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MODELING PROCESSES FOR PREPARING HIGH-TECH PRODUCTION USING THE VIRTUAL ENTERPRISE CONCEPT

The subject *of this research involves the processes for preparing high-tech production. Preparation for production requires organizational, economic, and technological actions that guarantee the transition to serial production, considering the requirements of Industry 5.0 and the use of scientific and technological innovations. Preparation is carried out with the aim of the effective development of a new serial product, the introduction of modern robotic equipment and information technologies, including the Internet of Things, and the development of new forms of production organization. In conditions of economic instability and global competition, there is a need to reduce the stage of preparation for production and the life cycle of creating a high-tech product. A new complex product can contain various types of components: reusable components, combined components that contain elements of innovation, as well as new innovative components that ensure its competitiveness. For each component, it is necessary to plan the production preparation stage. Among modern approaches to organizing production, the creation of a virtual enterprise is relevant, within the framework of which enterprises are united to implement a specific project for manufacturing high-tech products.* ***Tasks:*** *to build a structure of a multi-level model of functional modules for preparing the production of high-tech products; develop a model for selecting partners of a virtual enterprise for fulfilling a portfolio of orders for the creation of high-tech products; develop a model for selecting suppliers of a virtual enterprise; develop an agent model for assessing the risk of creating a virtual enterprise; build a multi-level multi-agent model for creating an organizational structure of a virtual high-tech enterprise; build a scheme of applied information technology for preparing the production of high-tech products based on a virtual enterprise. The purpose of the publication is to study the stage of preparing the production of complex technical products to synthesize the architecture of a multi-level component model of the product by creating functional modules for preparing the production of high-tech products, as well as to develop a set of mathematical models that ensure the formation of a portfolio of orders and the selection of performers for its implementation; selection of suppliers for fulfilling orders by manufacturing enterprises; risk assessment of a virtual enterprise project. The mathematical models and methods used are: system analysis, optimization using integer programming, multi-criteria optimization, and expert evaluation. The following* ***results*** *were obtained: the study proposes a multi-level multi-agent model of the organizational structure of a virtual instrument-making enterprise and creates an applied information technology for preparing the production of high-tech products based on the models proposed in the publication.* ***Conclusions.*** *The main contribution and scientific novelty of the results obtained is in reducing costs, risks and the duration of preparation for the production of high-tech products by using the concept of a virtual enterprise for the preparation of production by implementing applied information technology, based on a developed set of mathematical models that ensure the formation of a portfolio of orders and the selection of performers for its implementation; selection of suppliers for the fulfillment of orders by manufacturing enterprises; risk assessment of the virtual enterprise project. Production preparation processes are carried out within the framework of building a virtual enterprise, the rational organization of which helps to reduce the duration of the life cycle of creating complex technical products.*

Keywords: *high-tech products; life cycle of new technology creation; life cycle reduction; technological preparation of production; virtual enterprise; selection of suppliers, applied information technology.*

1. Introduction

To prepare production, it is necessary to perform a complex of interrelated organizational, technical, technological, planning, economic and other measures that ensure the implementation of the production program within the required time with minimal labor, material and technical and other resources to ensure product quality. Let's consider existing approaches to organizing technological preparation for high-tech production.

1.1. Motivation

Current trends require the creation of products of proper quality, reducing the impact on the environment, as well as reducing energy and other types of resources, increasing the informativeness of the process of monitoring the state of technological systems, increasing the degree of detection and tracking of the causes of defects in the creation of products. Accordingly, the requirements for management processes have increased. To

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obtain current data, it is necessary to plan processes for monitoring and regulating characteristics and production operations related to the life cycle of product creation and the life cycle of equipment [1]. It is advisable to use a new organizational structure of production based on virtualization and active use of digital technologies.

1.2. State of the art

Production planning can be carried out by forming a plan based on deterministic or probabilistic models with a discrete structure. Technological preparation of planned production is often based on economic and mathematical models and uses a matrix of multi-criteria production consequences. To select the best production system, it is possible to apply modeling of production processes using a simulation model, for production planning using appropriate technologies [2, 3]. For the manufacture of single products, there are also approaches to optimizing the planning and preparation of production. The article [4] presents an approach to standardizing the structure in a single-position production system without limiting flexibility. To achieve this goal, a model of the reference structure [4] is proposed, which is based on the product architecture. At the next stage, production and planning processes are adjusted based on this reference structure. Digital planning and optimization of production processes in a virtual environment reduces the risk of errors, increases the overall productivity of operations and procedures of production and maintenance. Creation of digital twins at the stage of production preparation is used to optimize and model production processes, as well as improve decision-making through the use of artificial intelligence methods [5, 6].

To prepare for the production of high-tech products, the labor intensity of manufacturing a unit of product is assessed; the norms of material resource consumption, which play an important role in the production costs of technological rationality of design solutions; the coefficient of unification of design elements, etc. There is a need for effective solutions to support the digital transformation of the manual approach, with which it is possible to speed up and increase the accuracy of cost estimation by automating specific tasks and optimizing decision-making processes [7]. Processing the design of the product for manufacturability should ensure a reduction in labor intensity and cost of manufacturing the product and its installation outside the manufacturing enterprise. During production preparation, issues related to the energy efficiency of production equipment are considered, which can be solved with the involvement of methods of intelligent data analysis [8]. The article [9] raises the problem of uncertainty in the event of production line failures and deviations from a given production plan, which is considered when planning production. To find optimal production plans, you can use a genetic algorithm, optimization based on modeling of production processes, and heuristic methods. In [10], an integrated approach to production planning is proposed, which includes optimization based on dynamic modeling and meta-learning-based failure prediction. For coordination of service and production decisions covering a small volume of production equipment, a hybrid deep learning approach is proposed [11]. In order to determine the optimal production plan with maximum profit and taking into account all related constraints, which is carried out at the stage of production preparation, in [12], the use of meta-heuristic methods is proposed. Production planning involves effective warehouse management, which is important for optimizing inventories, minimizing transportation costs and increasing overall production productivity, which can be implemented through the use of non-linear programming [13]. In [14], methods and technologies of data mining are defined, which are used in the context of production planning and scheduling. To solve the problem of sustainable-robust aggregate production planning, which takes into account labor productivity, outsourcing options, and supplier sustainability, a two-level decision-making system was proposed [15], which is developed based on the use of a multi-objective linear programming model. Production capacity planning and equipment selection for order fulfillment can be carried out using appropriate information technologies and virtual engineering approaches [16].

A manufacturing enterprise requires an effective production supply system. As for virtual enterprises, their coordinated work requires the availability of information technologies for flexible organization of deliveries to order performers [17, 18]. Management of a virtual enterprise can be carried out with the involvement of expert systems [19]. In the article [20], a procedure for planning an energy-efficient production supply system in accordance with specific user requirements has been developed. Integration of digital twins in the processes of production preparation contributes to the optimization of industrial processes, as well as to increasing the sustainability and efficiency of the industrial enterprise [21, 22]. The supply chain for order fulfillment within the framework of a virtual enterprise should be structured and can be a multi-agent supply system based on balanced cooperation of agents of order fulfillment enterprises [23]. In the context of a virtual enterprise, supply chain management becomes a key factor in ensuring a cooperative approach [24]. The study [25] considers a multi-objective fuzzy linear programming model designed to support decision-making in order to optimize the production plan, material flows and resource allocation throughout the supply chain. The model focuses on both cost and risk minimization based on asymmetric triangular fuzzy numbers. When organizing a virtual enterprise, the impact of risk factors on different stages of its life cycle should be taken into account, by using appropriate risk assessment approaches, including the formation of a matrix of probabilities and the impact of risk factors. Among the solutions proposed is the analysis of the fault tree [26, 27].

The publications propose methods and approaches focused on solving individual issues of modern production, but not enough attention is paid to forming a comprehensive solution for organizing and automating production preparation processes, taking into account the advantages of a component approach, which ensures a reduction in the duration, cost, and risks of a production modernization project.

1.3. Objectives and tasks

Given the state of war, economic instability and the existing demand for innovative military products, there is a need to look for new approaches to organizing high-tech production. Therefore, the proposed study examines the process of preparing for production with the aim of reducing the duration of this stage of the life cycle of creating innovative products.

The volume of work on production preparation is significantly influenced by certain factors. One of the important factors is the level of innovation and complexity of the product being manufactured, and the type of production organization. In this publication, we consider the preparation of serial production. Based on the component structure of a complex technical product, each component of a certain level of decomposition requires the use of a set of technical and technological solutions, requires the availability of equipment and qualified personnel. The complex technical product being created may include various types of components: reusable components (tested technical solutions), combined components that contain elements of innovation (may require adaptation), as well as innovative components that ensure the competitiveness of the product being created. Based on the formed component multilevel architecture of the product being created, it is necessary to build a structure of the necessary functional modules for production preparation, taking into account the presence of various types of components in the composition of a high-tech product.

The purpose of this publication is to study the stage of preparation for the production of complex technical products in order to build the structure and composition of the main functional modules of the production preparation process using a component approach and the creation of a complex of mathematical models and information technology that ensure efficiency, reduce time and costs for the preparation of high-tech production.

To achieve the goal, within the framework of this publication it is necessary to solve the following **tasks**:

1) build a structure of a multi-level model of functional modules for preparing the production of high-tech products;

2) develop a model for selecting partners for a virtual enterprise to fulfill a portfolio of high-tech production orders;

3) develop a model for selecting suppliers for a virtual enterprise;

4) develop an agent model for assessing the risk of creating a virtual enterprise;

5) build a multi-level multi-agent model for creating the organizational structure of a virtual high-tech enterprise;

6) develop applied information technology for preparing the production of high-tech products based on a virtual enterprise.

2. Materials and methods of research

When creating a complex technical system, a multi-level component architecture of the product is formed with a reasonable selection of existing components. In addition, a set of design actions is formed to create new innovative components, taking into account the time of development of a new component, as well as indicators of cost, quality, competitiveness, innovation and risks [28].

The proposed study is devoted to the formal presentation of the processes of preparation for the production of high-tech products. There are technical preparation of production, which includes the development of the release of new products, and organizational preparation, which ensures the management of the process of developing new types of products. It involves the development of technological processes; design of equipment; devices and special tools necessary to ensure the technological process; calculations of production capacities; preparation of regulatory documentation, etc.

In this study, it is proposed to carry out the production preparation processes using a virtual enterprise. An industrial enterprise of a machine-building profile can serve as a model of a virtual enterprise. A virtual enterprise can use the production capacities of other enterprises that have a shortage of orders. Among the advantages of using a virtual enterprise, the following can be distinguished: a new flexible form of organization based on the market; the ability to adapt in a global economy; the creation of high-quality products with less capital investment; reduction of production time and

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cost; the possibility of implementing innovative technologies and services that become less expensive due to the combination of various resources in the environment of electronic communications; network infrastructure, etc. [29]

A virtual instrument-making enterprise can be organized on the basis of a classical enterprise specializing in the manufacture of high-tech products of a certain type. Therefore, as a result of the component architecture of the product being created obtained at the design stage [28], a specification is formed for each of the components, and the norms of raw material and necessary materials are determined. Raw material and material costs are determined for: main production; auxiliary needs (manufacturing of tools and technological equipment, testing of products, equipment adjustment, packaging of finished products, manufacturing of samples of new equipment, manufacturing of non-standard equipment, conducting R&D and R&D); repair and maintenance needs of fixed assets.

Thus, for the preparation of production it is proposed to use a multi-level component architecture of the created product. If the manufacture of a separate component at a certain level of system decomposition is not appropriate, then in this case the virtual enterprise searches for the necessary new components and organizes their supply. In this case, it is necessary to take into account the type of the required component (a component from past experience, a combined component or an innovative one).

The structure of the proposed multi-level model of functional modules using component product architecture for preparing the production of high-tech products is presented in Fig. 1.

2.1. Model for selecting partners of a virtual enterprise for fulfilling a portfolio of orders for the creation of high-tech products

For effective management of a virtual enterprise, it is necessary to promptly distribute orders among participating enterprises (partners).

The logistics of the life cycle of creating high-tech products under virtual production conditions can be divided into the following main stages: formation of an order portfolio, preparation for production, production, and product sales.

Important for a virtual enterprise is the formation of a portfolio of orders and further preparation of production for the implementation of this portfolio. The formation of a portfolio of orders is influenced by the following indicators: duration T, costs of organizing production Z, quality P, competitiveness Q, innovativeness H, risk of unsuccessful organization of production R. It is necessary to take into account the level of detail of the product, which is determined within the framework of a multi-level component model of production preparation (see Fig. 1). The composition of the created complex technical product for which a portfolio of orders is planned may include various types of components: reusable components, combined components that contain elements of innovation in their composition, as well as innovative components that ensure the competitiveness of the created product.

To form a portfolio of orders, it is proposed to involve experts for evaluation according to selected indicators (T, Z, P, Q, H, R), since conditions of uncertainty are possible. Each order O_i from the portfolio of orders of a virtual enterprise can be evaluated by the degree of importance and then a priority series can be formed, at the beginning of which is the most relevant order, and at the end the less important order: O_i, O_i, …, O_m. Next, it is necessary to rank the indicators by importance (T, Z, P, Q, H, R).

Let for each order O_i possible set of alternatives N_i on the selection of possible production capacities for the organization of high-tech production. Taking into account the contradictions of the indicators T, Z, P, Q, H, R, for the selection of a specific composition of a virtual enterprise that will participate in the implementation of O_i, one can use the lexicographic ordering of the options for the composition of producers.

In the case of a large number of possible options for choosing productions to fulfill the order portfolio of a virtual enterprise, it is advisable to use the method of integer linear programming with Boolean variables x_{ij}, where i is the order number, j is the possible composition of manufacturers selected to organize the order fulfillment. Then the indicators for assessing the fulfillment of the order portfolio of a virtual enterprise will have the following form:

$$T=\sum_{i=1}^{m}\sum_{j=1}^{N_i}x_{ij}t_{ij}\ ,\ Z=\sum_{i=1}^{m}\sum_{j=1}^{N_i}x_{ij}z_{ij}\ ,$$

$$P=\sum_{i=1}^{m}\sum_{j=1}^{N_i}x_{ij}p_{ij}\ ,Q=\sum_{i=1}^{m}\sum_{j=1}^{N_i}x_{ij}q_{ij}\ , \qquad (1)$$

$$H=\sum_{i=1}^{m}\sum_{j=1}^{N_i}x_{ij}h_{ij}\ ,R=\sum_{i=1}^{m}\sum_{j=1}^{N_i}x_{ij}r_{ij}\ ,$$

Where

$$x_{ij}=\begin{cases}1, & \text{the selection of the j-th composition of} \\ & \text{manufacturers to fulfill the i-th order;} \\ 0, & \text{otherwise;}\end{cases} \qquad (2)$$

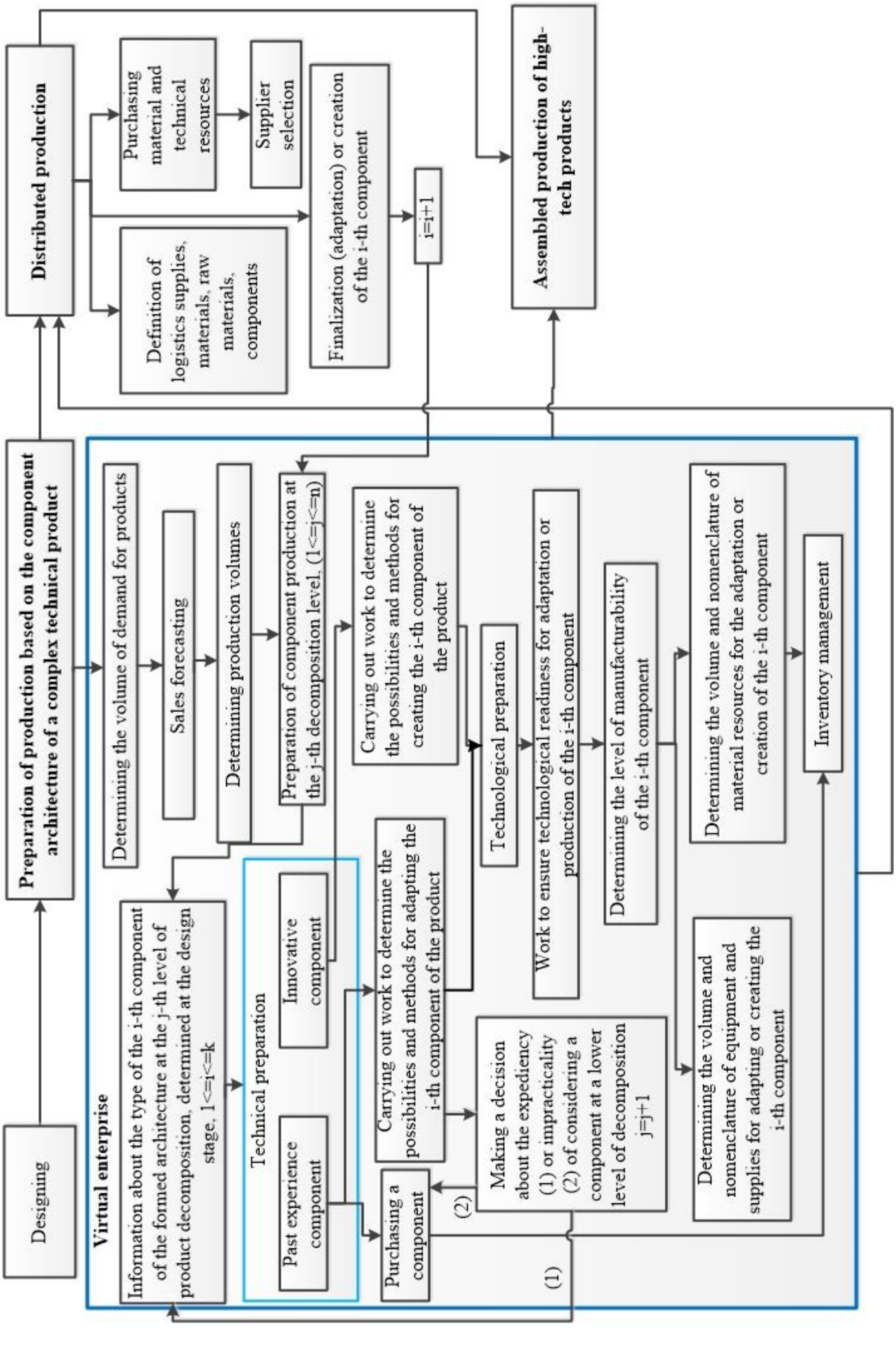

Fig. 1. Structure of a multi-level model of functional modules for preparing the production of high-tech products

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$\sum_{j=1}^{N_i} x_{ij} = 1$, which means the mandatory choice for fulfilling the i-th order of a specific j-th warehouse of manufacturers;

t_{ij} is quantitative assessment by experts of the duration of the i-th order execution when choosing the j-th composition of manufacturers;

z_{ij} is quantitative assessment of costs for organizing (adapting) the j-th warehouse of manufacturers to fulfill the i-th order;

p_{ij} is quantitative assessment of the quality of the organization of the j-th warehouse of producers to fulfill the i-th order ;

q_{ij} is quantitative assessment of the competitiveness of the j-th set of manufacturers for the fulfillment of the i-th order ;

h_{ij} is quantitative assessment of the innovativeness of the j-th producer in the composition for the fulfillment of the i-th order ;

r_{ij} is the risk associated with the inclusion of the j-th warehouse of manufacturers to fulfill the i-th order.

At the first stage, we will optimize individual indicators. It is necessary to minimize the duration of the project in order to reduce the preparation for the production of high-tech products:

$$\min\ T,\ T = \sum_{i=1}^{m}\sum_{j=1}^{N_i} x_{ij} t_{ij}\ , \tag{3}$$

$$Z \le Z',\ P \ge P',\ Q \ge Q',\ H \ge H',\ R \le R',$$

where Z', P', H', Q', R' are permissible values of indicators Z, P, H, Q, R.

Optimal values for other indicators can be obtained in a similar way by fulfilling the constraints:

$$\max\ P,\ P = \sum_{i=1}^{m}\sum_{j=1}^{N_i} x_{ij} p_{ij}\ ,$$

$$T \le T',\ Z \le Z',\ Q \ge Q',\ H \ge H',\ R \le R',$$

$$\max\ Q,\ Q = \sum_{i=1}^{m}\sum_{j=1}^{N_i} x_{ij} q_{ij}\ ,$$

$$T \le T',\ Z \le Z'\ ,\ P \ge P',\ H \ge H',\ R \le R',$$

$$\max\ H,\ H = \sum_{i=1}^{m}\sum_{j=1}^{N_i} x_{ij} h_{ij}\ ,$$

$$T \le T',\ Z \le Z'\ ,\ P \ge P',\ Q \ge Q',\ R \le R', \tag{4}$$

$$\min\ Z,\ Z = \sum_{i=1}^{m}\sum_{j=1}^{N_i} x_{ij} z_{ij}\ ,$$

$$T \le T',\ P \ge P',\ Q \ge Q',\ H \ge H',\ R \le R',$$

$$\min\ R,\ R = \sum_{i=1}^{m}\sum_{j=1}^{N_i} x_{ij} r_{ij}\ ,$$

$$T \le T',\ Z \le Z',\ P \ge P',\ Q \ge Q',\ H \ge H'.$$

To find a compromise solution for the indicators T, Z, P, Q, H, R, we can use multi-criteria optimization, taking into account the possible contradiction of the indicators. With this task, we introduce a complex indicator U. It will be formed in the form of an additive convolution:

$$U = \alpha_T \hat{T} + \alpha_Z \hat{Z} + \alpha_P \hat{P} + \alpha_Q \hat{Q} + \alpha_H \hat{H} + \alpha_R \hat{R}\ , \tag{5}$$

where $\sum_{l=1}^{6} a_l = 1$, a_l is given as the “weight” of the l-th indicator by experts, taking into account the peculiarities of the preparation of production of a virtual enterprise.

The indicators $\hat{T}, \hat{Z}, \hat{P}, \hat{Q}, \hat{H}, \hat{R}$ are normalized (converted to a dimensionless scale $0 \div 1$):

$$\hat{T} = \frac{T - T^*}{T' - T^*},\ \hat{Z} = \frac{Z - Z^*}{Z' - Z^*},$$
$$\hat{P} = \frac{P^* - P}{P^* - P'},\ \hat{Q} = \frac{Q^* - Q}{Q^* - Q'}, \tag{6}$$
$$\hat{H} = \frac{H^* - H}{H^* - H'},\ \hat{R} = \frac{R - R^*}{R' - R^*}$$

where, in turn $T^*, Z^*, P^*, Q^*, H^*, R^*$, are the extreme values of the indicators T, Z, P, Q, H, R.

The next stage is to minimize the complex indicator: $\min U$, which allows us to obtain a compromise solution.

2.2. Virtual enterprise supplier selection model

In the process of considering the multi-level component architecture of the product being created for the purpose of preparing production, the question of the expediency of manufacturing or purchasing components of a certain level of product decomposition by means of a virtual enterprise is resolved. It is possible to make a decision to use components of a lower level of decomposition. The type of component that is required for use influences the adoption of such a decision. After all, the use of innovative components requires a full cycle of production and procurement of components for these components, including at the lowest level of architectural decomposition. One of the functional modules of technological preparation of production is the selection of suppliers for partner enterprises that fulfill the order of a virtual enterprise. When purchasing product components, the enterprise determines what raw materials and materials need to be purchased to fulfill the order. The selection of suppliers is carried out by a virtual enterprise. Let's consider the stages of supplier selection:

1. To solve the problem of selecting suppliers, it is necessary to: announce a competition; study advertising materials: company catalogs, advertisements in the media; visit exhibitions and fairs; correspond and personal contacts with potential suppliers. As a result of the listed activities, a database of potential suppliers is formed, which is constantly updated and supplemented.

2. The composition of possible potential suppliers is analyzed based on the criteria that characterize each supplier. The criteria (indicators) for selecting the composition of suppliers are defined in the form of a set-theoretic description:

$$K = \{K_1,\ K_2,\ ...,\ K_i,\ ...,\ K_N\}, \qquad (7)$$

where $i = \overline{1, N}$, N is the total number of criteria for selecting a possible set of suppliers.

In this case, the set of potential suppliers for each production that is part of the virtual enterprise can be represented in the following form:

$$V = \{V_1,\ V_2,\ ...,\ V_t,\ ...,\ V_S\}, \qquad (8)$$

where $t = \overline{1, S}$, S is the total number of potential suppliers for all possible types of components.

It is advisable to use the following criteria as criteria: reliability of supply, distance of the supplier from the manufacturing enterprise that fulfills the order, terms of current and emergency deliveries, the ability to ensure the supply of spare parts throughout the entire period of order fulfillment, cost of raw materials, declared quality of raw materials, payment terms and the need for further storage of raw materials, the possibility of unscheduled deliveries, the supplier's financial condition and the dynamics of relations with the buyer, etc. The choice of suppliers can be significantly influenced by the results of work under already concluded contracts.

Purchased goods, raw materials and components are usually not equivalent in terms of the goals of the production process. The absence of components that are regularly needed can lead to a stoppage of the production process and disruptions in the work schedule of the virtual enterprise. Therefore, the criteria for selecting suppliers for the production enterprises that are part of the virtual enterprise are not equivalent.

3. At the next stage, a set of significant indicators (criteria) is selected for the j-th partner who fulfills the order of the virtual enterprise:

$$K_p^j = \{K_{p1}^j,\ K_{p2}^j,\ ...,\ K_{pi}^j,\ ...,\ K_{pM}^j\},\ M \le N, \quad (9)$$

where M is the number of possible indicators out of the total number N.

4. Determination of weighting coefficients W_i for M indicators that were selected from the total set of supplier evaluation criteria, taking into account the individual characteristics of the j-th manufacturing enterprise that fulfills the order (partner in the virtual enterprise). The determination of weighting factors is carried out by expert means. In this case

$$\sum_{i=1}^{M} W_i^j = 1. \qquad (10)$$

Thus, the selected indicators are ranked.

5. At the next stage, it is necessary to select a scale for evaluating each t-th supplier according to the selected criteria ($t = \overline{1, T}$, T is the number of relevant suppliers). The scale can represent qualitative assessments (for example, “good”, “satisfactory”, “bad”, etc.), possible linguistic values (A, B, C, D) or numerical values (for example, from 1 to 10). The selection of the scale, as well as the evaluation of the supplier, is carried out with the involvement of experts.

6. Assigning points to each p i-th criterion for the t -th supplier when selecting a supplier for the j-th partner who fulfills the order of the virtual enterprise a_{pit}^j.

7. Calculation of the integral indicator (rank) A_t^j for the t-th supplier for the j-th partner, which is carried out according to the formula:

$$A_t^j = \sum_{i=1}^{M} W_i^j * a_{pit}^j. \qquad (11)$$

8. Determining the supplier rating based on the integral indicator. Fixing selected suppliers for industrial partner productions that are part of the virtual enterprise alliance when fulfilling the order. Information on selected suppliers is stored and accumulated in the database of the virtual enterprise information system.

When interacting with a supplier over a certain period, it becomes necessary to evaluate his work for fur-

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ther use according to certain indicators:

1. Calculation of the weighted average rate of price growth (price indicator).

To evaluate the t-th supplier by the first criterion (price), the weighted average price growth rate ($\bar{\varpi}_{ct}$) for the goods it supplies is calculated:

$$\bar{\varpi}_{ct} = \sum_{i=1}^{n} \varpi_{ci} * d_i , \qquad (12)$$

where ϖ_{ci} is the rate of increase in the price of the i-th type of product;

d_i is share of the i-th type of product in the total volume of deliveries of the current period;

n is the number of types of goods supplied.

The rate of price growth for the i-th type of product is calculated by the formula:

$$\varpi_{ci} = \frac{P_i^2}{P_i^1} * 100\% , \qquad (13)$$

where P_i^1, P_i^2 is the price of the i-th type of product in the current and previous periods, respectively.

The share of the i-th type of product in the total volume of deliveries of the current period is calculated by the formula:

$$d_i = \frac{P_i^2 * \upsilon_i^2}{\sum_{i=1}^{n} P_i^2 * \upsilon_i^2} , \qquad (14)$$

where $\sum_{i=1}^{n} P_i^2 * \upsilon_i^2$ is the amount for which the goods of the i-th variety were delivered in the current period, in euro;

υ_i^2 is volume of goods of the i-th variety in the current period, units.

2. Calculation of the growth rate of deliveries of goods of inadequate quality (quality indicator).

To evaluate the supplier's performance based on the second indicator (quality of the goods supplied), we calculate the growth rate of the supply of goods of inadequate quality (ϖ_{fit}):

$$\varpi_{fit} = \frac{d_{fi}^2}{d_{fi}^1} * 100\% , \qquad (15)$$

where d_{fi}^2, d_{fi}^1 is the share of deliveries of inadequate quality in the total volume of deliveries of the current and previous periods, respectively.

3. Calculation of the growth rate of average delay (supply reliability indicator ϖ_{Lit}).

A quantitative measure of delivery reliability is the average delay, that's the number of days of delay per delivery. This value is defined as the total number of days of delay for a given period divided by the number of deliveries for the same period.

Thus, the growth rate of the average delay for each supplier is determined by the formula:

$$\varpi_{Lit} = \frac{\lambda_{Li}^2}{\lambda_{Li}^1} * 100\% , \qquad (16)$$

where λ_{Li}^2, λ_{Li}^1 is the average delay for each supplier per delivery in the current and previous periods, days.

2.3. Agent-based model for assessing the risk of creating a virtual enterprise

The process of organizing a virtual enterprise for the purpose of producing high-tech products can be considered as an investment project. An agent model was created to study the process of creating a virtual enterprise. It is proposed to use investment efficiency indicators to analyze the economic efficiency of a virtual enterprise.

The mathematical model of the movement of financial flows of an enterprise has the form:

$$D = \sum_{i=1}^{N} \sum_{t=0}^{T} \left\{ \begin{array}{l} \frac{F_{ti}}{(1+r)^t} + (1-y_i) * x_{Lti} * \frac{L_{ti}}{(1+r)^t} + \\ + y_i * \left[\frac{C_{ti}}{(1+r)^t} + x_{Lti} * \frac{yC_{ti}}{(1+r)^t} \right] \end{array} \right\} , \qquad (17)$$

where D is the net discounted income,

F_{ti} is the financial flow at time 't' associated with agent 'i',

L_{ti} is the losses when implementing the risk factor associated with agent 'i' at time 't' (a random variable distributed according to a normal law with given distribution parameters),

i is the agent number,

N is the number of agents,

T is the duration of the project,

t is the time interval number,

x_{Lti} is the logical variable corresponding to the realization of the risk factor associated with agent 'i' at time 't' (takes the value 1 if the risk factor is realized with probability p_{Lti}, and 0 otherwise),

r is the discount rate,

y_i is the logical variable related to the decision-making on risk management (can take a value equal to 1 in case of a decision to implement anti-risk measures and a value equal to 0 in other cases),

C_{ti} is the costs of carrying out anti-risk measures,

yC_{ti} is the losses when the risk factor associated with agent 'i' occurs at time t, provided that a risk management decision is made (a random variable distributed according to a normal law).

Risk management consists of identifying and analyzing risks and developing planned measures to minimize the negative consequences of the occurrence of risk events. For each specific case, different management methods can be considered, aimed both at minimizing losses in the event of the risk factor and at minimizing the probability of the risk factor occurring.

The process of creating a virtual enterprise occurs in the information space (virtually) in the conditions of integration of distributed resources of partner participants to solve dynamic market problems [30]. Therefore, the development of a virtual enterprise is associated with the intelligent modeling of the interaction of complex, heterogeneous, distant agents. At the same time, the importance of building multi-level friendly communications between agents, based on models of interaction between customers and performers, which provide the necessary flexibility and reactivity of the enterprise, is significantly increasing.

Thus, the creation of a virtual enterprise requires a clear organization of information flows between the entities involved in solving the tasks set for the virtual enterprise. The coordinated work of a virtual enterprise requires the development of an organizational structure of such an enterprise and applied information technology to automate the processes of preparing for the production of high-tech products.

It is proposed to use multi-agent modeling to build a multi-level organizational structure of a virtual enterprise. The structure of the multi-agent model and its composition are shown in Fig. 2.

3. Results and Discussion

As a result of the research, an applied information technology for preparing the production of high-tech products based on a virtual enterprise was developed, which has a composition of software modules presented in Fig. 3. The information technology is based on the models developed in the work and a multi-agent model and provides automation of the process of organizing a virtual enterprise and preparing production using a modern user interface.

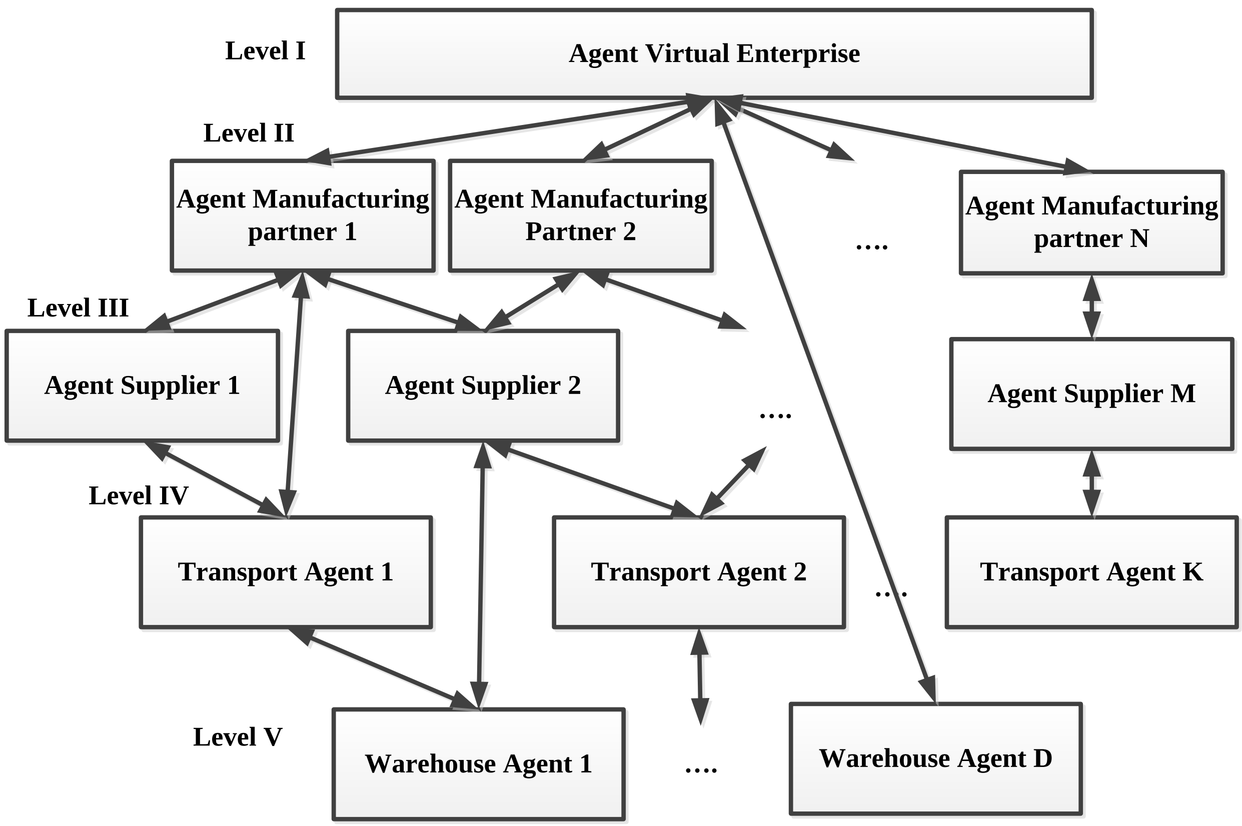

Fig. 2. Multilevel multiagent model of creating an organizational structure of a virtual high-tech enterprise

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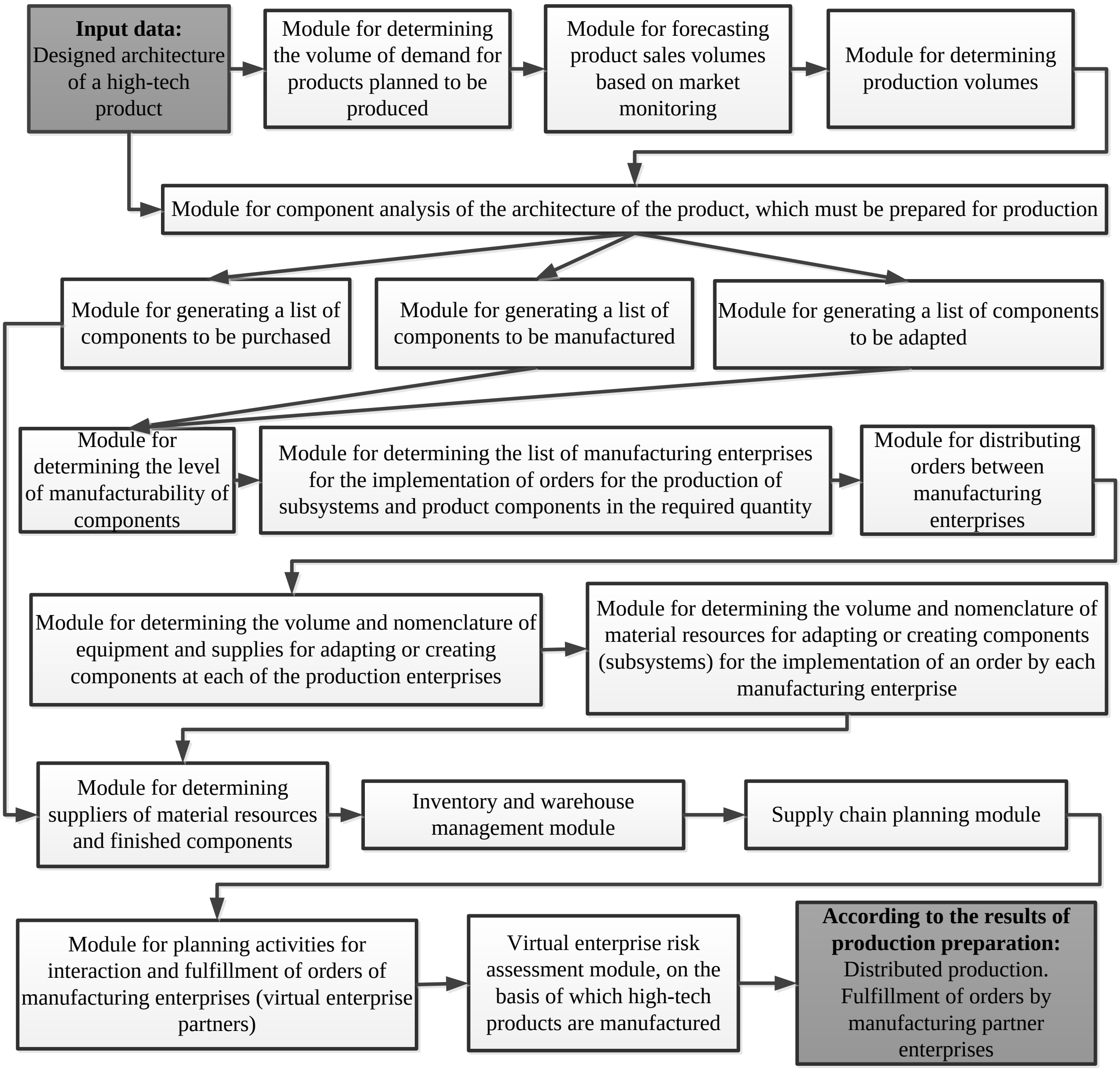

Fig. 3. Scheme of applied information technology for preparing the production of high-tech products based on a virtual enterprise

The effectiveness of the complex of models and applied information technology proposed in the study lies in reducing costs, risks, and the duration of preparation for the production of high-tech products by using the concept of a virtual enterprise for preparation of production, which allows for rapid response to market changes and rational use of resources based on coordinated interaction, and the organization of "end-to-end" business processes for preparation of production.

To implement production preparation processes, it is advisable to take into account the level of detail and various types of components that are part of the product architecture, which, in turn, is implemented within the framework of the formed multi-level component model of functional modules for preparing the production of high-tech products.

But in the process of considering the multi-level component architecture of the created product within the framework of the supplier selection model of a virtual enterprise, a decision must be made on the feasibility of manufacturing or purchasing components at certain levels of decomposition of a high-tech product. The type of component that is involved for use influences the adoption of such a decision. The supplier selection model proposed in the study does not contain a formalized description and a clear algorithm for solving the issue of the feasibility of manufacturing or purchasing components. Within the framework of the supplier selection model of a virtual enterprise, the supplier assessment is carried out with the involvement of experts. This may introduce some subjectivity into the decision-making process. In addition, information on selected suppliers is stored and accumulated in the database of the information system of the virtual enterprise. The structure of the formed database was not presented in this study.

4. Conclusions

The process of creating a virtual production for the production of high-tech products is presented. Building a virtual enterprise is a complex process of integrating technological, material and financial resources of different enterprises. A virtual enterprise must have a flexible structure. Such an organization can be contractual, not have a legally defined structure. The purpose of its existence is the production of a specific product. Heterogeneous enterprises that are not able to independently produce products can enter, as partners, into a virtual enterprise within the framework of a joint project. A virtual enterprise can have a single information structure capable of supporting the life cycle of a product.

The proposed study examines the stage of preparation of production of a virtual enterprise for the purpose of optimizing the processes of forming a portfolio of orders and distributing them among selected partners who have become part of the virtual enterprise for the purpose of manufacturing a new high-tech product. The following tasks were considered and solved in this article:

1. A multi-level component model of functional modules for preparing the production of high-tech products has been formed. The proposed model is based on the component architecture of the created high-tech product and takes into account its composition. The multi-level architecture of a complex technical product can contain various types of components: reusable components (tested technical solutions), combined components that contain elements of innovation (may require adaptation), as well as innovative components that ensure the competitiveness of the created product. The proposed model takes into account the preparation for production or acquisition of components of various types.

2. Preparation of production is carried out on the basis of a formed virtual enterprise, consisting of a community of territorially distributed subcontractors (partner enterprises), which interact in the production process and communicate via telecommunications. A virtual enterprise requires a virtual office that implements preparation of production, forms a portfolio of orders and distributes them between partner production enterprises. This is done by applying the model of selection of partners of a virtual enterprise proposed in the study for the execution of a portfolio of orders of high-tech production.

3. One of the important tasks of production preparation is the task of organizing the supply of material resources and components to manufacturing enterprises. This publication proposes a model for selecting suppliers that takes into account the importance of evaluation criteria when making a selection, and also evaluates the work of suppliers based on the results of their interaction with manufacturing enterprises in terms of quality, reliability and supply price.

4. An agent model has been developed for the organization of a virtual enterprise, which takes into account the influence of agents – subjects of a virtual enterprise – on the manifestation of risk factors.

5. The complex of all models proposed in this study was used to develop an applied information technology for preparing the production of high-tech products on the basis of a virtual enterprise, which will allow for a clear organization of information flows between entities involved in solving the tasks set for the virtual enterprise.

Financing

This study was conducted without financial support.

Data Availability

The manuscript has no associated data.

Use of Artificial Intelligence

The author confirms that she did not use artificial intelligence methods while creating the presented work.

Author have read and agreed to the published version of this manuscript.

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МОДЕЛЮВАННЯ ПРОЦЕСІВ ПІДГОТОВКИ ВИРОБНИЦТВА ВИСОКОТЕХНОЛОГІЧНИХ ВИРОБІВ З ВИКОРИСТАННЯМ КОНЦЕПЦІЇ ВІРТУАЛЬНОГО ПІДПРИЄМСТВА

Л. М. Лутай

Предметом дослідження є процеси підготовки виробництва високотехнологічної продукції. Підготовка виробництва потребує проведення організаційних, економічних та технологічних дій, що гарантують перехід на серійний випуск продукції з урахуванням вимог Industry 5.0 та використанням наукових і технологічних інновацій. Підготовка здійснюється з метою ефективного освоєння нового серійного виробу, впровадженням сучасного роботизованного обладнання, інформаційних технологій, у тому числі інтернету речей і освоєння нових форм організації виробництва. В умовах економічної нестабільності та глобальної конкуренції виникає необхідність скорочення етапу підготовки виробництва і життєвого циклу створення високотехнологічного виробу. У складі нового складного виробу можуть знаходиться різні види компонентів: компоненти повторного використання, комбіновані компоненти, що у своєму складі містять елементи інноваційності, а також нові інноваційні компоненти, що забезпечують його конкурентоспроможність. Для кожного компонента необхідно здійснювати планування етапу підготовки виробництва. Серед сучасних підходів щодо організації виробництва актуальне створення віртуального підприємства, в рамках якого об'єднуються підприємства для реалізації конкретного проекту по виготовленню високотехнологічної продукції. **Завдання:** побудувати структуру багаторівневої моделі функціональних модулів підготовки виробництва високотехнологічної продукції; розробити модель вибору партнерів віртуального підприємства для виконання портфелю замовлень по створенню високотехнологічних виробів; розробити модель вибору постачальників віртуального підприємства; розробити агентну модель оцінювання ризику створення віртуального підприємства; побудувати багаторівневу мультиагентну модель створення організаційної структури віртуального високотехнологічного підприємства; побудувати схему прикладної інформаційної технології підготовки виробництва високотехнологічної продукції на базі віртуального підприємства. **Метою** публікації є дослідження етапу підготовки виробництва складних технічних виробів на предмет синтезу архітектури багаторі-

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вневої компонентної моделі виробу шляхом створення функціональних модулів для підготовки виробництва високотехнологічної продукції, а також розробленню комплексу математичних моделей, що забезпечують формування портфелю замовлень та вибір виконавців для його реалізації; вибір постачальників для виконання замовлень виробничими підприємствами; оцінювання ризику проєкту віртуального підприємства. Використовуваними математичними моделями та методами є: системний аналіз, оптимізація за допомогою цілочисельного програмування, багатокритеріальна оптимізація, експертне оцінювання. Отримані такі **результати.** В дослідженні запропоновано багаторівневу мультиагентну модель організаційної структури віртуального приладобудівного підприємства та утворено прикладну інформаційну технологію підготовки виробництва високотехнологічної продукції на основі запропонованих у публікації моделей. **Висновки.** Головний внесок і наукова новизна отриманих результатів полягає у зниженні витрат, ризиків та скороченні тривалості підготовки виробництва високотехнологічної продукції за рахунок використання концепції віртуального підприємства для підготовки виробництва шляхом впровадження прикладної інформаційної технології, розробленої на основі розробленого комплексу математичних моделей, що забезпечують формування портфелю замовлень та вибір виконавців для його реалізації; вибір постачальників для виконання замовлень виробничими підприємствами; оцінювання ризику проєкту віртуального підприємства. Процеси підготовки виробництва здійснюються в рамках побудови віртуального підприємства, раціональна організація якого сприяє скороченню тривалості життєвого циклу створення складних технічних виробів.

Ключові слова: високотехнологічна продукція; життєвий цикл створення нової техніки; скорочення життєвого циклу; технологічна підготовка виробництва; віртуальне підприємство; вибір постачальників, прикладна інформаційна технологія.

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