Optimization-simulation approach to the computational resource allocation in a mechanical engineering enterprise

R A Uchaikin and S P Orlov

Samara State Technical University, 244 Molodogvardeiskaia str., Samara, 443100, Russian Federation

E-mail: orlovsp1946@gmail.com

Abstract. The complexity of modern engineering production requires the use of computer technology in design and technological processes. The problem is the need to efficiently distribute computers and software between departments in the enterprise. The article proposes an optimization-simulation approach to solving the problem of computer equipment allocation. It consists in an iterative procedure for solving an optimization problem and verifying the obtained solutions on simulation models. A discrete optimization problem with Boolean variables for assigning computers to tasks in departments is formulated. It is proposed to carry out a simulation model in the form of a timed Petri net. A graphical model of computer equipment repair and maintenance in the process of performing tasks is presented. A basic elementary timed Petri net is constructed, which is used to build a general simulation model. The properties of the basic simulation model are considered.

1. Introduction

The feature of the mechanical engineering enterprise of aviation and space technology is the presence of advanced block design and engineering departments. Their tasks include both the creation of samples of new products and the development of technological production processes. Therefore, the complexity of design tasks determines the use of powerful computers and advanced information technology. Costs for the purchase and maintenance of computer hardware and software are continually growing. Consequently, critical tasks are to optimize the allocation of computers and network equipment at departments of a mechanical engineering enterprise, and to allow effective routine maintenance [1, 2].

There are known works in which complex network models are proposed to study the influence of the communication structure on the sharing of resources in Systems of Systems (SoSs) [3, 4]. These approaches focus on socio-technical systems. In other articles, in most cases, attention is paid only to the financial aspect of providing production with the use computer equipment [5].

In many mechanical engineering enterprises, decisions on the distribution of computers between the design departments are made without taking into account the production program and specific schedules of design processes. The redistribution of the released computing resources is not considered. It is necessary to develop a systematic approach to the use of new types of computer resources: cloud technologies, virtual networks, data storage. The task is complicated by a high degree of uncertainty when taking into account the factors affecting the effective use of computer equipment [6, 7].
The authors have previously considered the formulation and solution of the discrete optimization problem in the allocation of computer equipment in the article [8]. We have proposed a complex of system models, which include:

- an optimization model in the form of a discrete programming problem,
- a discrete event simulation model,
- a DEA-based assessment model.

In this article, within the framework of the problem to be solved, we propose to use the optimization-simulation approach developed by A.D. Tsivirun [9, 10]. It is based on a joint analysis of the optimization and simulation models of the complex system. We will consider a complex organizational and technical system, which includes computer hardware and software in the divisions of the enterprise, and an activity network for the execution of design tasks.

2. Optimization-simulation approach

According to [8], the optimization problem of allocating computing resources has the form:

$$F = \min \left\{ \sum_{j=1}^{J} C_j(x_j) + C_j^E(x_j) \right\}, \quad x_j \in \{0,1\}, \quad j = 1, J,$$

under constraints

$$\sum_{j} f_i(x_j) \leq 0, \quad j \in J_i, \quad i = 1, K,$$

where $x_j$ is the Boolean optimization variable, specifying the computer equipment distribution $D(x_j)$, $K$ is the number of constrains, $J$ – the number of computer units, $J_i$ - index sets of computer units for $K$th constrain and $|J_i| \leq J$, $C_j$ - capital costs of computer equipment units, $C_j^E$ - operating costs. Variable $x_j = 1$, if the unit is assigned to execute some task in a department.

The complexity of solving this problem is associated with the discrete nature of data processing, which leads to the use of algorithmic constraints. In particular, one of the constraints in (2) prohibits assigning one task to several departments. This constraint is written as a logical expression. According to the optimization-simulation approach, problem (1) - (2) can be solved only with analytical constraints in the form of mathematical expressions such as "equality - inequality." Then the rest of the algorithmic constraints are checked on the simulation model.

However, when planning resource allocation over a long period, the solution (1) – (2) must be consistent with the activity network for the design task execution. A formal description of project $Q$ is represented as three-tuple:

$$Q = (Z_p, T_p, C_p),$$

where $Z_p = \{z_1, ..., z_{N_p}\}$ - project activities (tasks); $T_p = \{\tau_1, ..., \tau_{N_p}\}$ - a set of the task execution time $\tau_k$; $C_p = \{c_1, ..., c_{N_p}\}$ - the cost of performing each activity $z_k$.

The initial planning of the project defines a Gantt chart $G$ that sets the timing and sequence of the project:

$$G = (Z_p, T_p, V_G),$$

where $V_G$ - connections between activities.
Further, the critical paths in the Gantt chart are identified and parameters for each activity $z_i \in G$ are calculated: the earliest start time (ES) $t^{ES}_i$, the latest start time (LS) $t^{LS}_i$, the earliest finish (EF) $t^{EF}_i$, and the latest finish time (LF) $t^{LF}_i$.

Thus, after receiving the decision $D$ optimization problem $OM$ and using a Gantt chart $G$, a mapping $(G, D) \rightarrow SM$ into the simulation model $SM$ should be found. Then the optimization-simulation procedure is iterative and has the form:

$$OM_1 \rightarrow SM_1 \rightarrow OM_2 \rightarrow SM_2 \rightarrow \ldots \rightarrow OM_N \rightarrow SM_N.$$ 

3. Timed Petri Nets to simulate the performance of project activities in the departments

The choice of a simulation model as a component of the optimization-simulation procedure is essential for an adequate description of the design process. We will consider a Petri net

$$N = (P, T, W, \omega, M_0),$$

where $P$ is the finite set of places, $T$ is the finite set of transitions, $W \subseteq (P \times T) \cup (T \times P)$ is the incidence relation, $\omega: W \rightarrow N$ is the weight function on the arcs, and $M_0 : P \rightarrow N_0$ is the initial marking of the net.

A timed Petri net is a six-tuple

$$N = (P, T, W, \omega, M_0, D),$$

where $N = (P, T, W, \omega, M_0)$ is a marked Petri net, $D : T \rightarrow N_0$ is a firing time function that assigns a non-negative number to each transition on the net.

There is an advantage of a timed Petri net, which consists in the fact that some conclusions about the modeled process can be done on the net structure without directly carrying out the transition firing simulation.

Among other advantages, that a timed Petri net is a clear definition of the options for the activity interaction. Figure 1 shows the basic blocks of the net for all cases of the relationship between activities. An elementary fragment of a Petri net contains: $t_j$ - a transition that simulates the process of performing a task $z_j \in G$ with operation duration $\tau_j$; $t^{S}_j, t^{F}_j$ - the starting and finishing transitions whose firing interval equal to zero, or dependent on one of the values $t^{ES}_j, t^{LS}_j, t^{EF}_j, t^{LF}_j$.

![Figure 1. Basic block of the Petri net model: a) "Finish - Start"; b) "Start-Start"; c) "Finish-Finish"; d) "Start-Finish".](image-url)

The components of the Gantt chart or PERT chart are replaced with basic blocks, and the result is an assembled timed Petri net for the project.
The execution of the simulation model is the procedure of sequential-parallel transition firing with given initial markings and time parameters of network. Statistical testing allows analyzing the execution of critical paths, identifying critical activities and the presence of conflicts in the schedule. The probabilistic nature of the dynamics of project execution is realized in the stochastic Petri net model by comparing the probability distribution laws of events to the corresponding transitions or positions.

4. Example of a simulation model for the computer equipment distribution

Let there be a set of six computers (units) $u_1$, ..., $u_6$, which are assigned to the project with the five activities $z_1$, ..., $z_5$. Suppose that the optimization model $OM$ was solved and the Boolean vector $X = (1, 1, 1, 1, 1, 0)$ of computer distribution was obtained. It can be seen that unit $u_6$ is in reserve. Figure 2 presents a graph model showing the project schedule and computer equipment allocation.

A critical situation should be noted.

- Unit $u_2$ fails and is taken out of service and sent to the Repair (arc $Out$). Then the backup unit $u_6$ transferred to the department for the activity $z_2$ (arc $Rp$). Unit $u_2$ after the repair is transferred to the Reserve (arc $Rt$).
- According to the maintenance schedule, unit $u_3$ is taken out to the Maintenance (arc $Out$). In this case, another computer must be used to prevent stopping task $z_3$. However, there are currently no free computers in reserve. Then unit $u_4$ is used for task $z_3$ (arc $Rp$), provided that task $z_4$ has not started yet. A unit $u_3$ is returned from the Maintenance and, accordingly, the unit $u_4$ returns to perform activity $z_4$.

Such a scheme for the distribution of computer resources will work correctly under certain time conditions. For example, if there is a delay in servicing computer $u_3$, task $z_4$ will not receive the computer $u_4$ at the right time. It could be used $u_2$, but the repair delay may prevent it.

Thus, given an example shows that with a complicated network schedule and a large number of computers, conflict situations are possible.

Let us introduce the following algorithmic constraints in the graph model in figure 2.
The "Failure" and "Maintenance" events do not occur for any computer $u_k$ at the same time, i.e. $\forall k (t^F_k \neq t^M_k)$.

The maintenance time interval for any computer $u_k$ should not overlap with the time interval for its repair

$$\forall k (\{t^R_p, t^M_p\} \cap \{t^M_k, t^M_k\} = \emptyset).$$

Let's put in correspondence to each task in the graph model a fragment of a timed Petri net, which describes the transfer of a computer for repair or maintenance (figure 3). After the end of these operations, the computer is placed in a position of "Reserve".

![Figure 3. The timed Petri net fragment for activities in the graph model (figure 2).](image)

The computer can be returned from this position to perform such a task for which its configuration is appropriate. The set of fragments makes up a complete Petri net to simulate the process of performing tasks and repairing and maintaining units. The resulting general Petri net can be easily converted into a parallel O-net. The analysis of the O-network structure allows one to draw some conclusions about the properties of the processes in it without imitation.

In particular, for a K-dense O-network, the reachability graph $R$ is a distributive lattice. Then the verification of the K-density of the network is reduced to checking the distributivity of $R$. The known theorem of lattice theory implies that a lattice is distributive if and only if it does not contain sublattices isomorphic to the "diamond lattice" $M_3$ and "pentagon lattice" $N_5$. An algorithm for finding such sublattices was proposed in [14]. If the reachability graph $R$ is not distributive, this indicates possible conflicts in the simulation model of the information system.

5. Results

The proposed approach makes it possible to plan the effective use of computer equipment at different periods of time, taking into account the repair and maintenance of equipment. Creation of a reserve with a reasonable number of computers configuration leads to an effective use of funds.

The proposed model for the distribution of computer equipment can be detailed by introducing various computer configurations into consideration. Then we will consider models on colored Petri nets (CPN) and use software tools [15] for analysis. Further development of the work is planned in the direction associated with using the capabilities of private cloud technologies. This will reduce unproductive computer downtime in departments of the enterprise.
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