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MATHEMATICAL MODEL FOR DETERMINING THE DISTRIBUTION STRUCTURE OF AUTOMATED CONTROL SYSTEMS

МАТЕМАТИЧНА МОДЕЛЬ ВИЗНАЧЕННЯ СТРУКТУРИ РОЗПОДІЛЕННЯ АВТОМАТИЗОВАНИХ СИСТЕМ УПРАВЛІННЯ

According to the results of the work, a multi-level modular architecture with clearly defined interaction interfaces is recommended for a machine-building enterprise, which provides flexibility, scalability and efficient data flow. A methodology for creating an automated management system based on the principle of multiple use of information has been developed. This approach contributes to more efficient use of resources required for data collection, and also helps to avoid errors associated with discrepancies in the use of different data for the same parameter. It is proposed that the use of a modernized document management system allows to increase the level of automation of processes in the work of the personnel department and the labor department for wages.

Keywords: modeling, numerical methods, automation, mathematical modeling, aerospace and rocket and space technology, competition, distribution.

В Україні та світі набувають популярності автоматизовані системи управління, ERP-рішення та інші корпоративні інформаційні платформи. Повнофункціональна ERP-система служить фундаментом для вирішення комплексних задач управління та стратегічного планування, виходячи далеко за рамки простої автоматизації повсякденних операцій на підприємстві, таких як розрахунок матеріальних витрат або контроль наповненості складів. Запровадження ERP-систем на підприємствах є свідченням переходу до вищого рівня розвитку, адже вони надають можливість максимально ефективно реалізувати потенціал підприємства.

У роботі авторами досліджено принципи побудови ефективних моделей модернізації АСУ на підприємствах ракетобудування, за яким пропонується застосування модульної концепції побудови АСУ. Ця концепція базується на принципі відносної автономності кожного модуля, яка забезпечує їх самостійну роботу. Одночасно модулі можуть взаємодіяти один з одним, передаючи необхідну інформацію до загальної інформаційної системи, де вона піддається аналізу, обробці та спрямовується до відповідних підрозділів для подальшого використання.

За результатами проведених робіт для машинобудівного підприємства рекомендована багаторівнева модульна архітектура з чітко визначеними інтерфейсами взаємодії, що забезпечує гнучкість, масштабованість та ефективний потік даних. Розроблена методика створення

автоматизованої системи управління, яка ґрунтується на принципі багаторазового використання інформації. Такий підхід сприяє ефективнішому використанню ресурсів, необхідних для збору даних, а також допомагає уникнути помилок, пов'язаних із розбіжностями у використанні різних даних для одного і того самого параметра. Запропоновано, застосування модернізованої системи документообігу дозволяє підвищити рівень автоматизації процесів у роботі відділу кадрів та відділу труда за заробітної плати.

Ключові слова: моделювання, чисельні методи, автоматизація, математичне моделювання, аерокосмічна та ракетно-космічна техніка, конкуренція, розподіл.

Problem's Formulation

Automated management systems (AMS), Enterprise Resource Planning (ERP) solutions and other corporate information platforms are gaining popularity in Ukraine and the world. A fully functional ERP system serves as the foundation for solving complex management and strategic planning tasks, going far beyond the simple automation of everyday operations at the enterprise, such as calculating material costs or controlling warehouse occupancy. The introduction of ERP systems at enterprises is evidence of a transition to a higher level of development, as they provide an opportunity to realize the enterprise's potential as effectively as possible [1, 7]. Thus, the issue of introducing smart technologies and their integration into various processes of rocketry enterprises is a relevant topic of research.

Analysis of recent research and publications

As noted by Vatchenko O.B., Vatchenko B.S. and Cherevko O.L., Sebron D., Virole S. [3, 8], the integration of remote access to electronic databases and the use of functional AMS tools within the information and communication infrastructure forms one of the key factors promoting economic development. This conclusion is justified by the possibility of increasing user mobility, which is provided by remote access to AMS. The result of this process is an increase in labor productivity both at the individual level of individual employees and at the level of the enterprise as a whole.

The cost of software for automated enterprise management systems can vary significantly, posing a dilemma for the structure: to purchase a finished product or to create its own software solution. If the choice is inclined to purchase a finished product, a new need arises to assess its cost. When making such a decision, several key factors should be taken into account: the scale of the enterprise, the degree of uniqueness of production processes and their diversity. The scale of the enterprise is determined, for example, by the number of employees or the level of gross income. The larger the enterprise, the more financial resources it can allocate to the purchase of software and payment for its implementation services. The uniqueness and diversity of production processes also have a significant impact. Usually their growth is associated with the expansion of the scale of production. This, in turn, increases the costs of adapting a ready-made solution, often making it more profitable to choose in favor of creating your own software that will more accurately meet the specific needs of the enterprise.

In the works of Nechepurenko and Trokhymchuk [2, 9], the justification of the analytical model for the decision on the choice of software was investigated. On this basis, a decision-making matrix was determined depending on the gradation of the size and uniqueness of the enterprise. Moreover, there are three options for recommendations for enterprises: development of their own software; purchase of software of relatively low or medium cost; purchase of high-cost software in a tabl. 1.

Table 1. Decision-making matrix depending on the gradation of size and uniqueness of the enterprise

Product uniqueness	Enterprise size		
	Small	Medium	Large
High	Purchasing software at relatively low or average cost	Own development	Own development
Average		Purchasing average-cost software	Purchasing high-value software
Low			

Formulation of the study purpose

The purpose of the work is to build effective models for the modernization of AMS at rocketry enterprises, for which the following were done:

- Optimal methods for document flow analysis were determined.
- Methods for dividing the designed AMS into separate functional modules were determined.
- A mathematical model for determining the rational structure of a distributed AMS was developed.

Presenting main material

Optimal methods of document flow analysis. The basis for the development of an automated information processing and management system (AIPMS) is a compiled model of the existing information processing and management system. The construction of such a model is carried out as a result of the implementation of a diagnostic analysis of the organization and a detailed analysis of the existing data processing system.

Diagnostic analysis is a set of studies to identify trends in the development of an automation object and its control system, study typical management tasks, develop requirements and measures to improve the information processing and management system. The results of the analysis of the object and the control system are recorded in special documents. A set of these documents is called a system specification.

The use of system specifications allows you to systematize the data obtained as a result of the analysis and present them in a visual and convenient for further use form, simplify and facilitate the transfer of work results from one specialist to another, ensure the interchangeability of performers, formalize the procedures for introducing corrections and additions, and facilitate quality control of each stage.

To describe information flows between the units of an automation object, we will give it a definition. Information flow is a combination of two concepts: an information flow scheme and an information flow element.



Fig. 1 Example of a document flow chart

The information flow scheme is determined by specifying the entry relations for each flow element.

The elements of the information flow are documents and their elements (indicators, details) or operators (people, devices, units).

Two main parameters are determined in the information flow: the direction of the flow and the density of the flow. The direction of the flow is given by the place of its entry and exit, and the density is determined by the ratio:

$$\lambda = \frac{\Delta V}{\Delta t},$$

where ΔV — volume of information (in bytes, number of documents or document lines), Δt — the duration of transmission, reception, or processing of a given amount of information.

The mathematical support of AIPMS is a set of mathematical methods, models, algorithms and tools that provide a formalized description, analysis, optimization and decision-making in the processes of managing an object or system based on data processing (Fig. 1).

Here is an adapted table of the mathematical support of AIPMS for the IT department of an enterprise, where the key tasks are data processing, system administration, information security, IT infrastructure support and process optimization in a tabl. 2.

Table 2. Mathematical support of AIPMS for the IT department of the enterprise

Component	Content / description	Examples / Methods for the IT Department
1. Mathematical models	Modeling IT processes, system loads, IT infrastructure	Server availability model, SLA models, network load models
2. Data processing algorithms	Analysis of logs, traffic, user behavior, system monitoring	Log parsing, anomaly detection, data aggregation, log filtering
3. Optimization methods	Improving the efficiency of servers, networks, backup processes	Backup optimization, load balancing, hardware resource planning
4. Mathematical logic	Formalization of security conditions, access rights, automation of solutions	ACL rules, inter-event trigger logic, security conditions in scripts
5. Simulation methods	Virtual reproduction of failure scenarios, cyberattacks, testing IT policies	DDoS attack modeling, redundancy scenarios, scenario testing of access policies
6. Decision theory	Support for upgrade, procurement, software/hardware selection decisions	SWOT analysis of suppliers, AHP for cloud service selection, cost-effectiveness matrix
7. Statistical methods	Performance analysis, incident assessment, failure analysis, trend detection	System response time analysis, MTBF/MTTR, peak hour detection
8. Queuing methods	Analysis of user request handling, support services	Helpdesk queue theory, incident response time optimization, staffing calculation

Based on this table, we can conclude that the specifics of AIPMS in the IT department are primarily:

- Focus on stability, continuity of work, automation of support.
- Large volume of technical logs, metrics, events from various systems.
- High requirements for information security and fault tolerance.

Table 3. Example of a matrix information model (type A)

Source → / Consumer ↓	Supply department	Production department	Human Resources Department	Accounting	Leadership
Supply Department	–	Material supply data	–	Invoices	Supply reports
Production Department	Requests for materials	–	Data on staffing needs	Production reports	Production plan
Human Resources Department	–	Personnel data	–	Accrual information	Human resource reporting
Accounting	Payments to suppliers	Cost calculations	Salary calculations	–	Financial reporting
Management	Purchasing decisions	Production orders	Order	Budgetary guidelines	–

More complex is the so-called matrix information model in a tabl. 3, which is compiled for each subdivision of the automation object [4]. Matrix information model (type A) is a way of presenting information flows in the form of a table (matrix), which displays the relationship between information sources (who generates data) and information consumers (who uses them). In its simplest form:

- matrix rows — information sources (departments, services, systems),
- matrix columns — information users,
- cell — type of information being transmitted (or document/data code).

The model allows:

- to see information flows between departments;
- to identify redundant or duplicate data;
- to optimize document flow and management system.

Methods of dividing the designed AMS into separate functional modules. Designing an AIPMS using the modular principle is associated with the creation of software and information support for the system from a certain set of relatively independent parts or data processing modules that have informational relationships defined in such a way that each module does not receive information about the internal content of other modules, except for that contained in the interface specifications.

The use of the modular design principle allows reducing the design of an AIPMS to the synthesis of functionally independent individual parts (modules), which together perform the specified functions of the system with the required efficiency. In this case, the internal content of the modules may be unknown.

Modular design of AIPMS has the following advantages:

- the process of developing and debugging software and information support for the AIPMS is simplified;
- the subsequent modification of the system is simplified, since modular programs can be improved by simply replacing individual modules that are functionally equivalent, but have the best system characteristics;
- the organization of control programs is improved;
- opportunities arise for implementing advanced methods of development and automation of AMS design.

The implementation of the modular design principle of the AIPMS assumes that each module has the following qualities:

- functionality, i.e. the module must be a functionally complete, maximally independent set of data processing operations; the module is accessed as a single entity, and the values of the parameters called usually reflect the specifics of the module's functions;;
- coherence, i.e. the module must implement a set of interdependent functions that require the same data; part of this data is usually hidden from the system as a whole;
- algorithmic, i.e. the module's functions are grouped on an algorithmic basis;
- sequence, i.e. the module must include several functions that are implemented sequentially, with the output results of one function being the input for another, etc.; in addition, the module's functions are usually interconnected in time.

Different ways of dividing the information and software of the AIPMS into separate modules can be distinguished.:

- functional method — by the number of information and control connections between modules;
- resource method — by the available capabilities of the AIPMS hardware and software;
- elemental method — regarding the use of typical and standard elements of solutions;
- mixed method, which provides the methods listed above.

At the stage of technical design, during which general requirements for the system are formed, functions or procedures performed by the system for processing input information, obtaining intermediate and output results are determined, tasks arise — statements and models for solving the problem of dividing the information-logical model of the AIPMS into functional modules with a minimum number of information connections. The initial data for the task are:

- many different types of input, intermediate and output data,
- many necessary procedures for data conversion.

In this case, the tasks belong to the same level of information processing and management.

The division of the information and software of the AIPMS into modules is reduced in this formulation to the division of a set of tasks (data processing procedures) into disjoint subsets that have a minimum number of common information elements.

Mathematical model for determining the rational structure of a distributed AMS. When developing global AMS, there is a need to determine the rational structure of the system, the distribution of functions implemented by the system between its nodes or levels. The functions assigned to the technical means of the AMS depend on the corresponding mathematical models and methods for their solution, as well as on the possibility of their implementation by a set of technical means. In turn, the set of technical means is selected for a certain range of tasks to be solved, taking into account resource constraints when creating it and taking into account the fact that the tasks must be performed effectively.

It is under the definition of the AMS structure that we will understand the following operations:

- Selection of management tasks that rely on the technical means of the AMS.
- Selection of algorithms for their implementation in the system.
- Distribution of selected tasks by nodes (levels) of the system.
- Determination of the complex of technical means in the nodes of the AIPMS.

The chosen structure is considered rational if the overall efficiency of the AMS being developed is maximized. To formalize the problem, we introduce a number of notations.

Let E — this is a set of management tasks. Each task will be assigned a number (index) $i = 1, 2, \dots, I$. Let us denote M_i a set of algorithms for solving the problem with number i , including solving the problem without using technical means, $M_i = \{k / k = 1, 2, \dots, k_i\}$.

The matrix of connections between the tasks assigned to the designed system is denoted by $A_{ii} = \|\alpha_{ii'}\|$. Task i и i' are considered related if to solve the problem with the number i' information resulting from solving the problem with number i is used i , herewith $\alpha_{ii'}$ makes sense of the average flow of information from the problem with number i to the problem with the number i' . If the tasks are not related, then they are considered α_{ii} .

Let Q — a set of node numbers (levels) of the designed AMS, $Q = \{j / j = 1, 2, \dots, J\}$, a $\|\gamma_{jj'}\|$ matrix of specific costs for transmitting information from a node with number j to the node with the number j' ($\gamma_{jj} = \infty$, a $\gamma_{jj} = 0$).

Let us denote F many numbers of technical equipment, i.e. $m = \{l / l = 1, 2, \dots, L\}$, and m_l — value characterizing the resources of a technical means with the number l . In addition, we introduce the following notations:

a_{ikj} — efficiency of solving the problem with the number i , if it is solved using an algorithm with the number k and is located at node number j ;

m_{ik} — the need for hardware resources (e.g., machine time, memory, etc.) for problem number i if it is solved using algorithm number k ;

c_{lj} — costs of purchasing, installing and operating a technical device with number l , if it is located in a node with number j ;

K — capital costs for the purchase and installation of technical equipment;

K_{ik} — the costs of developing and implementing problem number i if it is solved using algorithm number k .

The term "task" will be understood as a set of interrelated operations for information processing and decision-making in the designed AMS. The selection of these tasks can be carried out, for example, by the expert method, as mentioned earlier. The expert method can also determine the effectiveness of solving tasks a_{ikj} , as well as other data necessary for building the model.

Thus, the task is to maximize the effect of the AMS structure being developed, which is determined by the efficiency of solving management problems in the relevant system nodes.

This effect depends on the choice of the level and algorithm for solving information processing and management tasks, taking into account the costs of information exchange between tasks solved at different levels and the costs of operating the system.

Let us introduce the following variables:

$$x_{ikj} = \begin{cases} 1, & \text{if problem } i \text{ is solved at node number } j \\ & \text{algorithm with number } k (k - \text{th method}), \\ 0, & \text{other} \end{cases}$$

$$x_{lj} = \begin{cases} 1, & \text{if the node with number } j \text{ is equipped with technical means with number } l \\ 0, & \text{other} \end{cases}$$

The task can be written in the following form:

$$\left[\sum_{\{i,k,j,i',j',k'\}} b_{ikj'j'k'} * x_{ikj} * x_{i'j'k'} - \sum_{\{l,j\}} c_{lj} * x_{lj} \right] \rightarrow \max_{\{x_{ikj}, x_{lj}\}}, \quad (1)$$

де

$$b_{ijki'j'k'} = \begin{cases} a_{ikj}, & \text{when } ikj = i'k'j'; \\ -a_{i*i'} * y_{jj'}, & \text{when } ikj \neq i'k'j'. \end{cases} \quad (2)$$

Size $b_{ikj'j'k'}$ determines the effectiveness of solving the problem i , located at node number j , if it is solved in the k -th way, i.e. a_{ikj} if $ikj = i'k'j'$ and is equal to the cost of transmitting information from node number j to node number j' otherwise.

The limitations of the task here are as follows:

- each problem must be solved, and only in one node and in only one way, that is:

$$\sum_{\{k,j\}} x_{ikj} = 1 (i = \overline{1, I}), \quad (3)$$

- total costs for the development of ACS, consisting of the cost of capital expenditures for technical means and for the development and implementation of tasks, should not exceed the given value K , i.e.

$$\sum_{\{l,j\}} k_l * x_{lj} + \sum_{ikj} k_{ik} * x_{ikj} \leq K, \quad (4)$$

- the technical means used have certain resource limitations, i.e.

$$\sum_{\{i,k\}} m_{ik} * x_{ikj} \leq \sum_{\{l\}} m_l * x_{lj}, (j = \overline{1, J}). \quad (5)$$

The formulated problem is a nonlinear mathematical programming problem.

If the technical means are selected in advance and it is known that the problems are independent, then criterion (1) will take the following form:

$$\max \sum_{\{ikj\}} a_{ikj} * x_{ikj}. \quad (6)$$

The restrictions will be as follows:

$$\sum_{\{k,j\}} x_{ikj} = 1 (i = \overline{1, I}); \quad (7)$$

$$\sum_{\{i,k,j\}} k_{ik} * x_{ikj} \leq K_1, \text{ де } K_1 = K - \sum_{\{l,j\}} k_l * x_{lj}; \quad (8)$$

$$\sum_{\{i,k\}} m_{ik} * x_{ikj} \leq m_j, \text{ де } m_j = \sum_l m_l * x_{lj}, \quad (9)$$

Problems (6)—(9) can be reduced to a two-index problem if we introduce the variable x_{fj} . One-to-one correspondence between sets of indices $\{f\}$ и $\{ik\}$ is established by the following relations:

$$f = k + b_i, b_i = \sum_{p=1}^i k_{p-1}, (i = \overline{1, I}; k = \overline{1, k_i}).$$

In this case, the optimization criterion for the task will look like this:

$$\sum_{\{f,j\}} a_{fj} * x_{fj} \rightarrow \max. \quad (10)$$

The restrictions will look like this:

$$\sum_{f=b_i}^{b_{i+1}} x_{fj} = 1; \quad (11)$$

$$\sum_{\{f,j\}} k_f * x_{fj} \leq K_1; \quad (12)$$

$$\sum_{\{f\}} m_f * x_{fj} \leq m_j, j = \overline{1, J}. \quad (13)$$

If the tasks are dependent, then instead of criterion (10), a criterion of this type should be taken:

$$\sum_{\{fj'j'\}} b_{fj'j'} * x_{fj} * x_{f'j'} \rightarrow \max. \quad (14)$$

Conclusions

Thus, to build effective models of modernization of AMS at rocket enterprises, it is proposed to use the modular concept of building AMS. This concept is based on the principle of relative autonomy of each module, which ensures their independent operation. At the same time, the modules can interact with each other, transmitting the necessary information to the general information system, where it is analyzed, processed and sent to the relevant departments for further use.

For a machine-building enterprise, a multi-level modular architecture with clearly defined interaction interfaces is recommended, which ensures flexibility, scalability and efficient data flow (Fig. 2).

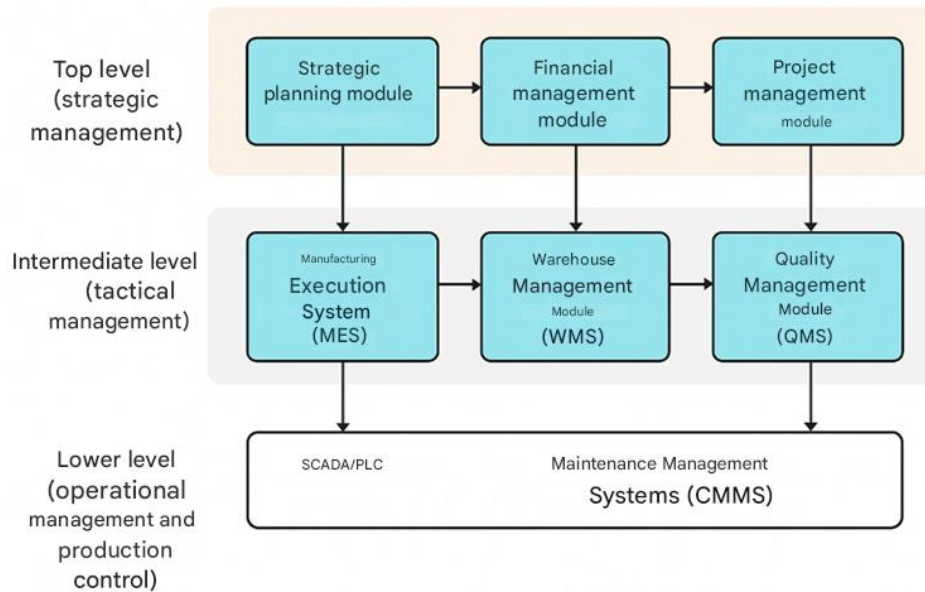


Fig. 2. Recommended scheme of interaction of functional modules of the automated management system of a rocket manufacturing enterprise

The development of an automated management system methodology should be based on the principle of multiple use of information. This approach will contribute to more efficient use of resources required for data collection, and will also help to avoid errors associated with discrepancies in the use of different data for the same parameter.

The use of a modernized document management system will increase the level of automation of processes in the work of the human resources department and the labor and payroll department [5, 6, 10, 11].

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