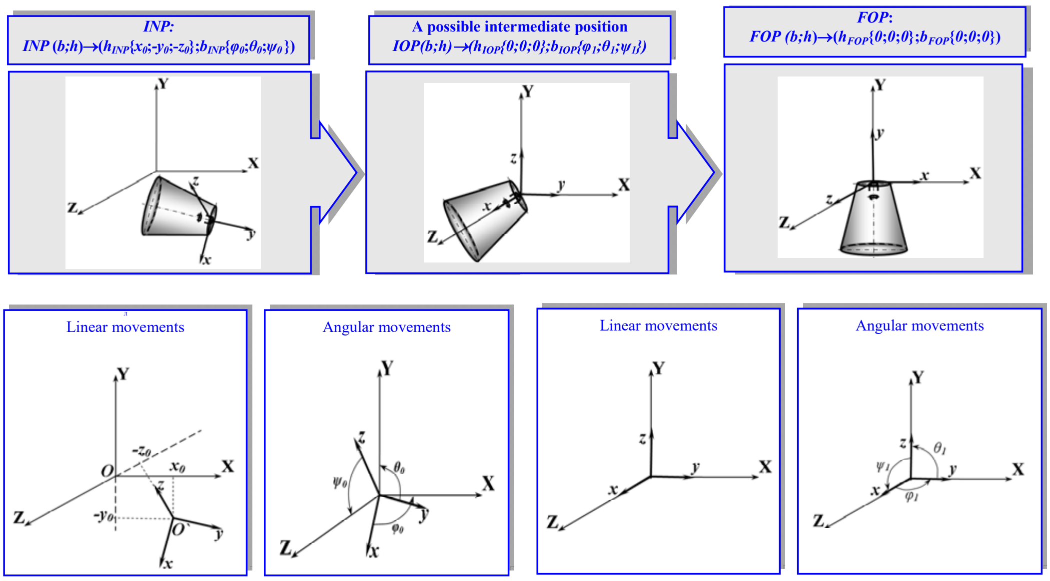


Fig. 6. Schematic representation of the process of automatic orientation of production objects

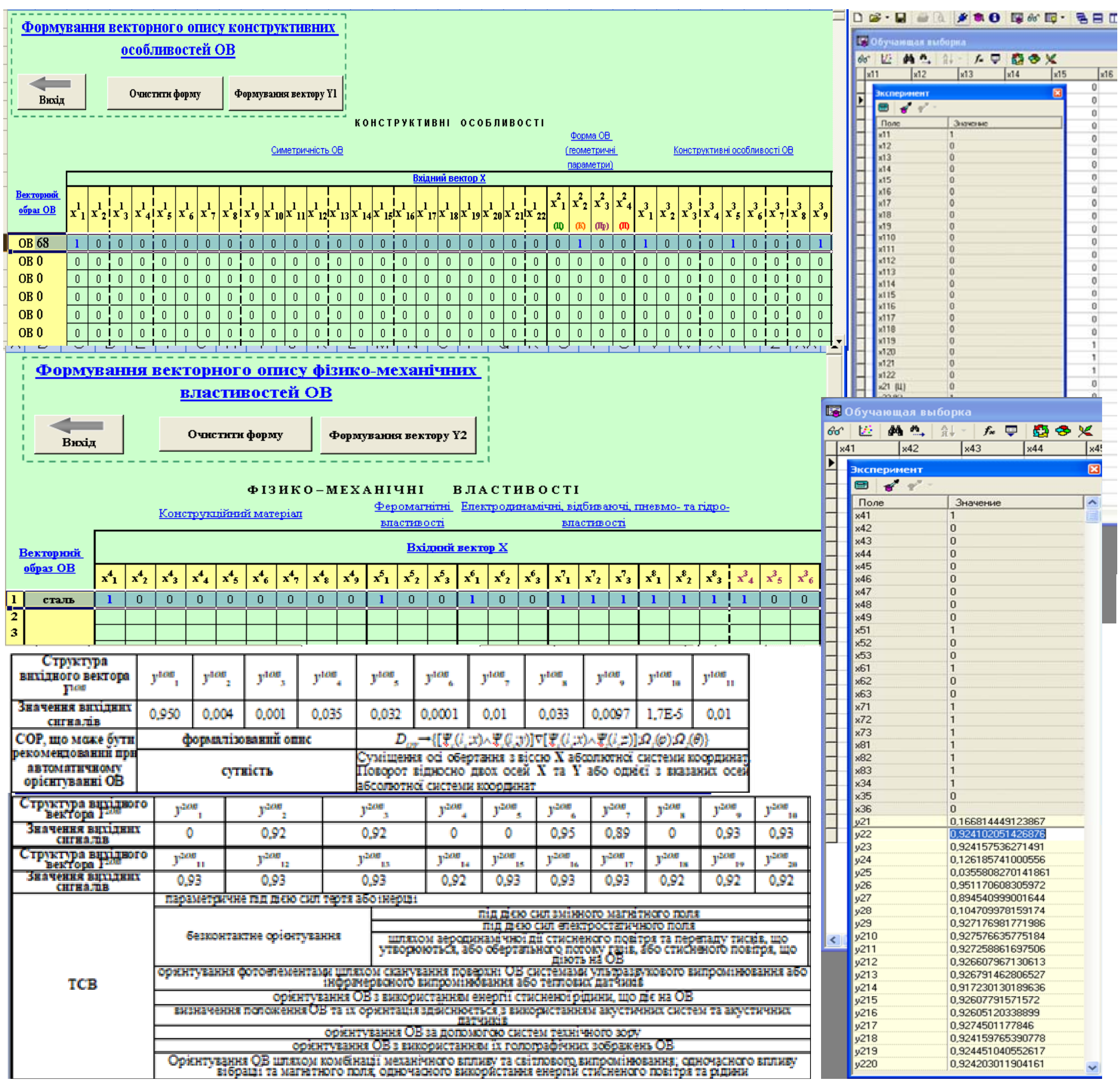
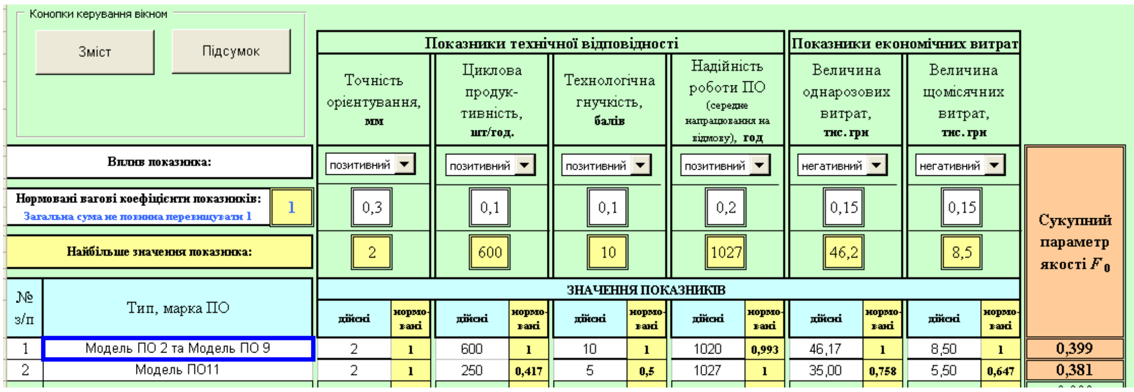


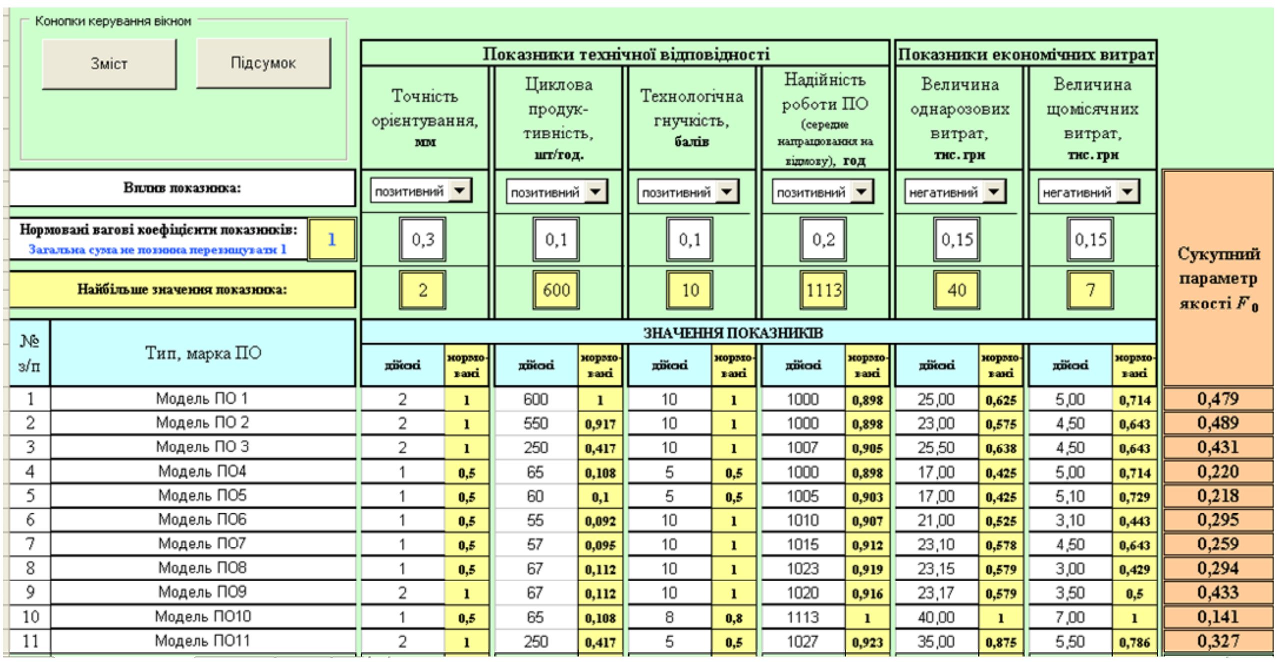
Fig. 7. Illustration of the module for automated identification, systematization and grouping of production objects



Кнопки керування вікном: Зміст | Підсумок

№ з/п	Тип, марка ПО	Точність орієнтування, мм (дійсні)	(нормовані)	Циклова продуктивність, шт/год. (дійсні)	(нормовані)	Технологічна гнучкість, балів (дійсні)	(нормовані)	Надійність роботи ПО (середнє напрацювання на відмову), год (дійсні)	(нормовані)	Величина одноразових витрат, тис. грн (дійсні)	(нормовані)	Величина щомісячних витрат, тис. грн (дійсні)	(нормовані)	Сукупний параметр якості F_0
	Вплив показника:	позитивний		позитивний		позитивний		позитивний		негативний		негативний		
	Нормовані вагові коефіцієнти показників: 1 (Загальна сума не повинна перевищувати 1)	0,3		0,1		0,1		0,2		0,15		0,15		
	Найбільше значення показника:	2		600		10		1027		46,2		8,5		
1	Модель ПО 2 та Модель ПО 9	2	1	600	1	10	1	1020	0,993	46,17	1	8,50	1	0,399
2	Модель ПО11	2	1	250	0,417	5	0,5	1027	1	35,00	0,758	5,50	0,647	0,381

Fig. 8. Screen copy of the dialog window of the module for automated determination of qualitative and quantitative compositions of systems for the automatic orientation of production objects



Кнопки керування вікном: Зміст | Підсумок

№ з/п	Тип, марка ПО	Точність орієнтування, мм (дійсні)	(нормовані)	Циклова продуктивність, шт/год. (дійсні)	(нормовані)	Технологічна гнучкість, балів (дійсні)	(нормовані)	Надійність роботи ПО (середнє напрацювання на відмову), год (дійсні)	(нормовані)	Величина одноразових витрат, тис. грн (дійсні)	(нормовані)	Величина щомісячних витрат, тис. грн (дійсні)	(нормовані)	Сукупний параметр якості F_0
	Вплив показника:	позитивний		позитивний		позитивний		позитивний		негативний		негативний		
	Нормовані вагові коефіцієнти показників: 1 (Загальна сума не повинна перевищувати 1)	0,3		0,1		0,1		0,2		0,15		0,15		
	Найбільше значення показника:	2		600		10		1113		40		7		
1	Модель ПО 1	2	1	600	1	10	1	1000	0,898	25,00	0,625	5,00	0,714	0,479
2	Модель ПО 2	2	1	550	0,917	10	1	1000	0,898	23,00	0,575	4,50	0,643	0,489
3	Модель ПО 3	2	1	250	0,417	10	1	1007	0,905	25,50	0,638	4,50	0,643	0,431
4	Модель ПО4	1	0,5	65	0,108	5	0,5	1000	0,898	17,00	0,425	5,00	0,714	0,220
5	Модель ПО5	1	0,5	60	0,1	5	0,5	1005	0,903	17,00	0,425	5,10	0,729	0,218
6	Модель ПО6	1	0,5	55	0,092	10	1	1010	0,907	21,00	0,525	3,10	0,443	0,295
7	Модель ПО7	1	0,5	57	0,095	10	1	1015	0,912	23,10	0,578	4,50	0,643	0,259
8	Модель ПО8	1	0,5	67	0,112	10	1	1023	0,919	23,15	0,579	3,00	0,429	0,294
9	Модель ПО9	2	1	67	0,112	10	1	1020	0,916	23,17	0,579	3,50	0,5	0,433
10	Модель ПО10	1	0,5	65	0,108	8	0,8	1113	1	40,00	1	7,00	1	0,141
11	Модель ПО11	2	1	250	0,417	5	0,5	1027	0,923	35,00	0,875	5,50	0,786	0,327

Fig. 9. Screenshot of the dialog window of the module for automated determination of the optimal alternative and assessment of the potential of systems of automatic orientation of production objects

Thus, our experimental studies have confirmed the functionality of the proposed ICS for the automated modeling of SAOPO and its ability to form reasonable and correct decisions. Based on the results of experimental studies, it can be stated that the proposed ICS for the automated modeling of SAOPO is the latest, original, and modern toolkit for supporting the adoption of correct, justified, and effective decisions. Application of the proposed ICS for the automated modeling of SAOPO makes it possible to increase the speed and efficiency of information processing at the stage of technological preparation of production in machine and instrument engineering.

6. Discussion of the research results related to the proposed information-computer system

The proposed ICS for the automated modeling of SAOPO is the latest, original, and modern decision-making support tool at the stage of technological preparation of production. It, in contrast to known solutions [4, 6, 7], takes into account all stages of technological preparation of production and a set of criteria that allow assessing the future effects and costs of using certain ODs. At the same time, it is taken into account that the costs should in no case exceed the effects obtained from the application of this SAOPO. Also, unlike known solutions [8, 9], all the diversity of structural features and physical and mechanical properties of POs and functional capabilities of ODs are taken into account, and, unlike [10–12, 14], all relationships between them are formalized in view of the specificity in the machine- and instrument-making industries. In addition, the social and economic effect of using the proposed ICS for the automated modeling of SAOPO is obvious. It manifests itself in increasing the quality and reducing the complexity of decisions that are made at the stage of technological preparation of production when choosing equipment, in particular OD. Also obvious is the reduction of financial, intellectual, and time costs for technological preparation of production as a whole. This is quite acceptable for economic reasons.

Owing to the detailing and formalization of the process of determining the composition and technique of SAOPO organization according to expressions (1) to (3), it was possible to establish all the relationships between OD and PO. The application of expression (4) made it possible to convert the correlation coefficients into weighting coefficients to substantiate the importance of the indicators of the assessment of the received probabilistic effects and costs. Owing to this, the procedure for finding effective alternative solutions has been formalized. In general, this made it possible to determine a comprehensive sequence of actions to determine the optimal composition and technique of SAOPO organization.

The developed structural diagram (Fig. 3) of the newly designed ICS for the automated modeling of SAOPO solves two problems. First, it offers a complex sequence of actions aimed at finding the final solution, as some kind of balance between expected effects and possible costs. This search is implemented using methods of computer vision, artificial intelligence, and system analysis. Computer vision and artificial intelligence methods make it possible to automatically analyze PO and OD and establish all relationships between them with high accuracy in real time. Experimental studies on the performance of the proposed ICS for the automated modeling of SAOPO, the results of which are reported in this paper, showed that the relative error does not exceed 5 %, and the time of information processing did not exceed 3 seconds. This corresponds to the real-time mode and the requirements of modern production. The methods of system analysis for finding the final solution make it possible to quantitatively assess the probabilistic effects and costs of using the so-called optimal alternative, which reflects the optimal qualitative and quantitative composition of SAOPO. Also, the methods of system analysis used make it possible to justify the importance of the evaluation indicators. Secondly, the developed structural scheme of the proposed ICS for the automated modeling of SAOPO (Fig. 3) reproduces the paradigm of modularity, aggregation, systematicity, integrity, effectiveness, and security. This makes it possible to use unified software-hardware and information-telecommunication tools to carry out its modernization and, if necessary, to change software components.

The developed structural diagram of the network integration of the proposed ICS for the automated modeling of SAOPO (Fig. 4) suggests its integration into FPS. Here, in addition to the integration of the proposed system into the general industrial network, protection of information from unauthorized access and preservation of commercial secrets is ensured according to the TCSEC international standard.

Experimental studies on the performance of ICS for the automated modeling of SAOPO were carried out for some abstract PO (Fig. 5). The results (Fig. 6–9) made it possible to verify not only its efficiency but also to determine compliance with the requirements of modern production in terms of accuracy and speed. This statement is based on the fact that the technologies of artificial intelligence, in particular, the neuro-fuzzy network that we developed earlier, used in this development, allow parallel processing of information in real time. At the same time, the high efficiency and probability of correct processing of information under conditions of its incompleteness and contradictions, as well as the ease of training and retraining of ANNs allow timely transition to new types of solved problems [20]. Thus, according to the results of experimental studies, for the example given in the paper (Fig. 5), the information processing time did not exceed 3 seconds, which corresponds to the real-time mode, and the maximum relative error did not exceed 5 %. In addition, ICS for the automated modeling of SAOPO has a convenient and intuitive interface (Fig. 7–9), which obviously simplifies the work of specialists with it.

It should be noted that the limitations of this research may be the insufficient level of knowledge and skills in working with artificial intelligence technologies and computer vision. Requirements regarding the need for basic knowledge of artificial intelligence technologies, in particular fuzzy logic and artificial neural networks, computer vision must be taken into account when trying to apply the proposed ICS for the automated modeling of SAOPO in practice, as well as in further theoretical studies.

The main drawback of the study is the dependence of the results on the completeness of the descriptions of the structural features and physical and mechanical properties of PO and the technological characteristics and functional capabilities of OD. This is due to the fact that the correctness of the determination of COM and TVS and the successful choice of the method of automatic orientation depend on the completeness of the descriptions of the structural features and physical and mechanical properties of PO. And the possibility of functional coordination of OD and PO depends on the completeness of the descriptions of technological characteristics and functional capabilities of OD.

In addition, the shortcoming of this study is its focus only on the modeling of SAOPO, that is, the determination of its composition and organization technique. At the stage of technological preparation of production, it is necessary to solve the tasks related to the selection of other types of equipment of MORPE systems (Fig. 2) in FPS. For example, transport devices (PTr), systems for accumulation, cut-off, etc.

It is obvious that the further development of this research can be carried out in the area of expanding the functionality of the proposed system in relation to the complex automation of the modeling of MORPE system, that is, determining its composition and the way of organization in FPS. It is obvious that on this path you may encounter difficulties of both a mathematical and methodical nature. In particular, when formalizing the process of determining the composition and the way of organizing the MORPE systems, establishing all the relationships between its components, as well as finding alternative solutions and evaluating their effectiveness.

7. Conclusions

1. The process of determining the composition and technique of SAOPO organization has been formalized. This formalized description reproduces the multi-stage process of determining the composition and technique of SAOPO organization. Formalization of the process of determining the composition and technique of SAOPO organization made it possible to carry out its decomposition and to highlight local tasks of OD selection. This decomposition is the basis of the ICS structure for the automated modeling of SAOPO. The defined local tasks are the main tasks of the functional modules of ICS for the automated modeling of SAOPO.

2. A structural diagram of ICS for the automated modeling of SAOPO and its functional modules has been constructed. Information flows, methods and means of automated data processing were defined. In addition, the principles of construction of ICS for the automated modeling

of SAOPO were determined. These principles provide for the integrity, uniformity, extensibility, possibility of modernization and changeability of the software components of the proposed ICS for the automated modeling of SAOPO. Integration of the proposed ICS for the automated modeling of SAOPO into the general industrial information network of FCIS in the machine- and instrument-making industries is also ensured. The proposed system provides automated determination of the optimal composition and technique of SAOPO organization at the stage of technological preparation of production in machine and instrument engineering. At the same time, information is processed with high speed (in real time) and accuracy. In particular, the relative error of recognition of PO and OD, their systematization, grouping, and determination of COM and TFE does not exceed 0.05 while the information processing time does not exceed 3 seconds, which meets the global requirements for modern production. This allows one to reduce time and increase the accuracy of information processing and the efficiency of decision-making.

3. A structural diagram of network integration of ICS for the automated modeling of SAOPO in FCIS in the machine- and instrument-making industries has been built. The developed scheme of network integration provides access for the company's specialists to the necessary information and at the same time ensures its confidentiality and four-level protection against unauthorized access according to the principles of the TCSEC international standard. This makes it possible to protect confidential information from unauthorized access.

4. The performance of ICS for the automated modeling of SAOPO was experimentally investigated. The results confirmed the functionality of the proposed system and its ability to form reasonable and correct decisions. The results of experimental studies reported in this work allow us to consider the proposed ICS for the automated modeling of SAOPO as the latest, original, and modern tool for supporting the adoption of correct, justified, and effective decisions. Therefore, it can be recommended for practical use as it makes it possible to quickly and efficiently process information and make correct and justified decisions when determining the composition and technique of SAOPO organization.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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