Modeling of the control of innovative processes of a production activity taking into account risks

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***Abstract**.:*The article considers the research of control of innovative processes of a production activity of an enterprise. It influences of various production and external factors, including risks. The content and a formulation of the problem of a multi-level process of control of the production innovative activity of an enterprise in the presence of risks is developed. Proposing method is based on the solution of the discrete optimization problem with a help of minimax. The established optimal management provides a guaranteed result for a solution to the problem of control of innovative processes, taking into account the risks. At the same time, we reduced the complex problem of dynamic optimization of control with the consideration of risks to the realization of a finite sequence of one-step problems of discrete optimization.

Keywords**:** modeling of control, control of innovative processes, risk-based optimization, minimax control, guaranteed result.

I. Introduction

THE decision-making innovative process under conditions of uncertainty and the risk, which exists due to them, leads to the need to solve a problem of the best choice under conditions of incomplete information about a system under consideration. In this case, bases of existing approaches to solving similar problems are mostly static models and the application of apparatus of stochastic modeling. To apply such a mathematical tool, it is necessary to know probabilistic characteristics of main parameters of the model and special conditions for the implementation of the considered innovative process.

In addition, using a stochastic modeling apparatus requires special conditions (for example, mass and homogeneity of a sample of values), which is usually difficult to execute in practice. It is necessary to take into account the specifics of a production innovative activity (PIA) of an enterprise, where, in particular, risks do not depend on us and are uncontrolled parameters.

Consequently, to solve the problem of the control of innovative process (CIP) of an enterprise PIA, we propose to use the minimax approach or finding a guaranteed result. Its essence lies in the fact that a value of the worst (maximum) vector of heterogeneous risks is the smallest in comparison with similar values for others at the minimum guaranteed optimal management. Thus, we minimize the influence of risks in the CIP problem, where risks are uncontrolled parameters, by choosing such optimal control that would guarantee the obtained result at the influence of any maximum of risks from a set of permissible ones.

We know that a modern enterprise is a complex multifactorial and multi-stage management object. Various types of risks can affect it. It consists of a large number of interconnected subsystems, which have relations of subordination in the form of a hierarchical structure. The hierarchical system of a control PIA of an enterprise leads to the need for further refinement of a concept of optimization of a CIP. Conflict situations arise when solving optimization problems between subsystems of different levels in complex control systems with a given hierarchical structure. A decision leads to the need for a choice of management within a coherent strategy. A solution to this problem relates to the decision-making problem taking into account multilevel governance, which must take into account possibilities of its choice at each level of management. In addition, there is a problem of processing of large volumes of information when solving such problems. This fact creates considerable difficulties in automation of PIA at an enterprise. Thus, optimization of an innovative process of control of enterprise’s PIA taking into account risks is a complicated and relevant task.

II. Literature review and problem statement

The current state of Ukraine's economy largely depends on accurate estimation, prediction, effective planning and management of innovation activity of enterprises. A modern enterprise is a complex integrated organizational and production system, the components of which are constantly changing, interacting with each other. Achievement of set goals in the face of increasing competition among enterprises results in an increase in the volume and complexity of processes of production, analysis, planning, management, internal and external relations with suppliers, intermediaries, etc.

However, innovative activity in the process of dynamic development of a company cannot be considered fully justified and adapted without involvement of contemporary approaches

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of economic-mathematical modelling. This, in turn, is an effective means of theoretical processing and practical generalization of mechanisms and tools for innovative activity of an enterprise. Moreover, production of an enterprise is a complex, open, capable of self-organization and self-development economic system with dynamically changeable non-determined and contradictory characteristics.

We will note that there are scientific studies focusing on problems of management of innovative processes (IP) at an enterprise, various economic-mathematical models and methods for finding managerial decisions. However, the problem of economic-mathematical modeling of adaptive IP management under conditions of uncertainty, taking into consideration the risk factor at enterprises has not been solved yet and is a relevant research topic.

Let us consider up-to-date approaches to modeling of socio-economic systems, in particular those related to IP management at an enterprise.

In this way, the problem of mathematical modeling of innovative development of different enterprise was studied. Models for formation and functioning of innovative systems of upgrading of agrarian clusters were proposed, and related models were developed. The methods of the theory of single-criterion optimization on hypergraphs with the help of deterministic and probabilistic automata of Moor, probabilistic-automatic simulation and stochastic Petri nets were used However, preliminary analysis of the exogenous factors proved the put forward hypothesis of determinism of the researched model and unacceptability of using stochastic values in it [1]. That is why solution of the problem of adaptive IP management at an enterprise, set in the work, requires a different mathematical tool set. In addition, according to the author, for a comprehensive study on effectiveness of IP management at an enterprise, it is advisable to use multicriteria optimization models.

The methods of optimization successfully apply the work of various enterprises. In the article [2] is proposed two different health-aware economic predictive control strategies that aim at minimizing the damage of components in a pasteurization plant. It is offered the damage is assessed with a rainflow-counting algorithm that allows estimating the components' fatigue. The overall control objective is modified by adding an extra criterion that takes into account the accumulated damage. The matter is that the single-layer approach is improved with a multi-layer control scheme, where the solution of the dynamic optimization problem is obtained from the model in two different time scales. However, the lack of the proposed method is seen in the fact that risks of both control strategies to achieve the advisable trade-off between minimal accumulated damage and operational costs are not taken into account in simulation over a utility-scale pasteurization plant.

Methods modeling, control and cptimization were emplemented in the natural gas industry for Natural Gas Processing Plants. Although Poe W.A. and Mokhatab S. [3] have presented the unique challenges plant managers and owners face when looking for ways to optimize plant performance and efficiency, including parameters such as the various feed gas compositions, temperatures, pressures, and throughput capacities. Unfortunately, the issues of optimizing the management of innovation processes at the enterprise that keep looking for better decision support tools remained unresolved.

Optimal Control and Variational Problems is researched in the area of optimal control and the calculus of variations. Paper [4] contains a number of results concerning well-posedness of optimal control and variational problems, nonoccurrence of the Lavrentiev phenomenon for optimal control and variational problems, and turnpike properties of approximate solutions of variational problems.

Recent publications consider scientific research based on the methods of network modeling. So neural network simulation and the back-propagation concept were utilized to develop data-driven models for predicting reverse osmosis plant performance and finding control strategies [5]. Dispite the process of three reverse osmosis plants was successfully modeled using an artificial neural network, the problem is that not always possible to obtain data for modeling on the basis of the proposed methods under the conditions of working of enterprises in the real conditions.

Solving the problem to optimization is estimated from a set of scenarios is a difficult integer programming problem. In [6] is offered the alternative approach which is to minimize CVaR for several different quantile levels and then to select the optimized portfolio with the best out-of-sample VaR. But it may demand using only a number of scenarios, which leads to poor out-of-sample performance.

Realization of the problems, associated with IP modeling in practice contributed to scientific development and widespread application of hybrid models based on a combination of formal and informal text, verbal and special graphic approaches. These tools offer simplified innovative models and in many cases involve graphic interpretation of [7]. As a result, most models of IP management were implemented by descriptive means or represented fragmentarily, with insufficient analytical formalization [8]. Some of them are characterized by lack of practical focus, integrity, and complexity in IP application [9], they simplify obtaining knowledge and offer opportunity to experiment with IP management. In this case, there is no possibility to assess the impact and consequences of different variants for IP management in the prospects of minimization of risks of innovation activity while making managerial decisions [10]. Thus, innovative management with the use of simulation remains an unresolved problem for researchers. In addition, existing models may have a limited availability and must be adapted to conditions of activity of specific enterprises.

Problems of modeling of IP management were most fundamentally studied in [11], which dealt with the overall problems of software and adaptive IP management at an enterprise. However, it is not covered by the problem of elaborating a detailed model for practical implementation in the workplace.

III. Substantial statement of the problem of the CIP PIA taking into account risks

Actually, a dependence of the replenishment of resources (production and investment) on a management vector (volumes of products produced in each period of time) reflects a multi-level management of an enterprise provided in the model in the management of PIA. Therefore, there are several levels of management for each fixed management for a selected period (that is, one of the permissible scenarios of CIP PIA). It goes from the upper level (first level) at an enterprise (for example, a planning department) to the next level (second level) of management. At this level, we calculate production resources corresponding to the management, as well as investment resources required for the implementation of this fixed management. The values are necessary then to perform necessary calculations in the model [12, 13]. Such a procedure at modeling is done for each possible management (hypothetically, during modeling). This is the real essence of the process of multi-level (in our case - two-level) management.

Given the above and relying on the principles of mathematical modeling and the theory of optimal management, we proceed to the modeling of CIP PIA problem.

Let us formulate a substantial statement. An enterprise plans its PIA, that is, it makes a transition to the production of products based on the desired CIP. This process takes into account different types of production factors, raw materials, variants of use and storage of raw materials, intermediate and final products, influence of various production and external factors, including risks, other components of the production process. It may consist of certain technological methods of organization of production, which involve a use of existing or replacement (partial or full) of technological equipment.

CIP includes a value of volumes of production of new products, a vector of replenishment of material and labor resources for production and a vector of current investments for the implementation of PIA, which form a scenario of management of a corresponding CIP. There is possibility of a use of different CIP scenarios depending on the variation of values of corresponding components of a production process.

It is necessary to carry out an optimal management of a process according to a corresponding scenario at a given time interval of its life cycle. This must be done by selection among a plurality of alternatives of possible managerial influences so that an overall performance criterion for CIP is maximal [14]. Moreover, if there are several variants of the implementation of different CIPs considered on the basis of the corresponding technologies [15], then it is also necessary to make a choice between them and to find optimal management for the chosen criterion.

We developed a substantial economic and mathematical model of an enterprise PIA. Now let us proceed to the formal setting and development in several stages.

IV. Formal statement of the problem of CIP PIA of an enterprise taking into account risks

Let us consider a multi-step dynamic system of enterprise PA on a given integer-valued time interval $\overline{0,T} = \{0,1,\ldots,T\}\ (T>0)$. It includes an enterprise (an object *I*) controlled by *P* player (a subject of management). The state of CIP is a linear discrete recurrent vector equation of the following form (dynamic model):

$$\bar{x}(t+1) = A(t)\bar{x}(t) + B(t)\bar{u}(t) + C(t)\bar{v}(t) + D(t)\bar{w}(t),$$
$$\bar{x}(0) = \{x_0, I_0\}, \tag{1}$$

where $t \in \overline{0,T-1} = \{0,1,\ldots,T-1\}\ (T>0)$;

$\bar{x}(t) = (\bar{x}_1(t), \bar{x}_2(t),\ldots,\bar{x}_{\bar{n}}(t))' \in \mathbf{R}^{\bar{n}}$ is a vector of phase variables or a phase vector – a set of basic parameters describing a CIP state at *t* time; $\mathbf{R}^{\bar{n}}$ is $\bar{n}$-dimensional Euclidean space of vector-columns, $\bar{n} \in \mathbf{N}$ is a set of positive natural numbers;

$\bar{u}(t) = (\bar{u}_1(t), \bar{u}_2(t),\ldots,\bar{u}_{\bar{p}}(t))' \in \mathbf{R}^{\bar{p}}$ is a vector of CIP management (managerial influence) of an enterprise satisfying the given limitation:

$$\bar{u}(t) \in \boldsymbol{U}_1(t) \subset \mathbf{R}^{\bar{p}},$$
$$\mathbf{U}_1(t) = \{\bar{u}(t) : \bar{u}(t) \in \{\bar{u}^{(1)}(t), \bar{u}^{(2)}(t), \cdots, \bar{u}^{(N_t)}(t)\} \subset \mathbf{R}^{\bar{p}}\}, \tag{2}$$

where $\mathbf{U}_1(t)$, for each $t \in \overline{0,T-1}$ is a finite set of vectors, that is, a finite set consisting of $\mathbf{N}_t$ ($\mathbf{N}_t \in \mathbf{N}$) vectors in $\mathbf{R}^{\bar{p}}$, that define all possible realizations of different CIP scenarios at *t* time; ($\bar{p} \in \mathbf{N}$);

$\bar{w}(t) = (\bar{w}_1(t), \bar{w}_2(t),\ldots,\bar{w}_m(t))' \in \mathbf{R}^{\bar{m}}$ is a vector of replenishment of material and labor resources at a period of time t ($t \in \overline{0,T-1}$), which depends on the permissible realization of management and must satisfy the following given limitation:

$$\bar{w}(t) \in \mathbf{W}_1(\bar{u}^{(i)}(t)) \subset \mathbf{R}^{\bar{m}},$$
$$\mathbf{W}_1(\bar{u}^{(i)}(t))\{\bar{w}(t) : \bar{w}(t) \in \{\bar{w}^{(1)}(t), \bar{w}^{(2)}(t), \cdots, \bar{w}^{(M_t(i))}(t)\} \subset \mathbf{R}^{\bar{m}}\}, \tag{3}$$

where $W_1(\bar{u}^{(i)}(t))$ for each time point $t \in \overline{0,T-1}$ and management $\bar{u}^{(i)}(t) \in U_1(t)$ is a finite set of vectors, that is, a finite set consisting of $M_t(i)$, ($M_t(i) \in \mathbf{N}$, $i \in \overline{1,N_t}$) of vectors in $\mathbf{R}^{\bar{m}}$, that determine all possible realizations of different scenarios of replenishment of material and labor resources and investment resources at *t* time in the investigated process; a matrix $D(t)$ at the vector $\bar{w}(t)$ determines the intensity of its effect on the vector $\bar{w}(t)$ at each time point.

Each realization of a phase vector is permissible for all $t \in \overline{0,T-1}$.

$$\bar{x}(t) = (x_1(t), x_2(t),\ldots,x_{\bar{n}}(t)) \in \mathbf{R}^{\bar{n}}$$

satisfies the following given phase limitation:

$$\bar{x}(t) = (x_1(t), x_2(t), ..., x_{\bar{n}}(t)) \in \boldsymbol{X}_1(t) \subset \mathbf{R}^{\bar{n}}, \quad (4)$$

where $\mathbf{X}_1(t)$ is a convex, closed and bounded polyhedron of space $\mathbf{R}^{\bar{n}}$, that is, a set, which limits permissible values of the realization of a phase vector at t time;

$\bar{v}(t) = (\bar{v}_1(t), \bar{v}_2(t), \ldots, \bar{v}_{\bar{q}}(t))' \in \mathbf{R}^{\bar{q}}$ is a vector of risks affecting CIP realization, which in each period of time t ($t \in \overline{0, T-1}$) depends on the permissible realization of management $\bar{u}(t) \in \mathbf{U}_1(t)$, that satisfies the given limitation:

$$\bar{v}(t) \in \boldsymbol{V}_1(\bar{u}(t)) \subset \mathbf{R}^{\bar{q}}, \quad (5)$$

where $\boldsymbol{V}_1(\bar{u}(t))$ is a convex, closed and bounded polyhedron of space $\mathbf{R}^{\bar{q}}$, that is, a set that limits possible realizations of a risk vector during CIP at t time t; $\bar{q} \in \mathbf{N}$.

Matrices $A(t)$, $B(t)$, $C(t)$ and $D(t)$ in the vector recurrence equation (1) describing CIP dynamics are real matrices of orders $(\bar{n} \times \bar{n})$, $(\bar{n} \times \bar{p})$, $(\bar{n} \times \bar{m})$ and $(\bar{n} \times \bar{q})$, respectively, are such that for all $t \in \overline{0, T-1}$ matrices $A(t)$ are non-degenerate, that is, for a matrix $A^{-1}(t)$, corresponding to it, and a rank of a matrix $B(t)$ is equal to $\bar{p}$ (the dimension of a vector $\bar{u}(t)$).

Let us describe informational capabilities of subject of management (P player) while CIP management in the discrete dynamic system (1)–(5) [16, 17].

We assume that the subject of control has certain information capabilities during a course of CIP realization and a fixed natural number s>>T>0 at each point of time $t \in \overline{1, T}$. They correspond to realizations of a phase vector of a system, managerial influence, and a risk vector at an integer-valued interval of time $\overline{-s, t}$. The phase vector precedes a considered one during CIP management:

1) we know a history of the realization of a phase system vector

$$\bar{x}_t(\cdot) = (\bar{x}_1(\cdot)_t, \bar{x}_2(\cdot)_t, \ldots, \bar{x}_{\bar{n}}(\cdot)_t) = \\ = \{(\bar{x}_1(\tau), \bar{x}_2(\tau), \ldots, \bar{x}_{\bar{n}}(\tau))\}_{\tau \in \overline{-s,t}} = \{\bar{x}(\tau)\}_{\tau \in \overline{-s,t}};$$

2) we know a history of the realization of managerial influence of a system

$$\bar{u}_t(\cdot) = (\bar{u}_1(\cdot)_t, \bar{u}_2(\cdot)_t, \ldots, \bar{u}_{\bar{p}}(\cdot)_t) = \\ = \{(\bar{u}_1(\tau), \bar{u}_2(\tau), \ldots, \bar{u}_{\bar{p}}(\tau))\}_{\tau \in \overline{-s,t-1}} = \{\bar{u}(\tau)\}_{\tau \in \overline{-s,t-1}};$$

3) we know a history of the realization of a vector of intensity of replenishment of production and investment resources

$$\bar{w}_t(\cdot) = (\bar{w}_1(\cdot)_t, \bar{w}_2(\cdot)_t, \ldots, \bar{w}_{\bar{m}}(\cdot)_t) = \\ = \{(\bar{w}_1(\tau), \bar{w}_2(\tau), \ldots, \bar{w}_{\bar{m}}(\tau))\}_{\tau \in \overline{-s,t-1}} = \{\bar{w}(\tau)\}_{\tau \in \overline{-s,t-1}};$$

4) we know a history of the realization of a vector of system risks

$$\bar{v}_t(\cdot) = (\bar{v}_1(\cdot)_t, \bar{v}_2(\cdot)_t, \ldots, \bar{v}_{\bar{q}}(\cdot)_t) = \\ = \{(v_1(\tau), v_2(\tau), \ldots, v_q(\tau))\}_{\tau \in \overline{-s,t-1}} = \{\bar{v}(\tau)\}_{\tau \in \overline{-s,t-1}}.$$

We should note that we can solve the problem of a posterior identification of all main elements of a discrete dynamic system based on these data (1). It is necessary to determine elements of the matrices $A(t)$, $B(t)$, $C(t)$ and $D(t)$ in the vector recurrence equation (3). It describes the dynamics of I object, that is, the object of CIP [18].

Let us assume that the subject of management (a person who makes decisions on CIP) – P player also knows equations (1) and limitations (2)–(5).

A value of the convex functional $\tilde{F}: \mathbf{R}^{\bar{n}} \to \mathbf{R}^1$, defined on possible realizations of the phase vector $\bar{x}(T) \in \mathbf{R}^{\bar{n}}$ of the system (1) at the final moment of time T determines a quality of selection of optimal CIP management from a standpoint of P player.

Then for the system (1)–(5), the objective of a minimax multi-level CIP from a point of view of P player can be formulated in the following way. It is necessary for P Player to form a management $\bar{u}_T^{(e)}(\cdot) = \{\bar{u}_T^{(e)}(t)\}_{t \in \overline{0,T-1}}$ (for all $t \in \overline{0, T-1}$: $\bar{u}_T^{(e)}(t) \in \mathbf{U}_1(t)$) at a given time interval $\overline{0, T}$. The value of the convex functional defined on realizations of the vector $\bar{x}(t) \in \mathbf{R}^{\bar{n}}$. must be minimal. Where $\bar{x}(T)$ is the realization of a phase system vector at T time and a vector $\bar{w}_T(\cdot)$ at the worst (that is, those that maximize the value of the functional $\tilde{\boldsymbol{F}}$) of permissible realizations of a risk vector $\bar{v}_T(\cdot) = \{\bar{v}_T(t)\}_{t \in \overline{0,T-1}}$ (for all $t \in \overline{0, T-1}$: $\bar{v}_T(t) \in \boldsymbol{V}_1(\bar{u}_T^{(e)}(t))$). At the same time, realization $\bar{w}_T(\cdot) = \{\bar{w}_T(t)\}_{t \in \overline{0,T-1}}$ (for all $t \in \overline{0, T-1}$: $\bar{w}_T(t) \in \boldsymbol{W}_1(\bar{u}_T^{(e)}(t))$) of a vector of intensity of replenishment of production and investment resources contributes to the achievement of objectives of P player. That is, an aim of selection (according to the P player's task) is minimization of this functional in accordance with the management chosen by him.

V. Solution of the Problem of Multi-Level CIP PIA of an Enterprise Taking into Account Risks

We turn to the solution of the problem of multi-level CIP taking into account risks after determination of all the parameters of the model:

1. We form a set of alternatives of possible CIP managements $U(t)$. The components of the first group of management vectors of the set represent output product volumes over a period of time (in accordance with the corresponding CIP) (first level of management).

2. We build a set of replenishment of material, labor resources and investment resources $W(\overline{u}(t))$ based on values of the first group of management vectors of CIP (second level of management).

3. We determine a set of permissible risks $V(t)$ with appropriate limitations.

4. We fix the management with the corresponding vector of replenishment of material and labor resources, investment resources consistently and "take away" all risks from the set of permissible ones. We construct the corresponding predictable sets of reach regions G for the final vectors $x(T)$ of the state of the system at the time T.

5. On the sets of reach domains, we solve the discrete optimization problem with the help of minimax and find the optimal control, which provides a guaranteed result of the solution of CIP PIA problem of an enterprise under the influence of any risks of the set of permissible ones.

VI. Conclusion and Future Work

The advantage of the conducted researches is that they make possible to solve the problem of dynamic optimization of the process of multi-level management of CIP of an enterprise taking into account risks. We applied an optimization tools, in which, unlike the methods of dynamic programming and the principle of Pontryagin's maximum, we used a method of construction of predictive sets (areas of reach) of states of CIP management at the end point of the management interval.

The proposed method makes possible to reduce the multi-step problem of CIP of a production activity of an enterprise taking into account risks to the realization of a finite sequence of one-step optimization problems. Thus, the obtained research results give possibility to avoid difficulties connected with the large dimensionality of the original problem [19].

The disadvantages of the study include the fact that risks taken into account in the model are deterministic values only. This fact causes difficulties in determination of the magnitude of potential losses associated with influence of risks. Moreover, situation with risks with probabilistic values may arise under real-life conditions of CIP of an enterprise [20].

Thus, the development of the study may consist in taking into account risks of a stochastic nature. In this case, it would be appropriate to introduce deterministic and stochastic risks into the model of a multi-level management of enterprise CIP.

In the future, the results of the study can become a basis for development of a software management system for an enterprise CIP. This will make it possible to automate the process of multi-level management of CIP and to adjust specific enterprises to working conditions.

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