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A Digital Tool for Capacity Load Optimization in Spatially Distributed Production Systems

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Abstract. Improving the efficiency of the use of fixed assets is one of the priority tasks facing modern machine-building enterprises. It is particularly relevant for spatially distributed holding structures that have emerged in the process of reforming the domestic machine-building complex and include enterprises that produce similar products and have similar types of production assets.

The purpose of the paper is to develop on the basis of mathematical modeling tools for solving problems of optimization of industrial enterprises' fixed assets development and use.

An approach to optimize the fixed assets load in a spatially distributed production system is proposed. A mathematical model in the form of a linear programming production and transport optimization problem is formulated, which allows one to find optimal production capacity load modes in a wide range of conditions. The optimal regimes of this model are studied. It is shown that in certain cases the capacity use optimization can be the only way to ensure the timely fulfillment of the customers' orders

The use of modern digital technologies that provide dynamic forecasting and optimization of the production capacity allows to achieve a number of improvements, including the production time and cost reduction and the growth in efficiently used production means.

1. Introduction

An important effect of digital transformation of manufacturing enterprises is an increase in the efficiency of their assets, including fixed assets [1]. This effect is particularly relevant for holding structures that have emerged as a result of reforming of high-tech branches of mechanical engineering (aircraft, shipbuilding, and the military-industrial complex) and include enterprises producing similar products and having similar types of production assets [2, 3].

In this paper, we consider an approach to solving problems of optimizing the fixed assets load in a spatially distributed production system based on mathematical modeling. A mathematical model in the form of a production and transport optimization problem is described, which allows us to find optimal production capacity load modes in a wide range of conditions.

2. Relevance

Large manufacturing enterprises with a distributed territorial structure have not yet been able to create flexible production plans due to the complexity of the information about the state and load of all production capacities, their compatibility and complementarity [4]. However, the use of modern



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digital technologies that provide dynamic forecasting and optimization of such systems' state allows achieving a number of improvements, including reducing the production time and cost and increasing efficiency of the production capacity use [5, 6]. A higher capacity utilization will contribute to profit growth and the financial stability of both individual enterprises and the holding structure as a whole [7].

Dynamic optimization of fixed assets utilization should take into account the modes of their operation and maintenance, the stage of the life cycle, individual characteristics, as well as local normative documents and standards that regulate these processes [8, 9].

As a rule, the composition of fixed assets of a large industrial enterprise is heterogeneous. It is characterized by a large number of possible states, the presence of resources shared during the operation, and random factors affecting the production [10].

In addition, the improvement of technologies leads to the joint use of fixed assets of different generations [11, 12]. As a result, the production process at the enterprise should be adjusted to the operation of fixed assets of new generations [13]. Additional problems in the organization of fixed assets operation, maintenance and repair arise in the context of sanctions, as well as in the implementation of import substitution programs [14].

All these factors increase the complexity of the problem of assessing the current state and potential utilization of fixed assets and require the use of computational models and methods to solve it.

3. Problem statement

Formally, the problem of optimizing production capacity in a spatially distributed production system can be represented as a production and transport problem of a specific structure. These problems include a wide class of tasks that involve simultaneous optimization of production capacity utilization, as well as transport flows in a spatially distributed system. Such problems were considered in [15, 16] for evaluating the effectiveness of large-scale investment projects.

The peculiar feature of the systems considered here is that the object of modeling is not an investment project, but a set of business processes running in a spatially distributed system of enterprises of high-tech industries. This type of enterprises is characterized by a number of specific features, namely [17]:

- long production cycle of high-tech products, as a result of which the same capacity can be used repeatedly at different stages of the production process;
- irregular orders due to the high cost and specificity of products, as well as a dependence on socio-political conditions;
- the oligopolistic nature of competition and the network structure of markets where high-tech enterprises operate, which causes a multiplicative effect of changes in production volumes.

In [18] it is noted that high-tech enterprises of the defense industry are significant sources of external effects in the social sphere. As a result, it is also necessary to take into account the social consequences of management decisions when planning their operational activities.

In [19] it is also noted that maintaining the competition in the markets of high-tech products requires that competing manufacturers have free production capacity, which maintenance leads to additional costs.

Let us consider a mathematical model for optimizing the capacity of a spatially distributed production system, which takes into account these factors.

4. The model

Consider a production system consisting of N enterprises (nodes) connected by a transport network. Each enterprise produces L types of products using K types of production capacity. The output can be used either as an intermediate product for the other goods and services production, or as a final product that goes to consumers outside the system. The amount of end-user orders for the l -th product placed in the n -th node is denoted by $c_l^n(t)$. The amount of the orders placed by the node m in the node

n for the l -th product is denoted by $r_i^{nm}(t)$. This value also represents the volume of transportation of the l -th product from the node n to the node m at the time t .

To simplify the model, we assume that production processes are the same in all nodes, and are described by two matrices: the capacity utilization matrix S^l and the direct cost matrix A^l . The matrix S^l represents the amount of production capacity of the k -th type used to produce a unit of the l -th good.

The amount of the production capacity installed in the n -th node at the time t is determined by the following equation:

$$M_k^n(t+1) = M_k^n(t) + M_k^{n+}(t) - M_k^{n-}(t), \quad M_k^n(0) = \text{const}, \quad (1)$$

where $M_k^{n+}(t)$, $M_k^{n-}(t)$ – commissioning and decommissioning of the k -th production capacity in the n -th node, respectively.

The elements of A^l represent the quantity of the m -th product used in the period t to produce a unit of the l -th product. The stock of the l -th product in the n -th node at the time t is

$$\begin{aligned} Z_l^n(t+1) = & Z_l^n(t) + x_l^n(t) - \sum_{m=1}^L \sum_{\tau=1}^{T_m} a_{l\tau}^m x_m^n(t+\tau) - \\ & - \sum_{n'=1}^N r_l^{nn'}(t) + \sum_{n'=1}^N r_l^{n'n}(t) - c_l^n(t), \end{aligned} \quad (2)$$

$$Z_l^n(0) = \text{const}.$$

Here $x_l^n(t)$ is the l -th product output in the node n , $\sum_{m=1}^L \sum_{\tau=1}^{T_m} a_{l\tau}^m x_m^n(t+\tau)$ – the intermediate consumption of the l -th product in the node n , $\sum_{n'=1}^N r_l^{nn'}(t)$, $\sum_{n'=1}^N r_l^{n'n}(t)$ – the total amounts sent from the node n to other enterprises and delivered to the node n from other enterprises, respectively, $c_l^n(t)$ is the volume of final consumption of the l -th product.

All nodes of the system should meet the capacity restriction:

$$\sum_{l=1}^L s_{lk}^{\tau} x_l^{\tau} \leq M_k^n(\tau), \quad (3)$$

as well as resources constraints:

$$Z_l^{\tau} \geq 0. \quad (4)$$

For the system (1) – (4), various criteria for optimal mode of production capacity use can be suggested. The most common one is economic efficiency in the form of profit maximization:

$$\Pi_n(t) = \sum_{l=1}^L (p_l(t) - v_l^n) c_l^n(t) - \varphi^n, \quad (5)$$

where $p_l(t)$ is the market price of the l -th product, v_l^n is the unit cost of the l -th product at the node n , and φ^n is fixed cost.

Under such optimality criterion the problem of maximizing the system's profit at the planning interval $[0, T]$ takes the form

$$\Pi = \sum_{t=1}^T \sum_{n=1}^N \Pi_n(t) \rightarrow \max. \quad (6)$$

Under given terms of external customers' orders, the problem of production costs minimization may be considered instead of (6). Let us estimate the relevant components of production costs.

To estimate the transport costs, consider the linear model, in which they are proportional to the amount of products being transported. Denote by θ^l the matrix representing the cost of transportation of a unit of the l -th product between nodes in the system. Then the total transport costs at the time t will be

$$\Theta(t) = \sum_{l=1}^L \sum_{n=1}^N \sum_{n'=1}^N \theta_{nn'}^l r_l^{nn'}(t). \quad (7)$$

The storage costs are also estimated using a linear model, in which the total cost of storing products in all nodes of the system is as follows:

$$\Xi(t) = \sum_{n=1}^N \sum_{l=1}^L \xi_l^n Z_l^n(t), \quad (8)$$

where ξ_l^n is the cost of storing a unit of the l -th product in the n -th node.

Then the problem of the total logistics costs minimization is as follows:

$$F = \sum_{t=1}^T (\Theta(t) + \Xi(t)) \rightarrow \min_{\{x,r\}}, \quad (9)$$

where T is the planning horizon; x is the output of all products in the system at $t = 1, \dots, T$; r is the amount of transportation of all types of products at $t = 1, \dots, T$.

The criterion (9) can be combined with other goals (e.g., social, ecological, safety etc.) in order to reflect the requirements of different stakeholders to the optimal regime of the capacity utilization. In this case, the corresponding optimization problem becomes multi-criteria, resulting in a set of Pareto-optimal modes [21].

5. Practical application

As an example, consider a system with $N = 2$ nodes, in which $l = 2$ types of goods are produced using $K = 2$ types of capacities. Diagrams of production processes are shown in Fig. 1. They represent a compact record of the capacity utilization matrix S^l and the dynamic direct cost matrix A^l .

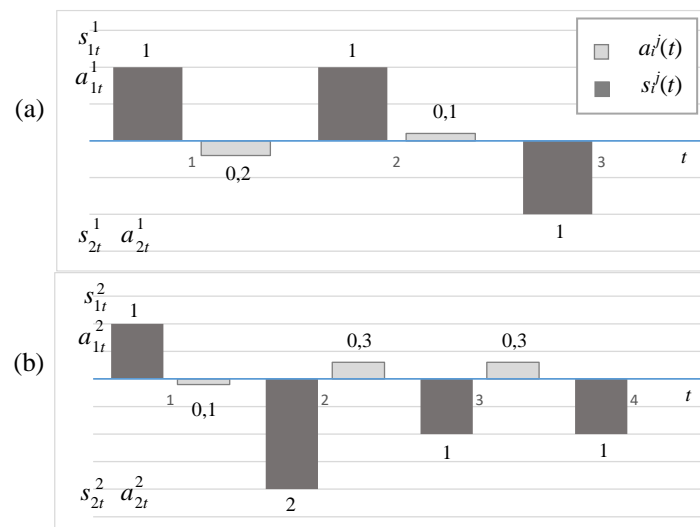


Figure 1. Diagrams of production processes of the first (a) and the second (b) type of product.

Consider the problem of minimizing transport and logistics costs with criterion (9). It is a linear programming problem that can be effectively solved using the simplex method [15]. As a result of analysis, three possible modes of operation were identified.

1. *Capacity load optimizing is not required.* The production capacities and stocks available at each node are sufficient to complete the orders within the established period. This mode is characterized by excess production capacity and stock to fulfill planned orders at each node.

2. *Capacity load optimizing lowers production and transportation costs.* In this case, the capacity and the stock available at each node allows completing orders on time. However, optimizing capacity utilization lowers total transportation and storage costs as compared to the initial mode.

3. *Capacity optimizing is a necessary condition for the customers' orders execution.* This mode is characterized by insufficient capacity or stock available in individual nodes for timely fulfillment of orders. In this regard, timely execution of orders by enterprises is possible only as a result of optimizing the use of capacity.

Thus, the developed approach offers a universal tool for solving problems of optimal use of production capacity in spatially distributed systems of enterprises. As shown above, it can be expanded and supplemented to take into account the specific features of the production process and the goals of various stakeholders.

6. Conclusion

Digital transformation of industry reveals the need in tools that provide a flexible real-time management of production assets of enterprises and their systems. The use of such tools should take into account the heterogeneous information that reflects both the technical aspects of the fixed assets' fleet and the economic characteristics of the enterprise's economic activity.

In this paper a mathematical model of the production capacity utilization is formulated, which can be used to solve the problem of capacity load optimization in spatially distributed production systems.

The optimal regimes of this model are studied. It is shown that in certain cases the capacity use optimization can be the only way to ensure the timely fulfillment of the customers' orders.

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