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LARGE SCALE SYSTEMS CONTROL

Models and Management Structure for the Development and Implementation of Innovative Technologies in Railway Transportation. II. An Incentive Mechanism for Saving Energy and Elements of the Project Management Structure

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Abstract—This paper consists of two parts. In the second part, the management mechanisms for implementing complex projects that improve the energy-saving characteristics of products and technologies are further studied. An incentive model for saving energy in the sequence of projects within a multi-project structure is considered, and an optimal mechanism for this model is proposed. This mechanism includes a planning procedure, penalty functions for the nonfulfillment of plans, and an incentive function for project results. The functioning of the system is treated as a game of the Principal and sequentially connected agents who implement projects. The Principal's strategy is the choice of a specific mechanism. The agents' strategies are messages, in which they report to the Principal some information about their parameters, and also the choice of the project results. The information about the agents' parameters is necessary to calculate the plans based on the planning procedure. At the same time, the agents may prefer not to tell the truth, reporting unreliable (distorted) information. It is shown that the optimal mechanism proposed below stimulates the agents to provide reliable information and also to choose the project results coinciding with the plans. The first part of this paper (see [3]) was devoted to the mechanisms of project assessment and resource allocation; the results established therein are used to propose a project management system for implementing complex projects.

Keywords: saving energy, resource allocation, incentive, control, management structure, organization

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1. INTRODUCTION

The first part of this paper (see [3]) described and studied the mechanisms for selecting the most promising projects in the field of developing products and technologies for using alternative types of energy for the propulsion of trains. Also, it described and studied the mechanisms for allocating a limited budget among the complex projects and their parts.

After selecting projects and determining the volumes of financial resources for them, it is necessary to establish planning and incentive mechanisms for executing the works within these projects. It should be taken into account that the control authority (Principal), who plans the activities and provides incentives, is less aware of the existing capabilities for implementing the works than their executors, experts in the field. Under these conditions, for planning and incentive purposes, the Principal is compelled to request this information from the executors. Since the Principal and the executors have their own interests, the natural problem is to eliminate the strategic behavior of the executors, i.e., any manipulations with the information reported by them to the Principal [4–6, 19, 20].

The second part of this paper considers the problem to design incentive-compatible organizational mechanisms ensuring such strategy-proofness in the case of a system of interconnected executors (agents) with a sequential technology of their works.

The considerations below are essentially based on [5, 6].

Also, the results established in the first part of this paper (see [3]) are used below to study the additional requirements and possibilities for designing a project management system for the scientific and technical activities of the organization implemented by the Principal.

2. ELEMENTS OF INNOVATIONS MANAGEMENT SYSTEM

2.1. Model of Incentive Mechanism for Saving Energy

As a rule, the projects selected for further development are complex; they represent a system of sub-projects, business processes, activities, and works with the input-output connections described by a network structure (Fig. 1). Each element of such a complex of works contributes to the energy-saving characteristics of the entire project. Therefore, the problem is to stimulate each element of this structure, which is responsible for a corresponding work of the project.

A methodology to design such incentive systems was developed within the theory of organizational control and management [1, 9, 10], mainly under the Principal's complete awareness of the models of agents involved in the implementation of a complex project. In the case of incomplete awareness, which usually occurs in complex projects management, this problem was studied only the hypothesis of weak contagion (weakly interconnected agents [7]). However, the works of a complex project are interconnected by the sequence of execution: the results of previous works strongly affect the results of subsequent works.

Consider an example of an elementary structure of works interconnected by a strict sequence of execution. (The approach introduced below, as well as the results of analysis, will not fundamentally differ in a more general case when the connections of agents are described by a tree.)

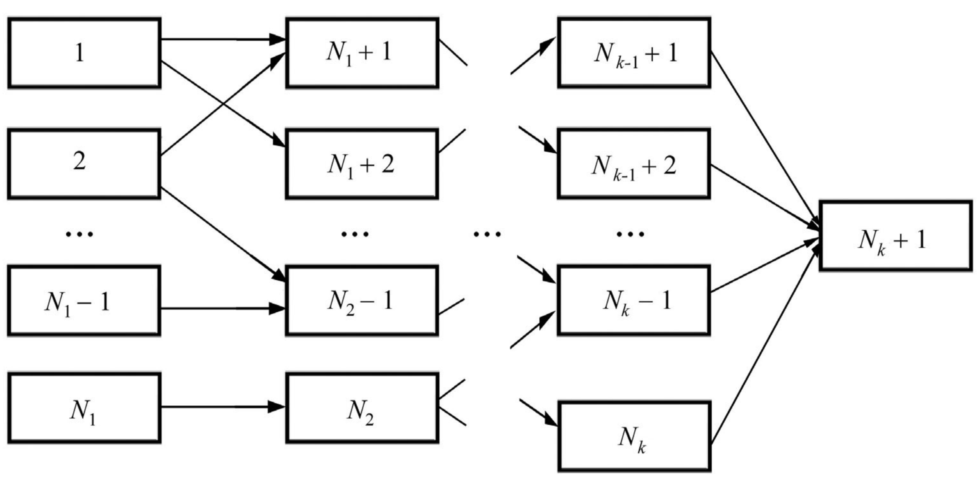

Fig. 1. Network structure of complex project: example.

Model description

Let the Principal's goal function be given by

$$\Phi(x,y,r) = c_1 y_1 - z_1(x_1,y_1) - v_1(y_1,r_1) + \sum_{i=2}^{n} [c_i(y_i - y_{i-1}) - z_i(x_i,y_i) - v_i(y_i,r_i)],$$

with the following notations: y_i as the agent's state characterizing the result of execution of the ith work by him (for example, the specific level of saving energy compared to the current or established norm); x_i as a plan for the ith work, assigned by the Principal; $z_i(x_i\ y_i)$ as the Principal's loss due to the non-coincidence of the result y_i with the plan x_i; $v_i(y_i\ r_i)$ as the loss due to the deviation of the result y_i from some best energy-saving level r_i; $r_i \in [r_i^{\text{low}}, r_i^{\text{upp}}]$, $y_i \in [0, r_i^{\text{upp}}]$, and $x_i \in [0, r_i^{\text{upp}}]$. Assume that the values r_i are given, but the Principal knows only the ranges of these parameters. Here r_i^{low} and r_i^{upp} are the lower and upper admissible limits of the level r_i; c_i is the given parameter characterizing the significance of the result y_i for the Principal.

Suppose that

$$0 \le y_i \le r_i,$$
$$z_i(x_i, y_i) \ge 0,$$
$$z_i(x_i, x_i) = 0,$$
$$v_i(y_i, r_i) \ge 0,$$

and

$$v_i(r_i, r_i) = 0.$$

In addition, let

$$v_i(y_i, r_i) = a_i(r_i - y_i),$$

where $0 \le a_i \le c_i$. Each agent executing the ith work (selecting the values y_i) knows the true value r_i, and the Principal knows only the admissible limits of this indicator, r_i^{low} and r_i^{upp}. The sequential works are interconnected by the following relations:

$$r_{i+1}^{\text{low}} = r_i^{\text{low}} + \Delta_{i+1}^{\text{low}}, \quad r_{i+1}^{\text{upp}} = r_i^{\text{upp}} + \Delta_{i+1}^{\text{upp}}, \quad i = 1, \ldots, n-1.$$

Assume that the goal function of agent 1 has the form

$$f_1(x_1, y_1, r_1) = \sigma_1(y_1) - \vartheta_1(x_1, y_1) - \omega_1(y_1, r_1),$$

where $\sigma_1(y_1)$ is an incentive function, $\vartheta_1(x_1, y_1)$ is a penalty function for the nonfulfillment of his plan, and $\omega_1(y_1, r_1)$ is his cost function. Represent the goal function of agent i (executor of the ith work) as

$$f_i(x_i, y_i, y_{i-1}, r_i) = \sigma_i(y_{i-1}, y_i) - \vartheta_i(x_i, y_i) - \omega_i(\delta_i, r_i),$$

where $\sigma_i(y_{i-1}, y_i)$ is the incentive function for the result y_i, given the state y_{i-1} of the previous agent; $\vartheta_i(x_i, y_i)$ is the penalty function for the nonfulfillment of the plan; $\omega_i(\delta_i, r_i)$ is the cost function of agent i, which depends on his contribution to the energy-saving characteristics of the complex project. Here $\delta_{i+1} = y_{i+1} - y_i$, $i = 1, \ldots, n-1$, $\delta_1 = y_1 \ge 0$. Let $\delta_{i+1} \ge 0$, $i = 1, \ldots, n-1$.

For the sake of simplicity, assume that the cost functions can be approximated with sufficient accuracy by a quadratic function: $\omega_i(\delta_i, r_i) = e_i \delta_i^2 / 2r_i$, where $e_i > 0$. The cost functions reflect the following important property: the higher the value of r_i is, the lower the costs are. In other words, the greater the reserve for saving energy is, the less effort is required for the agent.

In the model of the incentive system under consideration, the participants have the following order of decision-making.

First, the Principal establishes a mechanism $\mu = \{\sigma(\cdot), \vartheta(\cdot,\cdot), x(\cdot)\}$, which includes an incentive function $\sigma_i(\cdot)$, a penalty function $\vartheta_i(\cdot,\cdot)$ for the nonfulfillment of the plan on saving energy, and a rule $x(\cdot) = (x_1(\cdot), \ldots, x_n(\cdot))$ to assign plans x_i based on the available information ρ_i about the parameters r_i, $i = 1, \ldots, n$.

Thus, in the system under consideration, an incentive mechanism for saving energy is understood as the set of interconnected planning procedures, incentive functions, and penalty functions.

Second, the agents report to the Principal their estimates ρ_i of the parameters r_i, which are then used for assigning the plans on saving energy $x_i = x_i(\rho_i)$ in accordance with the procedures $x_i(\cdot)$. Third, the agents implement the activities on saving energy for achieving the level y_i. Finally, the incentives $\sigma_i(y_{i-1}, y_i)$ and penalties $\vartheta_i(x_i, y_i)$ are assigned to the agent in accordance with the functions $\sigma_i(\cdot,\cdot)$ and $\vartheta_i(\cdot,\cdot)$.

Let the efficiency index of the incentive mechanism be defined as the guaranteed value

$$K(\mu, r) = \inf_{\rho \in R(r)} \inf_{y \in Y(x(\rho))} \Phi(x(\rho), y, r)$$

of the Principal's goal function on the sets $R(r)$ (all rational strategies of the agent when choosing the messages $\rho = (\rho_1, \ldots, \rho_n)$) and $Y(x)$ (all rational strategies of the agents when choosing the values $y = (y_1, \ldots, y_n)$ under a given plan $x = (x_1, \ldots, x_n)$. Further analysis will be confined to the mechanisms for which the set $R(r)$ consists of the dominant strategies of different agents: for each agent, there exist messages maximizing his goal function, regardless of the messages of all other agents. The set $Y(x)$ is determined by the sequence in which the agents choose the results y_i according to the numbering: agent i maximizes his goal function under a given plan and the result y_{i-1} of the previous agent. The sets of rational strategies will be described in detail below when designing the optimal mechanism and formulating the results of this paper.

Optimal incentive mechanism design: problem statement

The problem is to determine a mechanism μ^* such that, for all values of the parameter $r \in [r^{\text{low}}, r^{\text{upp}}]$,

$$K(\mu^*, r) \geq \sup_{\mu \in M} K(\mu, r) - \varepsilon,$$

where M is a given compact set of admissible mechanisms and $\varepsilon > 0$.

Let the set M be defined by the following constraints imposed on the incentive functions, penalty functions and planning procedures:

—The incentive functions $\sigma_i(y_i)$ are piecewise continuous and $0 \leq \sigma_i(y_i) \leq g_i$.

—The penalty functions $\vartheta_i(x_i, y_i)$ are piecewise continuous and satisfy the maximum growth constraint,

$$\vartheta_i(x_i, y_i) - \vartheta_i(x_i, y_i') \leq \theta_i(y_i', y_i),$$

where $\theta_i(y_i', y_i)$ is a given value of the maximum growth rate of penalties [6] that satisfies the triangle inequality:

$$\theta_i(y_i', y_i) + \theta_i(y_i, x_i) \geq \theta_i(y_i', x_i).$$

—The planning procedures $x_i(\rho_i)$ are continuous functions, $i = 1, \ldots, n$.

As it was demonstrated in [5, 6], under these conditions the optimal incentive mechanism μ^* can be designed by solving the optimization problem

$$K(\mu^*, r) = \max_{\mu \in M_c} \Phi(x(r), x(r), r)$$
$$= \max_{\mu \in M_c} \left\{ c_1 y_1 - v_1(y_1, r_1) + \sum_{i=2}^{n} [c_i(x_i - x_{i-1}) - v_i(x_i, r_i)] \right\}; \quad (1)$$

here M_c is the compact set of admissible mechanisms determined by additional concordance conditions, under which the planning procedure $x(\rho)$ and the incentive system $\sigma(\cdot)$, $\vartheta(\cdot, \cdot)$ stimulate the agents to fulfill plans and report reliable information about their parameters to the Principal as their dominant strategies. The compactness of the sets M_c for the system model under consideration was also proved in [5, 6].

Thus, the design of such a mechanism is reduced to determining the set M_c and solving problem (1). The concordance conditions defining the set M_c, for which the maximum value of the efficiency index $K(\mu^*, r)$ is achieved, will be presented below when formulating the solution of problem (1). As it was shown in [6], the concordance conditions are satisfied for the optimal mechanism; moreover, they stimulate the agent to *fulfill* the plan and report *reliable* information to the Principal.

Concordance conditions for fulfillment of plans and truth-telling

First, consider the constraints imposed on the set of mechanisms under which the agents fulfill their plans.

The fulfillment of plans can be guaranteed by applying penalties for any deviations of the agent's result from the plan. For the set of admissible penalty functions considered here, the optimal penalties coincide with their maximum growth rate $\theta_i(x_i, y_i)$. The details can be found in [6].

The set $P_i(y_{i-1}, r_i)$ of plans maximizing the goal functions of agents (upon fulfillment) is determined by the expression

$$P_i(y_{i-1}, r_i) = \left\{ x_i | f_i(x_i, x_i, y_{i-1}, r_i) \geq f_i(x_i, y_i, y_{i-1}, r_i), \;\; x_i, y_i \in \left[0, r_i^{\text{upp}}\right] \right\}.$$

The following result was established in [6]: for the penalty functions $\theta_i(x_i, y_i)$ satisfying the triangle inequality, the set $P_i(y_{i-1}, r_i)$ coincides with the set

$$Y_i(y_{i-1}, r_i) = \operatorname{Arg} \max_{y_i \in [0, r_i]} f_i(x_i, y_i, y_{i-1}, r_i)$$

of all rational strategies of agent i, i.e.,

$$Y_i(y_{i-1}, r_i) = P_i(y_{i-1}, r_i).$$

The condition $x_i \in P_i(y_{i-1}, r_i)$ is called the maximum concordance condition.

For each agent, determine the sets $P_i\left(y_{i-1}, r_i^{\text{low}}\right)$ of all plans implementable for the minimum value of the uncertain parameter r_i^{low} under the penalty functions $\theta_i(x_i, y_i)$. Assume that for r_i^{low}, the assigned plan is fulfilled due to the penalties $\theta_i(x_i, y_i)$ only (the incentive function is equal to 0). The maximum value of the plan $x_i^{\text{c}} = x_i^{\text{c}}\left(y_{i-1}, r_i^{\text{low}}\right)$ in the set $P_i\left(y_{i-1}, r_i^{\text{low}}\right)$ is determined by the inequality

$$\theta_i\left(x_i^{\text{c}} - y_{i-1}, y_i - y_{i-1}\right) \geq \omega_i\left(y_i - y_{i-1}, r_i^{\text{low}}\right) - \omega_i\left(x_i^{\text{c}} - y_{i-1}, r_i^{\text{low}}\right) \quad (2)$$

for all y_i from the range $0 \leq y_i \leq r_i^{\text{low}}$.

The agents' truth-telling is guaranteed by the perfect concordance conditions: each agent is assigned plans for which his goal functions achieve maximum on the set of admissible plans. As is well known [5, 6], the optimal planning procedure can be found among the ones satisfying the perfect concordance conditions. The optimal planning procedures will be determined using the optimal mechanism design method presented in [5, 6].

Conditions (2) and the perfect concordance conditions define the set M_{c} of incentive-compatible plans.

Optimal mechanism

Note that the function

$$\begin{aligned}\Phi(x,x,r) &= c_1x_1 - v_1(x_1,r_1) + \sum_{i=1}^{n}[c_i(x_i - x_{i-1}) - v_i(x_i,r_i)]\\ &= (c_1+a_1)x_1 - a_1r_1 + \sum_{i=2}^{n}[(c_i+a_i)(x_i - x_{i-1}) - a_ir_i]\end{aligned}$$

increases in $(x_i - x_{i-1})$. Therefore, given the incentive funds $g = (g_1,\ldots,g_n)$, it suffices to maximize each term of the Principal's goal function.

Introduce the numbers $\gamma_i > 0$ and the corresponding inequalities

$$(c_i+a_i)(x_i - x_{i-1}) - a_ir_i \geq \gamma_i.$$

From these inequalities, find the set of plans for which the value of the terms in the Principal's goal function is not smaller than the corresponding value γ_i. This set is determined by the inequality

$$x_i \geq q_i(x_{i-1},\gamma_i,r_i) = x_{i-1} + (\gamma_i + a_ir_i)/(c_i+a_i).$$

Consider the planning procedure

$$\tilde{\pi}_i(\gamma_i,\rho_i,x_{i-1}) = \begin{cases} x_i^{\mathrm{c}} = x_i^{\mathrm{c}}\left(x_{i-1}, r_i^{\mathrm{low}}\right), & \text{if} \quad r_i^{\mathrm{low}} \leq \rho_i \leq \beta_i\\ q_i(x_{i-1},\gamma_i,\rho_i), & \text{if} \quad \beta_i < \rho_i \leq r_i^{\mathrm{upp}},\end{cases} \tag{3}$$

where the value β_i is obtained by solving the equation

$$x_i^{\mathrm{c}}\left(x_{i-1}, r_i^{\mathrm{low}}\right) = q_i(x_{i-1},\gamma_i,\beta_i), \quad i = 1,\ldots,n.$$

For the planning procedure (3) determine the incentive functions $\sigma_i(x_{i-1},y_i)$ that satisfy the perfect concordance conditions with $y_i = x_i = \pi_i(\gamma_i,\rho_i,x_{i-1})$.

In accordance with [6], this incentive function is calculated by the formula

$$\sigma_i(x_{i-1},y_i) = \begin{cases} 0 & \text{for} \;\; 0 \leq y_i \leq x_i^{\mathrm{c}}\\ \displaystyle\int_{x_i^{\mathrm{c}} - x_{i-1}}^{y_i - x_{i-1}} \omega'_{it}(t,\tilde{r}_i(\gamma_i,t))dt & \text{for} \;\; \mathrm{c} < y_i \leq q_i\left(x_{i-1},\gamma_i,r_i^{\mathrm{upp}}\right)\\ \bar{g}_i & \text{for} \;\; q_i(x_{i-1},\gamma_i,r_i^{\mathrm{upp}}) < y_i \leq r_i^{\mathrm{upp}}.\end{cases}$$

In this expression, $\tilde{r}_i(\gamma_i,t)$ denotes the inverse of the function $\tilde{\pi}_i(\gamma_i,\rho_i,x_{i-1})$ in the variable ρ_i; $\omega'_{it}(t,\tilde{r}_i(\gamma_i,t))$ denotes the partial derivative of the agent's cost function $\omega_{it}(t,r_i)$ with respect to the first variable; the value $\bar{g}_i$ is given by

$$\bar{g}_i = \int_{x_i^{\mathrm{c}} - x_{i-1}}^{q_i(x_{i-1},\gamma_i,r_i^{\mathrm{upp}}) - x_{i-1}} \omega'_{it}(t,\tilde{r}_i(\gamma_i,t))dt.$$

The maximum value of the Principal's goal function is achieved under the maximum values of the parameters γ_i, which are in turn achieved by exhausting the incentive funds $g = (g_1, \ldots, g_n)$.

Assume that the penalty functions are linear, i.e., $\theta_i(x_i y_i) = k_i|y_i - x_i|$.

Calculate $x_i^{\mathrm{c}} = x_i^{\mathrm{c}}\left(y_{i-1}, r_i^{\mathrm{low}}\right)$ from condition (2). For the penalty functions under consideration, condition (2) is equivalent to

$$\left.\frac{d\omega_i(x, r_i^{\mathrm{low}})}{dx}\right|_{x=x_i^{\mathrm{c}}} = e_i(x_i^{\mathrm{c}} - x_{i-1})/r_i = k_i.$$

Hence, $x_i^{\mathrm{c}} = x_{i-1} + r_i k_i/e_i$.

The parameter β_i in expression (3) can be obtained from the condition

$$x_i^{\mathrm{c}}\left(x_{i-1}, r_i^{\mathrm{low}}\right) = x_{i-1} + (\gamma_i + \alpha_i\beta_i)/(c_i + a_i),$$

which gives

$$\beta_i = \left[\left(x_i^{\mathrm{c}}(x_{i-1}, r_i^{\mathrm{low}}) - x_{i-1}\right)(c_i + a_i) - \gamma_i\right]/a_i = r_i k_i(c_i + a_i)/(e_i a_i) - \gamma_i/a_i.$$

As a result, expression (3) for the planning procedure takes the form

$$\tilde{\pi}_i(\gamma_i, \rho_i, x_{i-1}) = \begin{cases} x_{i-1} + r_i^{\mathrm{low}} k_i/e_i, & \text{if } r_i^{\mathrm{low}} \le \rho_i \le \beta_i \\ x_{i-1} + (\gamma_i + a_i r_i)/(c_i + a_i), & \text{if } \beta_i \le \rho_i \le r_i^{\mathrm{upp}}. \end{cases} \tag{4}$$

Determine $\tilde{r}_i(\gamma_i, t)$, the inverse of the function $\tilde{\pi}_i(\gamma_i, \rho_i, x_{i-1})$ on the interval

$$\left(x_i^c\left(x_{i-1}, r_i^{\mathrm{low}}\right) - x_{i-1}, (\gamma_i + a_i r_i^{\mathrm{upp}})/(c_i + a_i)\right).$$

Obviously,

$$\tilde{r}_i(\gamma_i, t) = (t - x_{i-1})(c_i + a_i)/a_i - \gamma_i/a_i.$$

Hence, the planning procedure (4) satisfies the perfect concordance conditions [6] if the incentive function is given by

$$\sigma_i(x_{i-1}, y_i) = \begin{cases} 0 \quad \text{for} \quad 0 \le y_i \le x_{i-1} + r_i^{\mathrm{low}} k_i/e_i \\ (y_i - x_{i-1} - r_i^{\mathrm{low}} k_i/e_i) a_i e_i/(c_i + a_i) \\ \qquad \text{for} \quad x_{i-1} + r_i^{\mathrm{low}} k_i/e_i < y_i \le (\gamma_i + a_i r_i^{\mathrm{upp}})/(c_i + a_i) \\ g_i \quad \text{for} \quad (\gamma_i + a_i r_i^{\mathrm{upp}})/(c_i + a_i) < y_i \le r_i^{\mathrm{upp}}. \end{cases}$$

Find the optimal value of the parameter γ_i^* from the exhaustion condition of the incentive fund:

$$g_i = \left[(\gamma_i^* + a_i r_i^{\mathrm{upp}})/(c_i + a_i) - r_i^{\mathrm{low}} k_i/e_i\right] a_i e_i/(c_i + a_i).$$

Hence,

$$\gamma_i^* = \left[g_i(c_i + a_i)/a_i e_i + r_i^{\mathrm{low}} k_i/e_i\right] - a_i r_i^{\mathrm{upp}}$$

and the optimal value of the Principal's goal function is

$$\Phi(x^*, x^*, r) = \sum_{i=1}^{n} \gamma_i^*.$$

It should be emphasized that in this optimal mechanism, the agents are assigned the plans beneficial for them based on the information they actually report. Therefore, the Principal can receive from the agents the plans x_i instead of the estimates $\rho_i = r_i$, under the assumption that the agents can calculate the plans themselves. In this case, the optimal mechanism under consideration acquires the features of a counter-planning mechanism [8].

Optimal counter-planning mechanism

Since the mechanism under consideration satisfies the maximum and perfect concordance conditions, the levels of saving energy chosen by the agents coincide with the plans assigned to them, $y_i = x_i$, and the agents are interested in truth-telling, $\rho_i = r_i$. In addition,

$$r_i = (x_i - x_{i-1})(c_i + a_i)/a_i - \gamma_i/a_i.$$

Substitute this result into the incentive function formula and take into account the equality $y_i = x_i$ to arrive at the following expression for the incentive function on the interval defined by the inequalities

$$x_{i-1} + r_i^{\text{low}} k_i/e_i < y_i \leq (\gamma_i + a_i r_i^{\text{upp}})/(c_i + a_i): \;\; A_i(x_i - x_{i-1}) - k_i|y_i - x_i|,$$

where

$$A_i = [a_i e_i - k_i(c_i + a_i + \gamma_i^*)]/(c_i + a_i).$$

The incentive function $A_i(x_i - x_{i-1}) - k_i|y_i - x_i|$, in combination with the planning procedure in which the agents report the plans instead of the parameters ρ_i, corresponds to the counter-planning mechanism [8]. In counter planning, the agents report to the Principal the plans that are beneficial for them (instead of the parameters ρ_i), and the Principal stimulates the agents to ensure the profitability of the "most intense" plans under given constraints on the incentive funds.

Thus, the optimality of the counter planning mechanism has been established.

2.2. Elements of Management Structure

In practice, the mechanisms for selecting priority projects, allocating financial resources among them, and stimulating energy-saving activities require some changes in the innovations management structure of the organization.

Consider two modes of management, in which these mechanisms are used. They will be called the modes of strategic and operational management. In the organizational structure, the blocks of strategic and operational management are formed accordingly.

The mode of strategic management covers the following problems:

—classification and selection of the most promising projects (some methods for solving these problems were discussed in Section 2 of the first part; see [3]);

—allocation of financial resources for the most promising projects and formation of orders on the development of financial models and business plans for their implementation, which are sent to the block of operational management (this problem can be solved using the modification of cost-effectiveness analysis described in Section 3 of the paper [3]);

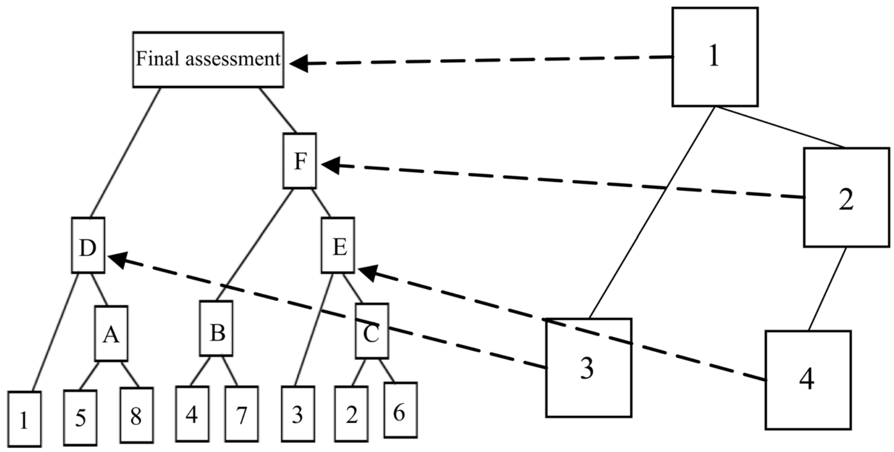

Fig. 2. Efficiency assessment elements included in project management structure: example.

—development and approval of incentive mechanisms for implementing the complex of projects (an incentive mechanism for a chain of project works has been described in Section 2.1 of this paper).

The mode of operational management covers the following problems:

—monitoring of current projects and development of corrective actions;

—provision of relevant information on any changes and the appearance of innovations for current projects, which is intended for the block of strategic management;

—development of financial models and business plans for further implementation of the projects selected;

—network planning and scheduling;

—implementation of incentive mechanisms.

The mechanisms described above can be applied under some necessary changes in the existing management structure of the organization.

Here are two aspects that can be taken into account in the management structure.

The first aspect is that the structure related to strategic management should include units (departments or persons) responsible for different levels of the integrated assessment procedure described above; see Fig. 2.

The left-hand side of this figure shows the structure of the integrated assessment procedure considered in Section 2 of the paper [3]. The right-hand side of this figure presents the elements of the hierarchical management structure responsible for the integrated and intermediate assessments of projects and their monitoring. For example, element 1 is responsible for calculating the final assessments (ratings) of projects and observing their dynamics over time; element 2 is subordinate to element 1, being responsible for the intermediate assessment and monitoring of projects in accordance with the intermediate assessment F. The responsibilities of elements 3 and 4 in this hierarchical structure are distributed by analogy, in accordance with the intermediate estimates D and E.

The second aspect of corrections in the management structure is determined by the resource allocation mechanism for different groups of projects; see Section 3 of the paper [3].

Large organizations such as JSC RZhD, as a rule, have complex distributed structures, by territory and functions. Therefore, when forming an innovative development program, it is important to consider the interests of all the main structural units. Otherwise, in the long run the lop-sided

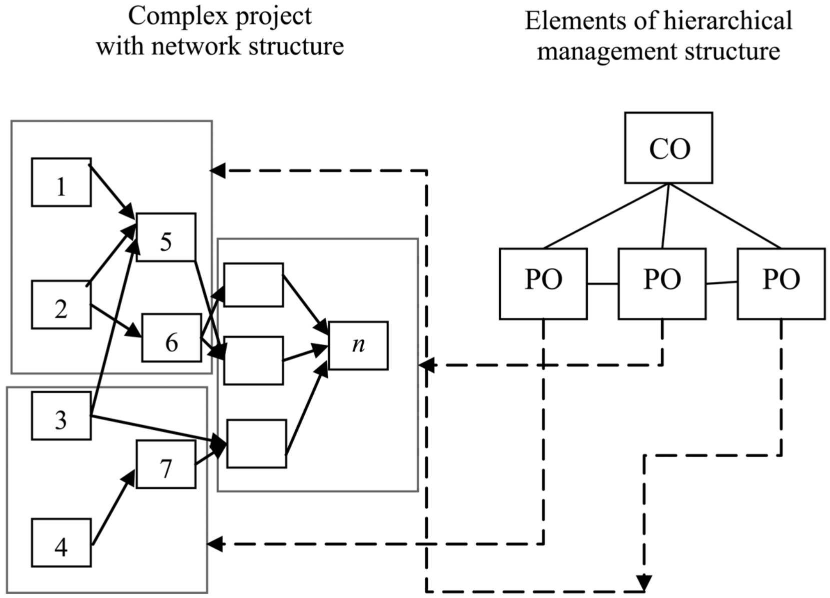

Fig. 3. Project offices in management structure: example.

innovation strategy will reduce the efficiency of the entire system. Consider the design problem of a concordant innovative program, in which each main structural unit is guaranteed some degree of participation. Two types of such guarantees (concordance conditions) will be considered as follows.

1. Concordance by resource, when each structural unit surely receives a minimum amount of funds for innovative development.

2. Concordance by effectiveness, when each structural unit is surely included in the program of projects with a total effect exceeding some lower bound.

Note that concordance by effectiveness has a significantly greater degree of manipulation (strategic behavior for distorting the actual information) than concordance by resource. Really, a structural unit surely included in the program of projects with a total effect exceeding some lower bound will be interested in overestimating the project costs.

On the contrary, in accordance with the resource concordance condition, the most efficient projects are included in the program. Therefore, further analysis will be confined to the case of concordance by resource.

In general, the allocation method of financial resources is similar to the one described in Section 3 of the first part (see [3]). It consists of two stages as follows.

Stage I. For each structural unit participating in the program, select the minimum set of projects with the volume of financing not smaller than a guaranteed threshold, using the algorithm from Section 3.

Stage II. Apply the algorithm described in Section 3 of the first part (see [3]) to the entire set of projects.

The allocation of financial resources among the complex projects of the network multi-project system under consideration is then used to determine the composition of the project offices (POs) of the hierarchical management structure (Fig. 3).

In Fig. 3, CO means the central project office; the numbers $1, 2, 3, \ldots, n$ indicate different projects in a multi-project system. As an illustration, projects 1, 2, 5, and 6 are combined into a group of projects with the first priority for financial resources, in accordance with the cost-effectiveness analysis procedure discussed in Section 3 of the first part (see the paper [3]);

projects 3, 4, and 7 form the group with the second priority; finally, the last group of projects to receive the residual financial resources contains four projects, including project n.

The proposals on possible corrections in the management structure of the organization are intended to improve the effectiveness of research, development, and implementation of the most promising projects. They can serve as additional tools for the implementation of the existing standards [15–18] and management system [11–14] of scientific and technical activity adopted in the organization.

3. CONCLUSIONS

The integrated assessment system and the allocation mechanism of investments proposed in this paper can be used to form a responsibility matrix for implementing complex projects within the organization. The models for assessing and identifying priority projects, as well as the allocation mechanism of financial resources based on the choice of the most effective projects, contribute to the concentration of financial resources on the most promising areas of scientific and technological development.

The system of projects selection and grouping into multi-project complexes can be employed for refining the process-based life cycle management models of scientific-technical and innovative developments.

The models studied in this paper can be used to form project offices for managing the implementation of complex projects; the incentive mechanisms can be embedded into the statutes for stimulating the scientific, R&D, and implementation activities of working groups.

Considered in the aggregate, the mechanisms presented in this paper give an example of an integrated mechanism for managing complex projects.

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REFERENCES

1. Belov, M.V. and Novikov, D.A., Network Active Systems: Models of Planning and Incentives, *Autom. Remote Control*, 2019, vol. 80, no. 12, pp. 2229–2244.
2. Burkov, V.N. and Enaleev, A.K., Optimality of the Revelation Principle. Necessary and Sufficient Conditions for the Reliability of Information in Active Systems, *Autom. Remote Control*, 1985, vol. 46, no. 3, pp. 341–348.
3. Burkov, V.N., Enaleev, A.K., Strogonov, V.I., and Fedyanin, D.N., Models and Management Structure for the Development and Implementation of Innovative Technologies in Railway Transportation. I. Mechanisms of Priority Projects Selection and Resource Allocation, *Autom. Remote Control*, 2020, vol. 81, no. 7, pp. 81–107.
4. Burkov, V.N. and Novikov, D.A., *Kak upravlyat' organizatsiyami* (How to Manage Organizations), Moscow: SINTEG, 2004.
5. Enaleev, A.K., Optimal Mechanism for an Active System with Communication, *Upravlen. Bol'sh. Sist.*, 2010, no. 29, pp. 108–127.
6. Enaleev, A.K., Optimal Incentive-Compatible Mechanisms in Active Systems, *Autom. Remote Control*, 2013, vol. 74, no. 3, pp. 491–505.
7. Enaleev, A.K., Optimal Incentive Compatible Mechanism in a System with Several Active Elements, *Autom. Remote Control*, 2013, vol. 78, no. 1, pp. 146–158.

8. *Mekhanizmy upravleniya* (Control Mechanisms), Novikov, D.A., Ed., Moscow: LENAND, 2011. Translated under the title *Mechanism Design and Management: Mathematical Methods for Smart Organizations*, Novikov, D.A., Ed., New York: Nova Publishers, 2013.

9. Novikov, D.A., *Setevye struktury i organizatsionnye sistemy* (Network Structures and Organizational Systems), Moscow: Inst. Probl. Upravlen., 2003.

10. Novikov, D.A. and Tsvetkov, A.V., *Mekhanizmy stimulirovaniya v mnogoelementnykh organizatsionnykh sistemakh* (Incentive Mechanisms in Multi-element Organizational Systems), Moscow: Apostrof, 2000.

11. *"Statute of the Technical Policy Department of OJSC Russian Railways,"* Statute of OJSC RZhD no. 53 dated May 25, 2009 (as amended on October 24, 2017). https://jd-doc.ru/2009/maj-2009/7782-polozhenie-oao-rzhd-ot-25-05-2009-n-53

12. *"On Approval of the Statute of the Elaboration and Implementation of the Innovative Development Program of the Russian Railways Holding,"* Order of JSC RZhD no. 2596r dated October 30, 2015. www.consultant.ru/cons/cgi/online.cgi?req=doc&base=EXP&n=651275

13. *"On Approval of the Statute of the Innovative Development Center—A Branch of OJSC Russian Railways"* (together with the Statute itself), Order of JSC RZhD no. 1761r dated August 29, 2016.

14. *"On the Distribution of Functions in the Management System for Technical and Technological Development, Innovative Activity and Safety Assurance of Production Processes in the Russian Railways Holding,"* Order of JSC RZhD no. 2168r dated September 12, 2014 (as amended on September 8, 2016).

15. *STO RZhD 08.007-2011. Standard of JSC RZhD. Innovative Activities in JSC RZhD. Management of the Implementation of Scientific and Technical Works*. Approved and put into effect by Order no. 1267r of JSC RZhD dated June 26, 2012. http://doc.rzd.ru/doc/public/ru?STRUCTURE_ID=704&layer_id=5104&id=6027

16. *STO RZhD 08.015-2011. Standard of JSC RZhD. Innovative Activities in JSC RZhD. The Examination Procedure of Innovative Projects*. Approved and put into effect by Order no. 1267r of JSC RZhD dated June 26, 2012. http://lawru.info/dok/2012/06/26/n170829.htm

17. *STO RZhD 08.005-2011. Standard of JSC RZhD. Innovative activities in JSC RZhD. The Procedure for Assessing the Effectiveness of Innovative Projects*. Approved and put into effect by Order no. 1267r of JSC RZhD dated June 26, 2012. http://doc.rzd.ru/doc/public/ru?STRUCTURE_ID=704&layer_id=5104&id=6024

18. *STK 1.04.001 Quality Standard of JSC RZhD. Project Management of JSC RZhD. Basic Regulations.* https://jd-doc.ru/2009/sentyabr-2009/7447-standart-po-kachestvu-oao-rzhd-n-stk-1-04-004-ot-14-09-2009-g-n-1902r

19. Bayiz, M. and Corbett, C.J., *Coordination and Incentive Contracts in Project Management under Asymmetric Information*, December 15, 2005. https://ssrn.com/abstract=914227

20. Cleden, D., *Managing Project Uncertainty*, Abingdon: Routledge, 2017.