System models of organization the use of computer equipment for mechanical engineering production

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Abstract. High responsibility and a wide variety of technological, design and project tasks are characteristic features of the machine-building enterprises of the space industry. The required product quality is achieved by automating engineering using computer hardware and software. The paper proposes complex system models for comparative evaluation of the effectiveness of the computer equipment allocation for the company units and controls the efficiency of their operation. The technique of using model of data envelopment analysis, aimed at both the identification of inefficient units and the definition of measures for the rational allocation of computer equipment, is proposed. A linear programming problem is formulated for a preliminary assessment of the use the computer technology in units. A mathematical model for constructing an efficiency practical frontier is proposed. The discrete programming problem for optimal computer equipment allocation is solved. Verification of the obtained solutions of the optimization problem is carried out using a simulation model based on the Petri net. The results of experimental studies are presented that confirm the adequacy and effectiveness of the proposed models.

1. Introduction

The modern engineering enterprise of the space industry has a complex organizational structure, which includes various purposes. It is due to the need for continuous improvement of produced spacecraft at every stage of the life cycle in tough resource constraints. Computer hardware and software (CHS), which are used to automate design, construction, engineering production and other processes, play a decisive role in the effectiveness of such production [1, 2]. Such tools include individual computers, as well as computer systems, including processors, programs, peripheral equipment and communication channels. The complex of hardware and software (CCHS) is the totality of all computing equipment units in the enterprise.

The problem of optimal use of CCHS at industrial enterprises is one of the most important in modern information technologies. The wide range of computer equipment, the high cost and the special role of CCHS in the operation of a large machine-building enterprise determine the number of new management tasks. However, at present, the focus is only on the accounting of the procurement and operation of computer equipment. Effective management of computer technology in machine-building production can be ensured only by using the appropriate automated information system [3, 4].
This article discusses the system models and the solution to the problem of the allocation optimizing and use of computer hardware based on some interrelated tasks and activities for the spacecraft production lifecycle.

2. Organization of the engineering production automation
Determining role in the efficient allocation and use of CHS is a set of tasks and jobs, which implementation requires the use of computer technology. Table 1 presents the kinds of departments and task executed, as well as the types used CHS.

| Enterprise department        | Executed Tasks                  | CHS types                                      |
|------------------------------|---------------------------------|------------------------------------------------|
| Construction                 | Construction work               | Graphic workstation, engineering computer, notebook |
| Design                       | Project Management              | Graphic workstation, engineering computer, notebook, office computer |
| Industrial engineering       | Process engineering             | Graphic workstation, engineering computer, notebook, office computer |
| Test                         | Product testing                 | Graphic workstation, engineering computer, notebook, office computer, specialized terminal |
| Financial and Economic       | Planning and accounting         | Notebook, office computer                      |
| Production                   | Spacecraft manufacturing        | Graphic workstation, engineering computer, notebook, office computer, specialized terminal |
| IT Department                | Automation control              | Server, graphic workstation, engineering computer, notebook, office computer |

In general, the statement and solution of the resource allocation problems in complex technical and network information systems are considered in [5, 6]. At the same time, attention was not paid to the following issues of optimizing the use of CHS resources at the enterprise:

- determination of the composition and CHS relationships located in the enterprise departments;
- task allocation to be performed on the department computing equipment;
- the formation of the CCHS overall structure of the enterprise and the distribution of selected tasks by departments.

3. The set of system models
The information and computing system of the enterprise, designed to ensure all production and business processes, changes its structure, adapting to the tasks performed during the life cycle. The methodology of structural synthesis of an evolving information system, built based on algebraic models, was proposed in [7]. A distinctive feature is the use of ordered algebraic structures, in particular lattices, in the description of an information system.

A CCHS system is called lattice if its model $\Psi_L$ is a triple:

$$
\Psi_L = (\Psi_a, \Psi_b, \rho_0(\Psi_a, \Psi_b)) = (M_a, S_{a1}, \ldots, S_{an}, M_b, S_{b1}, S_{b2}, \rho_0(\Psi_a, \Psi_b)),
$$

where $\Psi_a$ - a model describing the behavior of the system, $\Psi_b$ - a model of the system structure; predicate $\rho_0(\Psi_a, \Psi_b) = 1$ if there is a one-to-one transformation of the models $\Psi_a \rightarrow \Psi_b$ and is equal to zero otherwise, $M_a$ is a set of model $\Psi_a$ elements, $S_{a1}, \ldots, S_{an}$ - arbitrary operations, $M_b$ is a set of model $\Psi_b$ elements, $S_{b1}, S_{b2}$ - binary operations for which the laws of idempotency, associativity, commutativity, and absorption are satisfied.

Therefore, the CCHS behavior model is primarily determined by the set of tasks planned for a certain period. This article proposes a set of system models covering various stages of the life cycle of an enterprise information system. The set of models forms the basis of the CCHS control automation technique (figure 1).
One of the stages of managing a complex system is to evaluate how efficiently the individual departments of the enterprise work. As already noted, the machine-building enterprise space industry has a complex organizational structure. There is the problem of evaluating heterogeneous organizational and structural units. Recently, the DEA methodology (Data Envelopment Analysis) is finding more and more applications [8]. We use it to build models $M_1$ and $M_2$. $M_1$ model is designed for comparative evaluation of the effectiveness of the existing CCHS system in different departments. It is an output-oriented Charnes-Cooper-Rhodes model (CRR-Output) with the constant returns to scale (CRS) [9]. The second $M_2$ model also belongs to DEA and is the Banker-Charnes-Cooper model BCC-Output [10]. This model allows us to build a practical frontier of efficiency, which is a guideline for the further development of computer technology in specific units of the enterprise.

The $M_3$ model is an optimization problem for the distribution of CHS among departments. The $M_4$ model is a simulation environment based on Petri nets for studying the behavior of the obtained information system structure [11]. In the case of detection of conflict situations, critical paths, and other features of the operation of the CCHS, a repeated solution of the optimization problem $M_3$ is carried out. The final decision on the CCHS optimal allocation is the basis for the development of control actions in the decision support system DSS, which is implemented by the $M_5$ model.

### 4. Models for evaluating the CHS effectiveness

The CCR model is presented as follows:

$$
\min_{\theta, \lambda} \theta,
\begin{align*}
-\gamma_i &+ Y \lambda \geq 0, \\
\lambda x_i - X \lambda &\geq 0, \\
\lambda &\geq 0,
\end{align*}
$$

where $\theta$ - integral criterion for the department effectiveness, $X$ is the matrix of inputs, $Y$ is the matrix of outputs, $x_i$ and $y_i$ are the column vector of individual inputs and outputs for the $i$-th department in $X$ and $Y$, respectively. $\lambda$ is a semipositive vector (weighting factor), $\lambda_i \geq 0$, $\forall i = 1, ..., n$.

For each subset of units, the task of determining ways to improve efficiency further can be set. Model $M_2$ P-DEA border makes it possible to form some artificial objects with an efficiency greater than 1. Such artificial objects are interpreted as targets for further improvement of the performance of real units. We consider $N$ analyzed units for which $R$ input parameters and $S$ output parameters are given. The linear fractional programming problem for determining the criterion $J_0$ of the effectiveness of an artificial object is formulated as follows:

$$
J_0 = \max \left( \sum_{r=1}^{R} u_r y_{r0} + u_0 \right) / \left( \sum_{s=1}^{S} v_s x_{s0} \right),
$$

under constraints

$$
\left( \sum_{r=1}^{R} u_r y_{r0} + u_0 \right) / \left( \sum_{s=1}^{S} v_s x_{s0} \right) \leq 1; n = 1, N; \quad \text{or}
$$

$$
\left( \sum_{r=1}^{R} u_r y_{rm} + u_0 \right) / \left( \sum_{s=1}^{S} v_s x_{sm} \right) \leq 1; n = 1, N;
$$

**Figure 1.** The complex system models for managing computing resources in the enterprise.
where $J_n$ – an integral criterion for the effectiveness of the studied object, $x_{r0}, y_{s0}$ – the desired values of the inputs and outputs of the effective artificial object. Constraints (3) correspond to real units, and constraint (4) defines an artificial object. The expert determines the quantity $\delta$. Problem (2) - (4) is solved by the simplex method N times for a system of N linear equations. It should be noted that $x_{rn}, y_{sn}$ – are constant coefficients specified in the matrices $X$ and $Y$ and $u_r, v_s \geq 0, \forall r, \forall s$ – the unknown weight coefficients, which are the desired solution to the system of equations (2) - (4).

5. Optimization model $M_3$ for CCHS allocation

Suppose that the enterprise has a set of department $P_j, j = \overline{1, J}$, equipped with computers and software CHS. The set of computer tool types is equal to $Q = \{q_m\}, m = \overline{1, I^{T3}}$, where $I^{T3}$ is the number of all computer types included in the CHS complex. The type of computing tool $q_m$ can have a set of different configurations $D_{mn}, n = \overline{1, I_m}$, where $I_m$ is the number of possible configurations of this type of CHS. Each configuration is described by a vector of parameters $(d_{m,n,1}, ..., d_{m,n,L(n)})$, where $L(n)$ is the number of parameters. The sample of CHS is a separate computer tool located in the department.

Following the content of tasks to be solved, experts determine specific types of CHS and the sample number of each type. Then we have for the unit $j$ the set of assigned tasks $Z_j = \{z_k\}, k \in I^k_j$, where $I^k_j$ - the corresponding index set. For each configuration of CHS of the $m$th type, an $H_{int}$ resource is specified, that is, the number of samples available for allocation. Moreover, we denote $h_{k,jmn}$ - the number of samples of the $m$th type with $n$th configuration for unit $j$ assigned to task $k$.

We introduce the following notation:

- $C_{jmn}$ - the cost of $n$th configuration CHS samples of the $m$th type in the $j$th department;
- $C_{jkmn}$ - software costs for solving the $k$th task in the $j$th department in the presence of $m$th type CHS $n$th configuration;
- $C^E_{jkmn}$ - operating costs for solving the $k$th task in the $j$th department in the presence of the $m$th type CHS $n$th configuration;
- $P_{jmn}$ - the reliability of the technical equipment.

The boolean optimization variable is defined as:

$$x_{jkmn} = \begin{cases} 1 & \text{if the $n$th configuration is selected to solve the $k$th task in the $j$th department for sample of the $m$th type CHS} \\ 0 & \text{otherwise.} \end{cases}$$

Consider the problem of minimizing the CCHS cost in solving a given set $Z$ of tasks. Then the objective function $F$ is as follows:

$$F = \min \left\{ C + C^E \right\},$$

where $C$ - the capital cost of CCHS, $C^E$ - operating costs of CCHS.

The components of the objective function are defined as follows:

$$C + C^E = \sum_{k=1}^{K} \sum_{j=1}^{J} \sum_{m,n} \left( h_{jkmn} (C_{jkmn} + C^Z_{jkmn}) + C^E_{jkmn} \right) x_{jkmn}, \; \forall m,n,$$
Constraints for the problem (5):
1. The uniqueness of the choice of the CHS variant for the \( k \)-th task
   \[
   \sum_{k=1}^{K} x_{j_{k_{mn}}} = 1, \quad \forall m, n,
   \]  
   \( \text{(7)} \)
2. The uniqueness of the selection of a sample with a given configuration for the given type CHS
   \[
   \sum_{m,n} x_{j_{k_{mn}}} = 1, \quad k = 1, K; \quad j = 1, J,
   \]  
   \( \text{(8)} \)
3. The uniqueness of the assignment of tasks to the department
   \[
   I_{\alpha} \cap I_{\beta} = \emptyset, \quad \forall \alpha, \beta \in \{1, \ldots, J\},
   \]  
   \( \text{(9)} \)
4. Correspondence of the CHS configuration parameters to the given ranges of values when solving the task \( z_k \)
   \[
   d_{\text{min}} \leq d_{\text{min}} x_{j_{k_{mn}}} \leq d_{\text{max}}, \quad \forall k, j, m, n, \quad v = 1, L_{\text{max}},
   \]  
   \( \text{(10)} \)
5. The resources of CHS samples constraint
   \[
   \sum_{k,j} h_{j_{k_{mn}}} \leq H_{mn}; \quad k = 1, K; \quad j = 1, J; \quad \forall m, n,
   \]  
   \( \text{(11)} \)

where \( H_{mn} \) is the number of samples with the \( m \)th type and \( n \)th configuration, that can be assigned to the department.

The solution of problem (5) with constraints (7) - (11) was carried out using the branch-and-bound procedure.

6. CCHS life cycle simulation model

The solution to the optimization problem determines the structure of the CCHS among departments. As noted earlier, the verification of such an allocation is conducted using the simulation model \( M_k \). We assume that in the project management system was constructed Gantt chart for executed tasks. Therefore critical paths have been found, and for each task \( z_i \in G \), the time \( \tau_{i} \) of the task and the moments of its early and late start and end \( \tau_{i, \text{run}}, \tau_{i, \text{poof}}, \tau_{i, \text{run}}, \tau_{i, \text{poof}} \) have been calculated.

To analyze the dynamics of the processes in the network model should bring it to the bipartite representation of Petri nets. In the Gantt chart, task \( z_i \) is characterized by the executed time, given moments of the beginning and end of the task. Besides, it is important to link the tasks to the calendar schedule time to take account of public holidays and overtime. We will compare the elementary fragments of the Petri net to the time elements of the task (see figure 2).

In figure 2, an elementary fragment of a Petri net consists of the following components: transitions that simulate actions with a task and places that describe conditions and resources.

In figure 2, the following notation is used:
- \( t_i \) - a transition simulating the process of completing a task \( z_i \) with a fire time delay \( \tau_i \);
- \( t_i^H, t_i^K \) - initial and final transitions for which the fire time is either equal to zero or depend on one of the values \( t_i^H, t_i^K, t_i^H, t_i^K, t_i^H, t_i^K, t_i^H, t_i^K \);
- \( x_{1_{im}}, \ldots, x_{in} \) - input places that determine the conditions for task starting;
- \( y_{1_{im}}, \ldots, y_{in} \) - output places that are input to other fragments of the model and allowing the start of their execution.
6

\( x_i^K \) - external input place of the final transition \( t_i^K \); \( y_i^H \) - external output place of the initial transition \( t_i^H \).

Full Petri net is used to simulate the performance of production tasks in departments and analysis of the use of computer technology.

\[ 
\begin{align*}
\tau_i & \\
\tau_{i, ran} & \\
\tau_{i, pozd} & \\
\end{align*} \]

\[ 
\begin{align*}
x_{l, t} & \\
m_{i, t} & \\
\tau_i & \\
\end{align*} \]

\[ 
\begin{align*}
x^K_i & \\
y^K_i & \\
x^K_i & \\
\end{align*} \]

\[ 
\begin{align*}
x^H_i & \\
y^H_i & \\
x^H_i & \\
\end{align*} \]

Figure 2. Convert the Gantt chart in the Petri net.

7. Experimental results

Test solutions for \( M_1 \) and \( M_2 \) models were performed for ten units (DMU): two construction departments \( C1 - C2 \), three design \( D1 - D3 \) and five production departments \( P1 - P5 \). For this, the PIM-DEASoft-V3.0 software was used [12]. Baseline data for the analysis are presented in table 2.

Table 2. Baseline data for DEA-analysis.

| DMU | \( X1 \) | \( X2 \) | \( X3 \) | \( X4 \) | \( Y1 \) | \( Y2 \) | \( Y3 \) |
|-----|---------|---------|---------|---------|--------|--------|--------|
| C1  | 44      | 52      | 7212.8  | 7       | 12     | 0.80   | 88     |
| C2  | 29      | 27      | 4761.6  | 5       | 6      | 0.79   | 94     |
| D1  | 51      | 54      | 7705.6  | 15      | 13     | 0.80   | 87     |
| D2  | 81      | 93      | 11891.2 | 12      | 22     | 0.79   | 78     |
| D3  | 54      | 59      | 8889.6  | 16      | 14     | 0.80   | 86     |
| P1  | 430     | 191     | 13126.4 | 25      | 45     | 0.70   | 55     |
| P2  | 469     | 155     | 6444    | 21      | 37     | 0.72   | 63     |
| P3  | 244     | 76      | 1964.8  | 19      | 18     | 0.69   | 82     |
| P4  | 218     | 80      | 2744    | 20      | 19     | 0.66   | 81     |
| P5  | 206     | 92      | 4913.6  | 24      | 22     | 0.67   | 78     |

Input variables: \( X1 \) - number of employees in the unit; \( X2 \) is the CHS number in the unit; \( X3 \) - CHS performance (GFlops); \( X4 \) - the volume of tasks performed in the unit. Output variables: \( Y1 \) - the CHS downtime ratio per month, (%); \( Y2 \) is the CHS reliability; \( Y3 \) - the coefficient of completed tasks, (%). The examples of the obtained efficiency boundaries are shown in figure 3.

The most effective unit is the construction department C2. Close to the efficiency boundary are also construction and design units C1, D1, and D3. The worst performance indicators have production units P1 and P2. At the same time, production departments P2, P3 and P4 form a group having performance indicators close to the maximum value.

The program PIM-DEASoft-V.3.0 has tools for determining such changes in the input parameters of inefficient units that will transfer them to the efficiency boundary. To clarify the necessary changes, only a subset of units of the same type may be considered. As an example, figures 4 and figure 5 show graphs of efficiency boundaries for production departments P1 – P5 only. As already noted, the worst units are P1 and P2. The analysis of the CHS in the corresponding departments P1 and P2 showed that a large number of outdated computers are used, and this led to significant downtime and failure to complete tasks on time. In order to transfer to the efficiency boundary, it is necessary to change the number of input parameters. For unit P1 this is the target changes: \( \delta X1=-42\%; \delta X2=-60\%; \delta X4=-22\% \). For unit P2, this is the target changes: \( \delta X1=-46\%; \delta X2=-49\%; \delta X4=-5\% \). This will provide an increase in output parameters \( Y1 \) and \( Y3 \) to 83% and 86%, respectively.
The solution to the optimization problem M3 at the stage of experiments was carried out for departments of the Design Division. This is since such tasks require the use of several types of CHS: graphic, engineering, office, server. Information about the types and configurations of computers are in the CCHS database.

**Table 3.** Test solution results,

|                      | The cost of CHS, million RUB | Operating cost, million RUB |
|----------------------|------------------------------|-----------------------------|
|                      | 2017 yr | 2018 yr | 2017 yr | 2018 yr |
| Actual CHS allocation| 12.1    | 14.6    | 3.16    | 3.89    |
| Optimal solution     | 11.37   | 13.28   | 2.86    | 3.41    |
| Economical Effect    | 6%      | 9%      | 9.5%    | 12.3%   |
Dimensions of the problem for the case under consideration: the unit number in the Design Division is 5; the number of design tasks - 50; the CHS type number - 7; the number of different configurations of CHS is 45. In the process of research, a test solution was made for the periods 2017 – 2018 years to compare with the actual CHS allocation at the enterprise during these periods (see table 3). It is seen that the use of the proposed methodology would reduce the average capital cost by 7.5% and operating costs by 11%.

8. Conclusion
The proposed set of system models underlies the construction of an automated computer management system for a machine-building enterprise. Further development of the proposed approach lies in the path of integration with CAD / CAM and PDM systems. Thus, we achieve rapid changes in the composition and characteristics of computer hardware and software when changing market conditions and the release of new technology.

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