Bilevel Models for Investment Policy in Resource-Rich Regions

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Abstract. This article continues the research of the authors into cooperation between public and private investors in the natural resource sector. This work aims to analyze the partnership mechanisms in terms of efficiency, using the game-theoretical Stackelberg model. Such mechanisms determine the investment policy of the state and play an important role in addressing a whole range of issues related to the strategic management of the natural resource sector in Russia. For bilevel mathematical programming problems, the computational complexity will be evaluated and effective solution algorithms based on metaheuristics and allowing solving large-dimensional problems will be developed. This opens up the possibility of a practical study on the real data of the properties of Stackelberg equilibrium, which determines the design of the mechanism for forming investment policies. The simulation results will allow not only to assess the impact of various factors on the effectiveness of the generated subsoil development program but also to formulate the basic principles that should guide the state in the management process.

Keywords: Stackelberg game · Bilevel mathematical programming problems · Subsoil development program · Probabilistic local search algorithm

1 Introduction

The development and evaluation of mechanisms for stimulating private investment presents an as-yet unresolved problem for the Russian government. The established practice of making this kind of decisions in subsoil resource management tends to operate with political arguments and most unsophisticated effectiveness evaluations, which are derived from analysis of technological projects and current raw materials prices [1–3].

This problem cannot be solved separately from the general problems of strategic planning, the core of which lies with the goal of forming a program of development of the mineral raw materials base (MRB) [4–6]. This program would set a framework for decision-making on many issues, e.g., the follows.

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What production infrastructure do we need to facilitate spatial development and attract investors? Can we spend additional money from the state budget to help investors when it comes to infrastructural or environmental projects?

How can we help the investor overcome the barriers posed by the lack of necessary infrastructure and by the high costs of environmental protection, which are so typical of most of Siberian and Far-Eastern regions of Russia? What kind of mechanism should we employ to stimulate private investment? If we want this mechanism to unite the various measures of government investment policy and lay a foundation for a program of development of regional natural resources?

These problems are at the center of attention in this work. The aim of this article is to work out a model that could lay a foundation for a practical methodology to generate an MRB development program. To this end, we propose to use the apparatus of bilevel mathematical programming [7] and thus take into account the features of the hierarchy of interactions between the government and the private investor in the mineral raw materials sector. This approach allows us to find a compromise between the interests of the state budget and those of the private investor and generate a natural resources development program that should be effective in terms of sustainable development prospects.

The first section of the article presents the problem statement and formulates a model. The second one focuses on analyzing the computational complexity of the model and on building effective solution algorithms by means of random local search. The third section presents the results of numerical experiments, which make it possible to study the properties of the Stackelberg equilibrium using real data and determine the principles of investment policy formation. The fourth section discusses the results obtained and formulates recommendations for subsoil resource management.

2 Mathematical Models

Here, we consider a model of cooperation between the government and the private investor in the mineral raw materials sector. This model is a generalization of two models, which were considered by the authors in [8,9].

The first one is the classical model of public-private partnership [10–12]. In this model, the investor coordinates with the government a list of infrastructural projects that open for him an opportunity of realizing the desired mineral resource development projects and then implements the coordinated infrastructural projects at his own expense. The government compensates for his expenses when it begins to receive taxes from the private investor's mineral resource extraction operations.

The second model has been in practical use in Russia for a while. This model suggests that on a frontier territory, the government can help the investor build the infrastructure and conduct some of the necessary environmental activities [13–15]. Thus levying some of the issues that arise from the territorial linkage of development projects, the government encourages the arrival of the investor.

In the generalized cooperation model, the government uses an "all-in-one" investment policy by taking on the responsibility for a part of the infrastructural and environmental projects. The investor also builds the infrastructure, and the corresponding expenses are compensated by the government with a time lag. The aim of the government is to develop the territory and obtain the maximum possible share of the natural resource rent in the form of tax payments.

The investor seeks to maximize his net present value, i.e., an overall effectiveness estimate of his participation in the MRB development program, which commensurates his expenses and revenues, respectively, incurred and obtained at different times during the forecasting period. The key role here belongs to the mechanism of compensating the investor's expenses related to the infrastructural projects.

In the first case, the investor claims compensation of his expenses regardless of the overall outcomes of the MRB development program (model A). Thus, the government builds a schedule of payments within its budget constraints in order to compensate for the infrastructural expenses of the investor with a discount factor. The second scheme of the mutual settlements builds upon coordinated estimation of the investor's integral effect from his participation in the joint (i.e., implemented together with the government) MRB development program. The estimation takes into account the investor's infrastructural expenses and the government's compensation payments, which guarantee that the investor's resulting net present value is positive (model B).

Thus, the input data of the investment policy model are as follows:

– a set of industrial projects implemented by the private investor to open mineral deposits;
– a set of infrastructural projects, which can be implemented both by the private investor and by the government;
– a list of environmental projects necessary to compensate for environmental losses due to the implementation of the industrial projects; a part of the environmental projects can be implemented by the government.

The output of the model is the key investment policy parameters, which define the compensation schedule and the investor incentivation (i.e., expense sharing) mechanism. Formally, these data fully defines the MRB development program and the lists of infrastructural and environmental projects implemented by the government and the private investor, respectively.

A formal description of the model can be presented as follows. We use the following notation:

T is a planning horizon; T_0 is a compensation lag; I is a set of investment projects; J is a set of infrastructure development projects; K is a set of environmental projects;

Investment project i in year t:

CFP_i^t is the cashflow (the difference between the incomes and expenses of all kinds, taking into account a transaction costs, constructive borrowed from [3]);
EPP_i^t is the environmental damage from the implementation of the project;
DBP_i^t is the government revenue from the implementation of the project.

Infrastructure development project j in year t:

ZI_j^t is the costs of implementation of the project;
EPI_j^t is the environmental damage from the implementation of the project;
VDI_j^t is the government revenue from local economic development as a result of the implementation of the project.

Environmental project k in year t: ZE_k^t is the costs of implementation of the project.

The matrices μ and ν define the relationship between the projects, where μ_{ij} is a coherence indicator for the infrastructure and investment projects, $i \in I$, $j \in J$, and ν_{ij} is a coherence indicator for the environmental and investment projects, $i \in I$, $k \in K$:

$$\mu_{ij} = \begin{cases} 1, & \text{if the implementation of investment project } i \\ & \text{requires the implementation of infrastructure development project } j, \\ 0 & \text{otherwise;} \end{cases}$$

$$\nu_{ik} = \begin{cases} 1, & \text{if the implementation of investment project } i \\ & \text{requires the implementation of environmental project } k, \\ 0 & \text{otherwise.} \end{cases}$$

The discounts of the government and the investor:
DG is the discount of the government; DI is the discount of the investor;
The budget constraints:
b_t^G is the government budget in year t; b_t^O is the investor budget in year t.
We use the following integer variables:

$$\bar{x}_j = \begin{cases} 1, & \text{if the government is prepared to launch infrastructure development project } j \\ & \text{(the government has included it into the budget expenses),} \\ 0 & \text{otherwise;} \end{cases}$$

$$x_j = \begin{cases} 1, & \text{if the government launches infrastructure development project } j, \\ 0 & \text{otherwise;} \end{cases}$$

$$\bar{y}_k = \begin{cases} 1, & \text{if the government is prepared to launch environmental project } k \\ & \text{(the government has included it into the budget expenses),} \\ 0 & \text{otherwise;} \end{cases}$$

$$y_k = \begin{cases} 1, & \text{if the government launches environmental project } k \\ & \text{as agreed with the investor,} \\ 0 & \text{otherwise;} \end{cases}$$

$$v_j = \begin{cases} 1, & \text{if the investor launches infrastructure development project } j, \\ 0 & \text{otherwise;} \end{cases}$$

$$z_i = \begin{cases} 1, & \text{if the investor launches investment project } i, \\ 0 & \text{otherwise;} \end{cases}$$

$$u_k = \begin{cases} 1, \text{ if the investor launches environmental project } k, \\ 0 \ \text{ otherwise.} \end{cases}$$

W_t, $\bar{W}_t$ is the schedule of compensation payments for infrastructure development in year t, which was proposed by the government and used by the investor.

The government problem $\widetilde{\mathcal{PS}}$ can be formulated as follows:

$$\sum_{t \in T} \Big(\sum_{i \in I} (DBP_i^t - EPP_i^t) z_i + \sum_{j \in J} (VDI_j^t - EPI_j^t)(x_j + v_j) \\ - \sum_{j \in J} ZI_j^t x_j - \sum_{k \in K} ZE_k^t y_k - W_t \Big) / (1 + DG)^t \to \max_{x,y,W,v,u,z} \tag{1}$$

subject to:

$$\sum_{1 \le t \le \omega} \Big(\sum_{j \in J} ZI_j^t \bar{x}_j + \sum_{k \in K} ZE_k^t \bar{y}_k + \bar{W}_t \Big) \le \sum_{1 \le t \le \omega} b_t^G; \omega \in T; \tag{2}$$

$$\bar{W}_t \ge 0; t \in T; \tag{3}$$

$$\bar{W}_t = 0; 0 \le t \le T_0; \tag{4}$$

$$(x, y, W, z, u, v) \in \mathcal{F}^*(\bar{x}, \bar{y}, \bar{W}). \tag{5}$$

The set $\mathcal{F}^*$ is a set of optimal solutions of the following low-level parametric investor problem $\widetilde{\mathcal{PI}}(\bar{x}, \bar{y}, \bar{W})$:

$$\sum_{t \in T} \Big(\sum_{i \in I} CFP_i^t \, z_i - \sum_{k \in K} ZE_k^t u_k - \sum_{j \in J} ZI_j^t v_j + W_t \Big) / (1 + DI)^t \to \max_{x,y,W,z,u,v} \tag{6}$$

subject to:

$$\sum_{t \in T} \Big(W_t - \sum_{j \in J} ZI_j^t v_j \Big) / (1 + DI)^t \ge 0; \tag{7}$$

$$\sum_{1 \le t \le \omega} \Big(\sum_{k \in K} ZE_k^t \, u_k + \sum_{j \in J} ZI_j^t v_j - \sum_{i \in I} CFP_i^t \, z_i - W_t \Big) \le \sum_{1 \le t \le \omega} b_t^O; \omega \in T; \tag{8}$$

$$x_j + v_j \ge \mu_{ij} \, z_i; i \in I, j \in J; \tag{9}$$

$$x_j + v_j \le 1; j \in J; \tag{10}$$

$$y_k + u_k \ge \nu_{ik} \, z_i; i \in I, k \in K; \tag{11}$$

$$y_k + u_k \le 1; k \in K; \tag{12}$$

$$\sum_{i \in I} \nu_{ik} \, z_i \ge y_k + u_k; k \in K; \tag{13}$$

$$\sum_{t \in T} \Big(\sum_{i \in I} (DBP_i^t - EPP_i^t) z_i - W_t \Big) / (1 + DG)^t \ge 0; \tag{14}$$

$$x_j \leq \bar{x}_j; j \in J; \tag{15}$$

$$y_k \leq \bar{y}_k; k \in K; \tag{16}$$

$$W_t \leq \bar{W}_t; t \in T; \tag{17}$$

$$x_j, y_k, v_j, z_i, u_k \in \{0, 1\}; i \in I, k \in K, j \in J. \tag{18}$$

There are mixed integer linear programming problems at each level. In the formulated model, the investor maximizes his NPV and the government sets its aim on obtaining the highest possible budget revenues, taking into account the costs of infrastructure and environmental protection and a cost estimate for environmental losses from the MRB program. The government starts the infrastructure compensation payments to the investor after a lapse of T_0 years (e.g., since the time of receipt of the first tax payments from the investor) (3), (4). The schedule of the compensation payments should ensure: (i) for the government, a balance between the budget revenues and the compensation payments to the investor (14), and (ii) for the investor, a compensation of his infrastructure expenses with a discount factor (7).

Constraints (9)–(13) formalize the relationships between the industrial, infrastructural, and environmental projects. Each infrastructural and environmental project can only be launched by one of the partners and must be necessary for the realization of some industrial project. An infrastructural or environmental project can likewise be assigned to the government only under the condition that the government has put the respective project onto its list (15), (16). The model output provides the key investment policy parameters: x, y, W, v, u, z, which define the investor incentivization (expense sharing) mechanism and the long-term effective MRB development program.

Problem (1)–(18) describes model A and the cooperation mechanism whereby the investor has low trust in the government, i.e., does not expect the latter to fairly compensate for his infrastructural expenses. Constraint (7) formalizes the first mechanism of compensation payments, which arises from unconditional reclamation of the incurred infrastructural expenses, regardless of the overall outcome of the MRB development program. If the partners have high trust in each other, the second scheme of mutual settlements can take place (model B), which builds upon coordinated estimation of the investor's integral effect in the joint (with the government) MRB development program. This scheme is formalized in problem (1)–(6), (8)–(18).

3 Computational Complexity and Solution Algorithm

We recall the definition of the first level of the polynomial hierarchy of complexity classes of decision problems. The first level consists of classes P, NP and *co*-NP. The class P contains problems solvable in polynomial time on deterministic Turing machines. The class NP is defined as the class of problems solvable in polynomial time on nondeterministic Turing machines. The third basic class *co*-NP consists of decision problems whose complements belong to NP. These classes are also denoted as Δ_1^P, Σ_1^P, and Π_1^P, respectively. The second level of the polynomial hierarchy is defined by deterministic and nondeterministic Turing machines with oracle [16]. It is said that the decision problem belongs to class Δ_2^P if there exists a deterministic Turing machine with an oracle that recognizes its in polynomial time, using as oracle some language from class NP. Similarly, the decision problem belongs to class Σ_2^P if there exists a nondeterministic Turing machine with an oracle that recognizes its in polynomial time, using as oracle some language from class NP.

The paper showed that the public-private partnership problem with static budget distribution (without carry-over to next year and to the investor) is Σ_2^P-hard. Based on the ideas of the proof of this fact, we obtain the following statement.

Theorem 1. *The problem (1)–(6), (8)–(18) is Σ_2^P-hard.*

Proof. Consider the Subset-Sum-Interval problem [18]. There are positive integers $q_i, i \in \{1, ..., k\}$, R, and r, where r does not exceed k. It is required to determine whether there exists an S such that $R \leq S < R + 2^r$ and for any $I \subseteq \{1, ..., k\}$ it holds $\sum_{i \in I} q_i \neq S$. It is known that the Subset-Sum-Interval problem is Σ_2^P-hard [18].

We construct the next input of the government problem. Let there be $k + 2^r + 2$ production projects and $R + 2^r - 1$ ecological projects. Suppose that no infrastructure projects are required to implement production projects. Planning Horizon $T = T_0 = 3$. For the first k production projects $CFP_i^1 = 0$, $CFP_i^2 = -q_i$, and $CFP_i^3 = 2q_i$. Suppose that $CFP_{k+1}^2 = -1/2$, $CFP_{k+1}^3 = 1$, $DBP_{k+1}^3 = \Delta$, $CFP_{k+2}^3 = DBP_{k+2}^3 = 2\Delta$, where $\Delta = (R + 2^r + 1)^2$, and $CFP_i^1 = -1$, $CFP_i^3 = R + 2^r + 1$, $k + 3 \leq i \leq k + 2^r + 2$. All other parameters of production projects will be set equal to zero. All production projects, with the exception of the $(k + 2)$th, do not require the implementation of ecological projects. The production project (k + 2) requires the implementation of all ecological projects. $ZE_j^1 = ZE_j^2 = 1$, for any ecological project j. All other parameters of ecological projects are equal to zero. The government's budget in any year is equal $R+2^r-1$. The investor's budget in the first year is equal 2^r, in the second years it is $R + 2^r - 1$, in the third year it is equal to zero.

Obviously, in the optimal solution, a production project $(k + 2)$ is being implemented. For this, due to the limited budgetary opportunities of the investor in the first year, the government must implement S ecological projects, where $R \leq S < R+2^r$. The investor has to implement the remaining projects and then he will spend the remainder of the budget in the first year on the production projects $\{k + 3, ..., k + 2^r + 2\}$. After that, the investor in the second year has exactly S left from the budget, which he can spend on the first $k+1$ production projects. Obviously, if there is $I \subseteq \{1, ..., k\}$ such that $\sum_{i \in I} q_i = S$, then the investor will not implement the project $(k + 1)$. Note that the $(k + 1)$th project is very beneficial to the government. This means that the government will select S $(R \leq S < R + 2^r)$ in such a way that for any $I \subseteq \{1, ..., k\}$ it will be carried out $\sum_{i \in I} q_i \neq S$, if possible. The theorem is proved.

Corollary 1. *The problem (1)–(18) is Σ_2^P-hard.*

Also in [17], an algorithm for solving the public-private partnership problem with static budget distribution is proposed. We modify this algorithm to solve our problem. The first two steps are similar to the original algorithm. Key differences are in the third step. We describe the algorithm scheme.

Step 1: Compute the upper bound UB by solving the government's problem with constraints of the investor's problem.
Step 2: Let *iter* be the number of iteration of the algorithm on step 2. Find a feasible solution using the following procedure:
Step 2.1: Solve the investor's problem with constraints of the government's problem and additional constraint on the value of the objective function of the government: value $\geq UB/iter$.
Step 2.2: In the previous step, we obtain the values of the government's variables. Solve the investor's problem to get the real objective function value. If the real objective function value is very different from optimal value of the investor's problem with constraints of the government's problem and additional constraint then iter:= iter - 1 and repeat the step 2.1.
Step 3: We apply steps 3.1 and 3.2 a given number of times to the solution obtained in the previous step:
Step 3.1: For a fixed value of $\overline{W}$, a specified number of times randomly change the value of the government's Boolean variables. Take the best.
Step 3.2: For a fixed values of the government's Boolean variables, a specified number of times randomly change the value of $\overline{W}$. Take the best.

Note that all auxiliary problems and the investor's problem are solved by CPLEX software. To solve the examples described in the next chapter, the following values of the algorithm parameters were a posteriori selected. In the step 2, *iter* is 30. The step 3 is limited to 2 hours. At steps 3.1 and 3.2, 100 repetitions are performed.

4 Numerical Experiment

The database of model (1)–(18) builds upon special forecasting models, which describe in detail the processes of realization of all the three types of projects [17]. The actual data describe a fragment of the Zabaykalsky Krai MRB, which consists of 50 deposits of polymetallic ores. The experiment considers the implementation of 50 environmental and 10 infrastructural projects (railroad, powerlines, autoroads), combined in such a way that the realization of the entire infrastructural and environmental program would enable the launching of all the MRB development (i.e., industrial) projects.

The numerical experiment technique builds upon analysis of the changes in the properties of solutions of (1)–(18) under varying parameters of the model. These properties include: the values of the objective functions of the government and the investor; the number of implemented infrastructural and industrial projects; the expense sharing proportions; the share of rent received by the government in the form of taxes; etc. This list allows for a meaningful economic interpretation of the implications of a chosen investment policy and helps identify the expected tendencies of change in effectiveness evaluations based on sustainable development criteria.

The following figures present the results of the calculations that studied the reaction of solutions of models A and B to changes in the key model parameters, i.e., the discounts of the investor and the government.

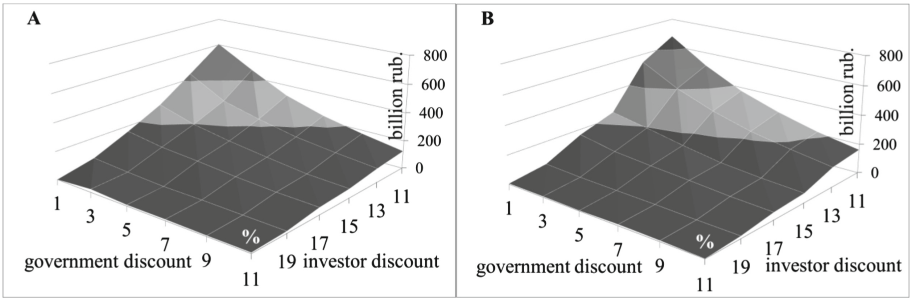

Fig. 1. The government objective function and the partner discounts

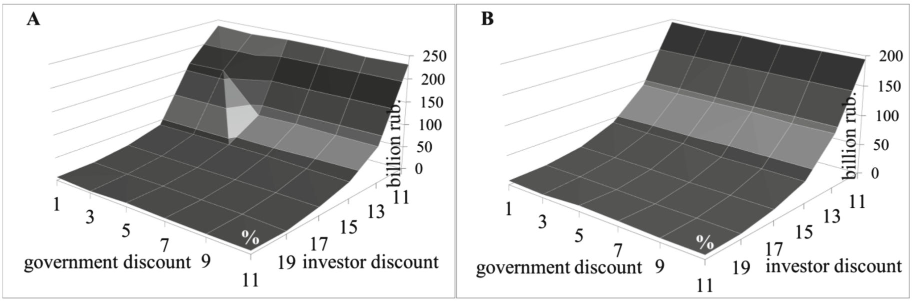

Fig. 2. The investor objective function and the partner discounts

Figure 1 shows the dependence of the government's objective function on the discounts of the MRB development stakeholders. Both surfaces reach their highest values at small discounts, consistent with the fact that under the conditions of a good investment climate, the government finds effective both investment policies, generated by models A and B, respectively. If the conditions worsen (i.e., the discounts increase), the effectiveness of the interaction between the government and the investor drops, predictably, to almost zero in both models. Thus, the problem of policy choice comes to the fore: What policy will provide the best results in the range of high discounts for the majority of resource-rich regions in Russia?

The optimal strategy for a small-discount investor is to claim unconditional compensation of all his infrastructure expenses (model A, Fig. 2). In contrast to Investor in model B, whose functional depends on his discount only, Investor in model A reduces the volume of his infrastructure building operations if the government begins to raise its discount.

Which model is preferable from the viewpoint of the functional (i.e., the decision effectiveness indicator) for the government and the investor? And under what conditions?

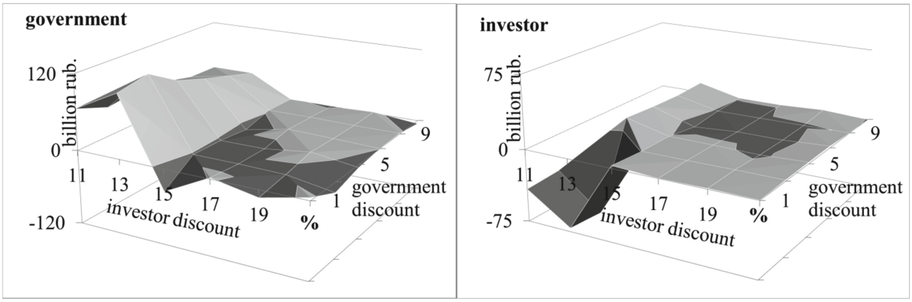

Fig. 3. Difference between the values of the objective functions in models B and A

The answers to these questions are contained in Fig. 3, which presents the difference between the functionals in models B and A. The light-colored part of the surfaces corresponds to the case where model B is preferable in terms of the functional, within these parameter ranges. A meaningful interpretation of Fig. 3 enables the government to choose a strategy that would underpin its investment policy under given conditions.

Thus, in resource-rich regions with a good investment climate, which induces a small investor discount, the government should consider using model B. Under worse investment conditions (high inflation, volatile exchange rates, growing transaction costs, etc.), which force the investor to take decisions with higher discounts, the government should use model B and a high subsoil owner discount.

A small-discount investor should consider the option with unconditional reclamation of his infrastructure expenses. At high investor discounts, model B becomes preferable if the government chooses its investment policy accordingly. This policy builds upon choosing a discount that defines the volume of government investment into the infrastructure and ensures "hitting" the light zone of the surface in Fig. 3.

Which model is preferable from the point of view of the government costs?

Figure 4 shows a relationship between the government costs on compensation payments to the investor in the different models. Here, model B proves to be more effective for the government.

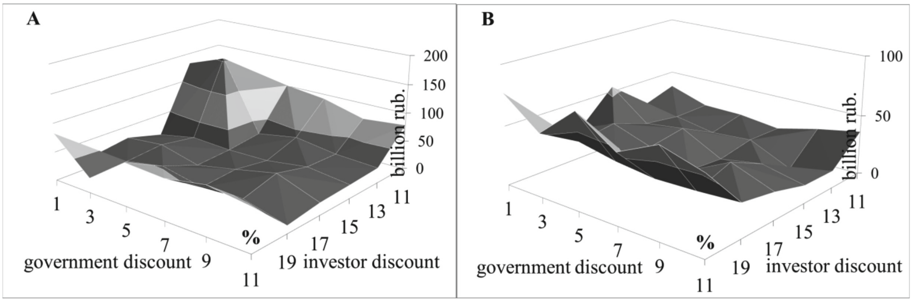

Fig. 4. Government expenses on the compensation payments

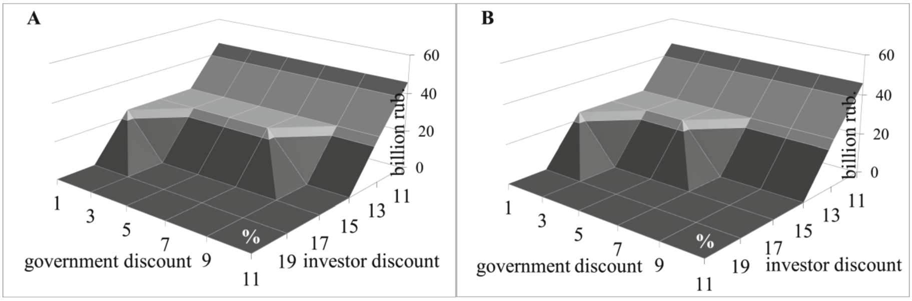

Fig. 5. Government expenses on the infrastructure projects

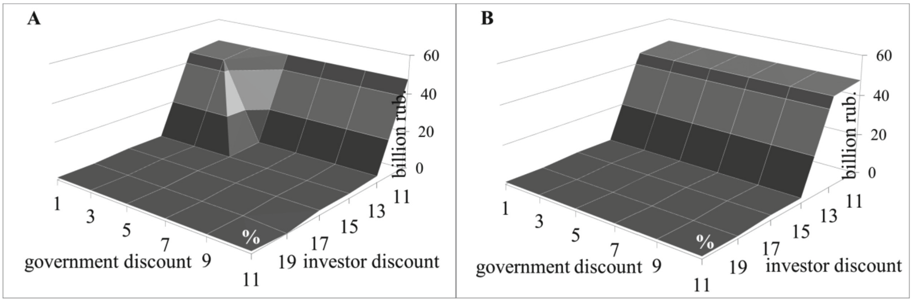

Fig. 6. Investor expenses on the infrastructure projects

Figures 5 and 6 show the dependence between the volumes of the government and investor infrastructure investments on their discounts. Model B gives a greater volume of infrastructure building operations to a small-discount investor. Under adverse conditions, infrastructure is built in both models mostly by the government, and the volume of these operations narrows down with the growing investor discount. As a result, model B is also more preferable in terms of the share of government investment in the infrastructure projects (Fig. 7).

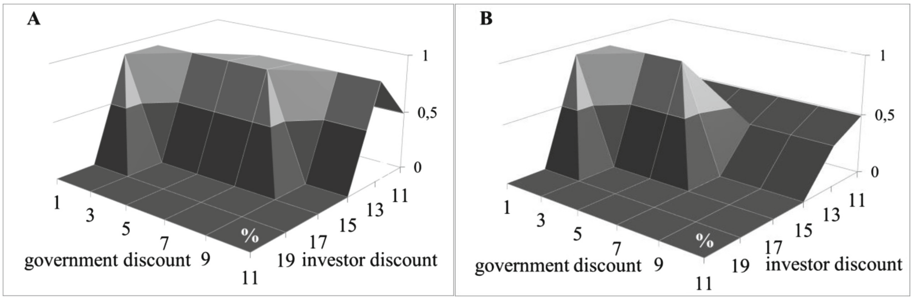

Fig. 7. Share of the government in infrastructure investments

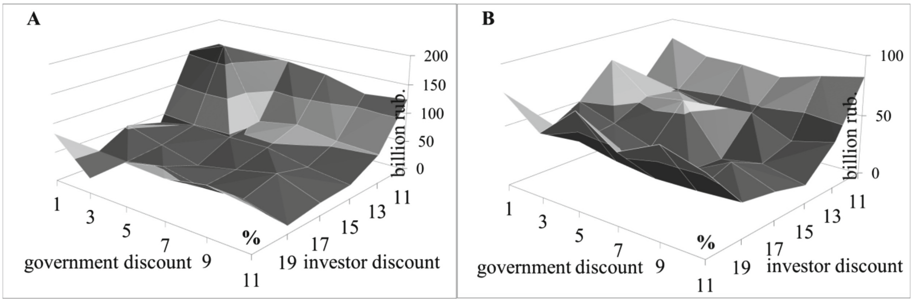

Fig. 8. Total government expenses

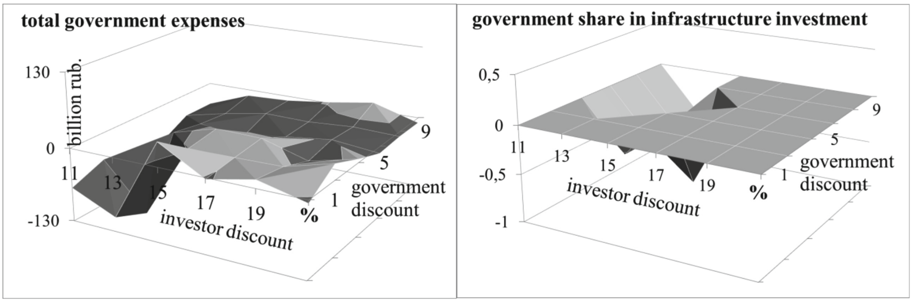

Fig. 9. Difference between the solutions of models B and A

The total government costs, including the expenses on investments and compensations, are shown in Fig. 8. Figure 9 fixes the parameter ranges within which model B is more preferable than A in total costs, which are negative and are marked with dark color in the figure. This figure means that the government costs in model B can be made lower than in A by choosing an appropriate investment policy. At low investor discounts, this happens automatically; under worse investment conditions, the government must choose a high discount, which corresponds to the dark part of the surface.

As for the government's share in infrastructure investments, model B is also preferable for the government (Fig. 9, right panel).

How do the results of this article, [8] and [9] compare?

Substantially, the models differ in the key mechanism for building infrastructure. In [8], infrastructure projects are implemented by the government. In [9], an investor builds infrastructure, its costs are compensated with some lag. The infrastructure is built by both partners in this article.

A comparative analysis of the calculation results allows us to draw the following conclusions. The model [8] provides the highest values of the objective function of stakeholders, however, it requires the highest government spending. The classical model of public-private partnership [9] minimizes budgetary costs but does not provide a sufficient level of profitability today. Models A, B occupy an intermediate position, realizing a compromise of budget savings and efficiency. The choice in favor of a particular model depends on the prevailing conditions of a particular region.

5 Results and Discussion

The bilevel mathematical programming models described above can serve as a foundation for a practical methodology to form a complex of investment policy measures in a resource-rich region. The algorithms proposed in this work may help solve problems of high dimension and formulate real strategic plans for building industrial infrastructure, which encourage the arrival of the private investor.

The numerical experiments conducted on the actual data reveal the practical significance of the proposed tools. Based on the results of the experiments, we can draw the following main conclusions to underpin the process of management in the mineral raw materials sector.

1. In regions with a favorable investment climate and mature institutions, which together ensure a small discount of the potential investor, both models maintain an acceptable effectiveness level for the government. Under the same conditions, the investor should consider a strategy of unconditional reclamation of his infrastructure expenses.
2. If the conditions worsen (the investor discount increases), the government must use model B and a high subsoil owner discount. This discount defines the government investment policy and should be chosen in such a way that model B becomes preferable for the investor as well.
3. Given a budget deficit, the government should consider model B. This model would enable it not only reduce the volume of compensation payments but also cut the total costs incurred by it, which include, apart from the payments to the investor, the government's own expenses on infrastructure.

Thus, the main goal of the government on a frontier territory rich in natural resources when it comes to investment policy formation is to create the conditions for model B to realize. The key condition is a high level of mutual trust between the government and the investor, which enables them to use a mutual settlement scheme based on coordinated estimation of the investor's integral effect in the partnership-based MRB development program. If the parties achieve such a level of trust, then the proposed mathematical tools will allow the formation of a long-term effective investment policy.

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