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INTEGRATED CLIMATE CHANGE IMPACT ASSESSMENT AND AN ADAPTATION FINANCING MECHANISM FOR INFRASTRUCTURE FACILITIES

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Abstract. This paper addresses the planning and management aspects of adaptation measures for mitigating the adverse impacts of climate change on economic infrastructure facilities. We navigate through the complexities of risk assessment in the face of climate change uncertainties. The integrated assessment of infrastructure facilities using climate forecast maps and facilities vulnerability maps is structurally described. An approach is proposed to form a portfolio of infrastructure facilities. They are selected in two stages as follows. In the first stage, a preliminary portfolio of facilities is formed using integrated assessment. In the second stage, investment resources are sequentially allocated to preliminary portfolio's facilities in descending order of their specific risk assessment. Due to a limited investment fund, the second stage yields the final portfolio of facilities for implementing adaptation measures. We present an incentive mechanism for adaptation measures under the Principal's incomplete information. This mechanism is optimal and provides reliable data from the facilities to the Principal (possesses strategy-proofness).

Keywords: climate change, adaptation, integrated risk assessment, selection of infrastructure facilities, allocation of investment funds, costs, financing mechanisms, incentives.

INTRODUCTION

When developing projects of significant infrastructure facilities (IFs), e.g., industrial, energy, and transport infrastructure facilities, with long construction and operation periods, it is required to analyze and forecast their life cycles. For such a facility, the life cycle forecast—from the beginning of its construction to the end of its operation——includes the forecast of external impacts on the facility at the design stage. One of the facility's most important external factors is the impact of climate changes (CCs) on the course of its construction and operation. Consequently, during the design, construction, and operation of facilities, it is necessary to provide in advance for adaptation measures concerning the forecasted adverse impacts of CCs.

The initial basis for planning and carrying out adaptation measures is climate change forecasts. CCs up to 2050–2059 and 2090–2099 on the territory of the Russian Federation and their impact on the environment and economic agents were forecasted in [1]. Also, the current and expected CCs, their impact on the environment, population, and economy of the Russian Federation, their consequences, and the main adaptation measures for CCs were described in [2].

Roshydromet presented R&D results in the field of scientific and methodological justification of sectoral and regional adaptation strategies for current and expected CCs [3]. In particular, the problem of the economy's adaptation to CCs was systematically analyzed, the main concepts, goals, and tasks of adaptation were considered, and the ways and difficulties of achieving these goals were outlined.

The standard [4] is the fundamental document in this area. It describes the domains of application, terms and definitions, and the general principles of adaptation of IFs to CCs, including requirements for planning and implementing adaptation processes. The document refers to related international standards and publications.

Challenges and opportunity windows in the field of adaptation to CCs were considered in [5]. As was noted by the author, a climate insurance system should be developed. Domestic publications on the description of CC risks and their impact on the sustainable development of the country's socioeconomic sphere were overviewed in [6].

In the sectoral context, the problem of adaptation to CCs was studied in several works as follows. Mikheev outlined the problems associated with the impact of CCs on oil and gas industry facilities and discussed approaches to the creation of a risk management system and adaptation to CCs [7]. The increase in the costs of eliminating environmental consequences in the absence of proper preventive measures was analyzed in [8]. Khlebnikova, Datsyuk, and Sall considered the possible impacts of climatic factors on construction, land transport, and fuel and energy facilities and described some directions for applying adaptation measures. It was argued that CCs cause risks but also give new opportunities, especially with the development of alternative energy [10]. The issues of risk assessment, crediting, and insurance in the construction of facilities considering adaptation measures were discussed in [11].

The problems of risk assessment for CCs, including planning and implementation of adaptation measures, were addressed in many foreign publications. The related studies and their major results were presented in several reviews. The most comprehensive treatment of this range of problems was provided in [12–14], the papers focused on the railway industry. The references to the main publications on the subject can be found therein. Note that the problems of adapting the railway infrastructure to CCs are typical for the infrastructure of other economic sectors as well. Therefore, we provide references to these reviews only.

The problems arising when assessing the consequences of adverse impacts and the possibilities of carrying out adaptation measures for railway infrastructure facilities were overviewed in [12]. The cited authors considered the relationship between various climatic factors and their possible impacts on infrastructure facilities, gave examples of particular adaptation measures, and analyzed problems of assessing the risks of CCs for railway infrastructure. The operational features and construction measures to ensure climate-resilient railway infrastructure were described in [13]. Requirements for the strategy of adaptation measures to CCs for railway transportation were specified in [14].

In the UK, the report entitled *Tomorrow's Railway and Climate Change Adaptation* (TRaCCA) was prepared for the key representatives of the railway transport industry [15]. The report covered the following issues: the current understanding of weather hazards on the railroads; how these may change in the future; current resilience and adaptation measures for CCs; opportunities for further resilience and adaptation measures; and requirements for further structures and tools to support cost-effective actions.

Dawson et al. presented a systems framework for national assessment of climate risks to infrastructure in the context of different countries [16].

According to the analysis of domestic and foreign publications, IFs are interdependent and require a complex response to climate impacts. To understand the benefits of adaptation, it is necessary to have information about initial conditions and an adequate risk assessment. Traditional risk assessment methods are not applicable under deeply uncertain conditions and inaccurate climate forecasts for the long term [12]. Due to these ambiguities, the risk characteristics of climatic hazards and impacts on facilities are assessed using ranking indicators of potential risk, which can take, e.g., such values as "low," "moderate," "high," and "very high"; for details, see [7, 17].

This paper deals with the problems of risk assessment under uncertainty as well as possible solution approaches. In the case of several types of hazards acting simultaneously on a facility, the issue of risk assessment still remains insufficiently investigated. We propose an integrated assessment procedure for several hazards and their impact on different IFs. This procedure is used to form a portfolio of the most important facilities from a large number of IFs to implement adaptation measures. The general principles and application examples of the procedure for assessing alternative fuels in railway transportation were described in [18].

The standard [4] requires reliable initial data for adaptation planning. More accurate and reliable data are usually concentrated among the staff of the facilities for which adaptation investments and measures have to be planned. Requesting these data by a control authority may result in their deliberate distortion (misrepresentation) due to the desire of IFs to receive higher funds (their strategic behavior). We propose an incentive mechanism for adaptation measures that stimulates the IF staff to report reliable data to the control authority.

1. CHALLENGES, CONSTRAINTS, AND APPROACHES OF ADAPTING INFRASTRUCTURE TO CLIMATE CHANGE UNDER UNCERTAINTY

During the construction and operation of IFs, decisions on adaptation to CCs are based on the forecasts of CCs and the risk assessments of their adverse impact. According to the classical description of risk for CCs [12], the risk of the adverse impact of CCs is usually understood as the probability of CC hazards multiplied by the amount of expected damage due to these hazards. However, using the classical definition of risk entails certain difficulties and is acceptable under very restrictive assumptions; see [12, 16] and the references in [12].

Since the implementation of adaptation decisions often requires significant investments and is designed for the long term, long-term CC forecasts are required. However, such forecasts have neither acceptable accuracy nor reliability.

Climate changes generate the following chain of factors affecting IFs: "CC factors—hazards—impacts––vulnerabilities—consequences" (Fig. 1). Each factor mentioned may have different intensities and is described by a conditional probability given the previous factors in this chain. Unfortunately, it is difficult to estimate the intensities and the probabilities of these factors due to the insufficient statistics of meteorological, hydrological, and climatic monitoring and, most importantly, due to the significant uncertainty of long-term forecasts. In addition, the relationship between the factors is uncertain and unstable.

The impact of these factors on IFs depends on the type of facilities, their cost and service life, and the design and construction standards used. Infrastructure facilities have different vulnerability depending on their design features, geographical location, and operational life.

The inherent uncertainty of CC forecasts and realization scenarios of this chain generates several fundamental problems when developing a plan of adaptation measures for the adverse impact of CCs.

The first problem is an uncertain intensity and unreliable estimates for the probabilities of hazards in different regions and territories where facilities are located. Therefore, it is necessary to consider the geographical distribution of factors in a country with the landscape and natural and climatic features of its regions.

The second problem consists in the following. Let the probability and intensity of CC hazards be determined. It is required to assess the impact and probability of each hazard for an IF in the region under consideration. The matter is that the manifestation of a hazard not necessarily leads to an impact on the facilities due to their protection on the territory. On the contrary, a small manifestation of a hazard may have a strong impact. (For example, a facility located in a low-lying area or a river floodplain may suffer from waterlogging even under moderate rainfall.)

The third problem is related to assessing the IF's vulnerability. It is necessary to examine and diagnose a facility in situ to reliably assess its vulnerability under different types of impacts and CC hazards. In most cases, this procedure is expensive and time-

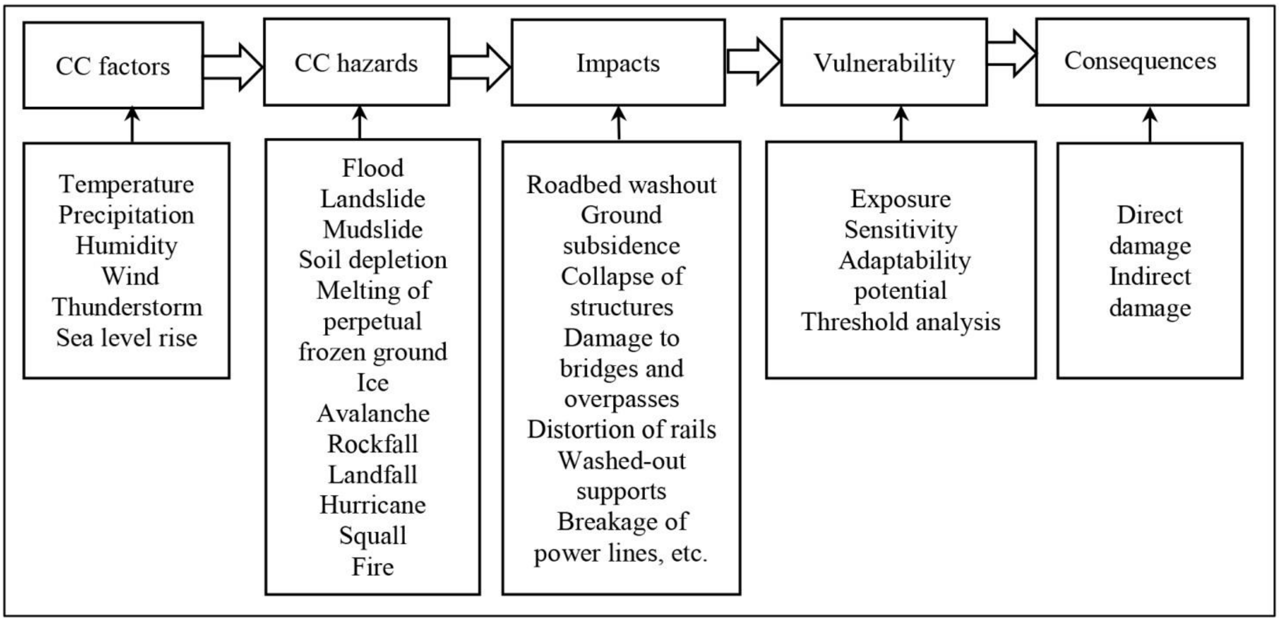


Fig. 1. The factors of adverse impact of CCs in IF risk assessment.

consuming. For newly constructed or designed facilities, vulnerability assessment should be performed at the project development stage. For the railway industry as one example, in addition to climate forecasts, it is necessary to consider the evolution of railway infrastructure and rolling stock, transition to alternative fuels, variable demand for transportation, higher load on the railway bed under the increased volume of transportation services, the impact of high-speed traffic, etc.

The fourth problem concerns assessing the consequences of the impact of CC hazards on IFs. Depending on the intensity of impacts and the facility's vulnerability, the consequences may include:

- direct damage (the loss of useful properties of the facility and the costs of its restoration);
- indirect damage (system losses due to the terminated or limited operation of the facility, i.e., the impact on the operation of related facilities and systems).

There are three main components of the economic costs of infrastructure incurred by climate changes:

– the cost of damage from the direct impact on an IF, which resulted in the facility's destruction or the disruption of its functions;

– the cost of losses for the consumers of facility's services due to the disruption of its functions;

– the cost of adaptation measures.

The dependence of such consequences on forecasted natural impacts is difficult to assess in quantitative terms. For example, the destruction of bridges leads to their long-term inoperability and high costs of restoration. It is necessary to consider the failure severity of some IFs, which can be systemic in nature and have a significant impact on the state, economy, and life and health of the population. Systemic projects and measures that impact dependencies within and outside the region are crucial to understand. As for road infrastructure, one should also consider the availability of possible bypasses in the event of road destruction.

In addition, we emphasize the existence of a nonlinear relationship between different hazards. The combined effect of two or more hazards may have a cumulative effect with hard-to-predict consequences.

These risk assessment problems point to the complexity of planning adaptation decisions.

When implementing projects and measures on adapting IFs to CCs, investment constraints become significant. The number of IFs exposed to CCs is measured in hundreds or even thousands; therefore, it is necessary to determine the set of priority facilities and the implementation level of adaptation measures.

In view of these uncertainties and limitations, in practice, reliable risk assessments cannot be obtained fast and, consequently, the best decisions cannot be made under incomplete information. In such conditions, one has to find "boundedly rational" decisions, i.e., approximate, but adequate and effective enough, alternatives for the optimal adaptation decisions of the ideal case (accurate CC forecasts and complete information about the impact, vulnerability, and damage for the facilities under consideration).

Due to its complexity, the accurate risk assessment problem under unreliable climate forecasts and incomplete information about the impact of CCs and the vulnerability of facilities should be decomposed into several tasks as follows:

- identify regions exposed to the most hazardous factors of CCs;
- form a set of the most vulnerable IFs in these regions;
- describe the CC scenarios at the locations of these IFs;
- assess the impact of CCs on the IFs in these scenarios, including the (direct and indirect) damage considering the cost of restoration or construction of the facility;
- assess the need for investments in adaptation measures and select the IFs with the maximum reduction of CC risks;
- collect updated information about the impact of CCs and the vulnerability of IFs and ensure the reliability of this information (strategy-proofness);
- develop projects and plans for implementing adaptation measures.

These tasks are solved through complex R&D works, including organizational, scientific, and project measures. For the successful implementation of these measures, it seems fruitful to apply the framework of organizational control and management [19, 20].

In this paper, we develop three methods within this framework to solve the tasks mentioned above:

- determine a set of priority IFs for adaptation measures;
- allocate investment resources among IFs to finance adaptation measures depending on their volume;
- ensure the reliability of the facility's staff information (strategy-proofness).

We apply the integrated assessment method to determine the facilities with the highest risk. This method is based on ranking indicators [7, 17, 18] and is applicable under incomplete and inaccurate initial data.

The diagram in Fig. 2 describes the sequence of actions in the technology for selecting IFs, investing, planning, and incentivizing adaptation measures, as well as the methods under consideration within this technology. Blocks 1–4 correspond to the preliminary selection of IFs using the integrated assessment method. This method is described in Section 2. Blocks 5 and 6 mean the works on the initial examination of IFs from the preliminary portfolio (obtained in blocks 1–4). The description of these works goes beyond the scope of this paper: they are specific for each IF and require an analysis of its peculiarities. The initial examination results in approximate numerical estimates of risk and investments needed for adaptation measures. By assumption, the number of facilities in the preliminary portfolio is much smaller than the number of initial IFs. Blocks 7 and 8 are intended to form the final portfolio, in which the number of IFs can be much smaller compared to the preliminary one. Blocks 7 and 8 are described in Section 3.

Blocks 9–11 indicate the design of a planning mechanism for an indicator characterizing the volume of adaptation measures and the selection of an incen-

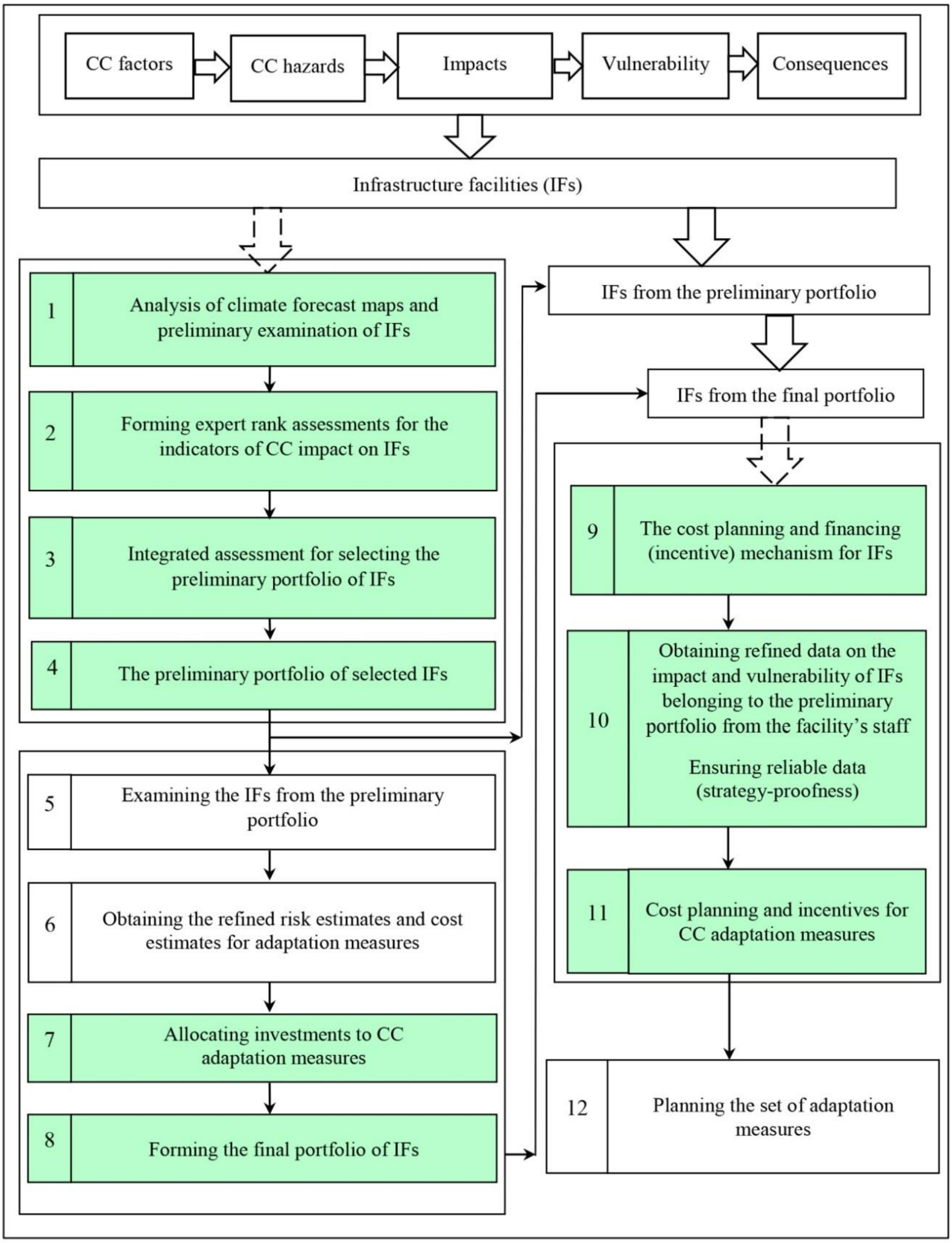


Fig. 2. The technology for selecting IFs for adaptation measures and their investment mechanism.

tive function for the IF's staff. When selecting the planning mechanism and the incentive function, the objective is to stimulate the IF's staff to report reliable data (the impact of CC hazards on the IF and its vulnerability) to the control authority of adaptation measures. By assumption, the IF's staff has more meaningful and accurate data about the facility, as opposed to the control authority. Blocks 9–11 are described in Section 3. Let the output data of blocks 9–11 be supplied to the input of block 12, where adaptation measures for the IF are planned in detail. The content of this block depends on the specifics of a particular IF and is not considered in this paper.

2. ASSESSING AND SELECTING INFRASTRUCTURE FACILITIES FOR ADAPTATION MEASURES: DECISION SUPPORT

Consider a given territory of the country with a large number of IFs, which can be exposed to CCs to a different extent. By a natural assumption, adaptation measures to CCs can be implemented at part of the facilities. This is due to a possibly insignificant influence (i.e., the low risks of the adverse negative impacts of CCs at some facilities) and a limited investment fund for adaptation measures. Hence, it is required to select facilities from the set of IFs for implementing adaptation measures. Note that facilities should be selected in descending order of the risk of the adverse impact of CCs. Generally speaking, assessing this risk for each IF is a time-consuming and expensive procedure that requires costly examination and diagnosis of the facility. Therefore, in practice, this procedure cannot be performed for all IFs. Moreover, it is not always possible to perform this procedure due to different uncertainties; see the discussion in Section 1. In such conditions, one has to apply an approach combining regular methods and expert opinions.

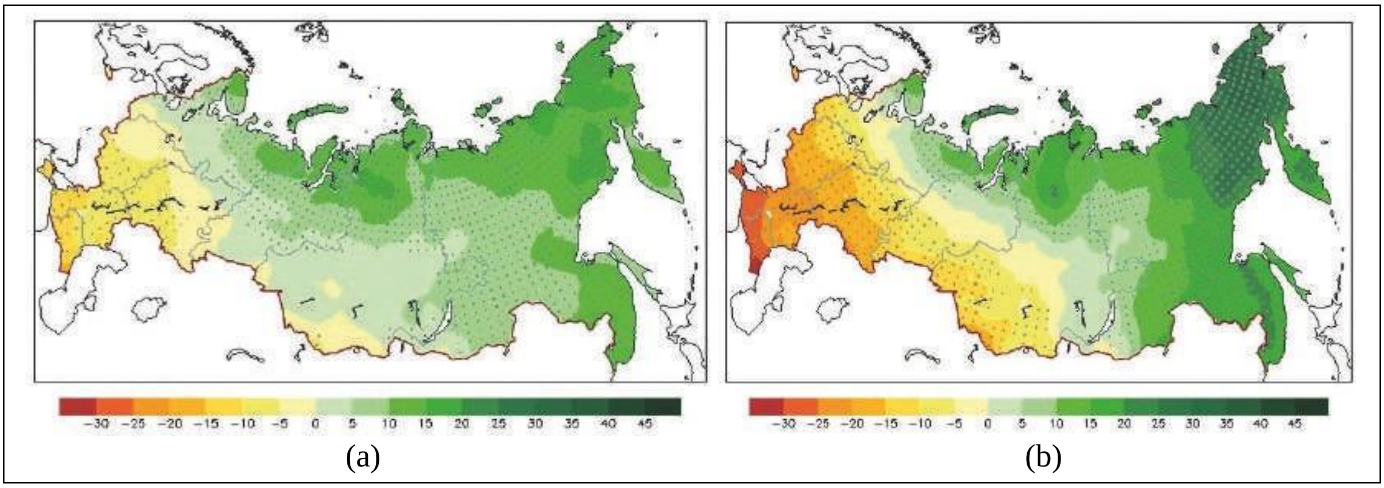
This problem can be solved in two stages as follows. In the first stage, we form a large set of candidate facilities (the preliminary portfolio) for implementing adaptation decisions using expert risk assessments.

In the second stage, sufficiently adequate numerical estimates are obtained for necessary investments in adaptation measures and the risk of adverse impacts of CCs for the IFs selected in the first stage. By assumption, such estimates can be obtained for a finite set of IFs selected in the first stage. The second stage requires examination and yields a refined risk assessment through an in-depth audit of IFs, a forecast of possible consequences and damage from CCs based on meteorological and hydrological monitoring data, climate forecasts, and a forecast of the vulnerability of IFs considering their updating and depreciation.

In the first stage, the need to implement complex infrastructure projects to support adaptation decisions is estimated using the integrated assessment mechanism [18]. This mechanism involves the following sequence of actions.

1. Form an exhaustive set of IFs (if possible) for potential adaptation projects.
2. Determine a set of CC hazard factors for the risk of adverse impacts of CCs on the IFs.
3. Form a convolution tree for the indicators characterizing the hazard factors and damage from CCs for all IFs. The initial damage indicators and characteristics of the hazard factors should correspond to the leaves of this tree.
4. Define discrete (ranking) measurement scales for each damage indicator and hazard factor of CCs. Continuous scales are transformed (by appropriate algorithms) into discrete scales to compare them with the indicators that are initially measured in ranking scales. To restrict the dimension of the assessment procedures, it is recommended to choose three- or four-rank scales.
5. For each vertex of the tree built at Step 1, assign a pairwise convolution matrix of indicators. These matrices have the following structure. The number of rows corresponds to the dimension of the discrete scale of the first indicator in the pair, and the number of columns equals the dimension of the discrete scale of the second one. The matrix elements are the convolution values of the indicators having the values of the first and second indicators. The ranks of all indicators are determined for each IF.
6. Move down the tree, leaves to the root. Calculate the intermediate and final values of the integrated assessment using the convolution matrices.

Consider an example of building an integrated assessment system to form a preliminary portfolio of IFs. Let the following hazard factors affect IFs: precipitation, flood, landslide, slump, washout, and cyclone. These factors are characteristic of the IFs due to climatic impacts in the Far Eastern and Southern Federal Districts of Russia. For each of these hazard factors, we establish a four-rank scale. Considering its location, ranks for each IF are assigned by analyzing climate forecast maps. Figure 3 shows an example of such maps describing seasonal variations in the amount of precipitation.



(a) (b)

Fig. 3. Climate maps showing changes in the average seasonal (summer) amounts of precipitation (in %): (a) years 2018–2100 vs. (b) years 1995–2014 [2].

Note that the intensity of precipitation on the maps has 17 grades marked by different colors. By comparing the change in the amounts of precipitation (corresponding to the color change) at a fixed point on the two maps, we can form a ranking scale for the precipitation factor. The color change on the maps is considered at the IF's location. We divide all changes in the hazard factors of CCs into four ranks as follows: critically unfavorable changes (rank 4), strong changes (rank 3), weak changes (rank 2), and insignificant or zero changes (rank 1). Such operations are performed for all hazard factors. Thus, for each IF, a rank is assigned to each of its hazard factors.

Now we describe the formation of damage ranks for a hazard factor. The damage rank depends on the impact of the hazard factor, the vulnerability of the IF, and the consequences. An example of forming this rank is presented in Fig. 4.

Forming an integrated assessment implies using expert opinions about the vulnerability of facilities and possible damage when determining the scales and ranks of IF indicators. Experts are the representatives of regional organizations responsible for maintaining infrastructure objects.

The lower part of Fig. 4 presents initial data for the integrated assessment of damage from each hazard factor of the IF. When determining the scales and ranks of IF indicators, expert opinions about the impact and vulnerability and possible consequences of the hazard factor are used. The upper part of Fig. 4 presents the scheme of transforming the initial ranking indicators into the final ranking indicator of damage using convolution matrices for the hazard factor.

Let all initial indicators be assigned a four-rank scale (1, 2, 3, and 4). Ranks 4 correspond to the maximum vulnerability, the maximum impact, and the critical values of direct and indirect consequences. Ranks 3 correspond to moderate values of these characteristics; ranks 2, to small values; ranks 1, to negligible values (no significant vulnerability, impact, or direct and indirect consequences).

Integrated assessments are based on measuring the initial data in ordinal scales. Ranking scales for the risk assessment of hazard factors of CCs were justified in [7, 17], and some examples of such scales were provided. Climate maps describing CC parameters in ranking scales were presented in [1–3].

The ranks and convolution matrices can be estimated using the approach and example considered in [18]. As a rule, such matrices are obtained based on expert opinions. The problems of convolution matrix formation based on a training sample for an integrated assessment system were investigated in [21]. In particular, methods were proposed to build convolution matrices for indicators within an integrated assessment system based on empirical data. According to the integrated assessment experience, it is possible to apply the following scheme. First, convolution matrices are formed from common sense and consultation with potential users of the system; then, the matrices are tuned during the pilot operation of the system.

Consider an illustrative example of filling the convolution matrices for the scheme in Fig. 4.

Table 1 contains the initial data for calculating hazard ranks based on the climate impact sensitivity scale.

The corresponding ranks are calculated for each damage characteristic according to Table 1. Then the integrated damage assessments are determined using the convolution matrix and the scheme in Fig. 4. This scheme requires filling the elements of the convolution matrix. First, the impact and vulnerability ranks are convoluted. Table 2 shows a variant of filling the corresponding matrix.

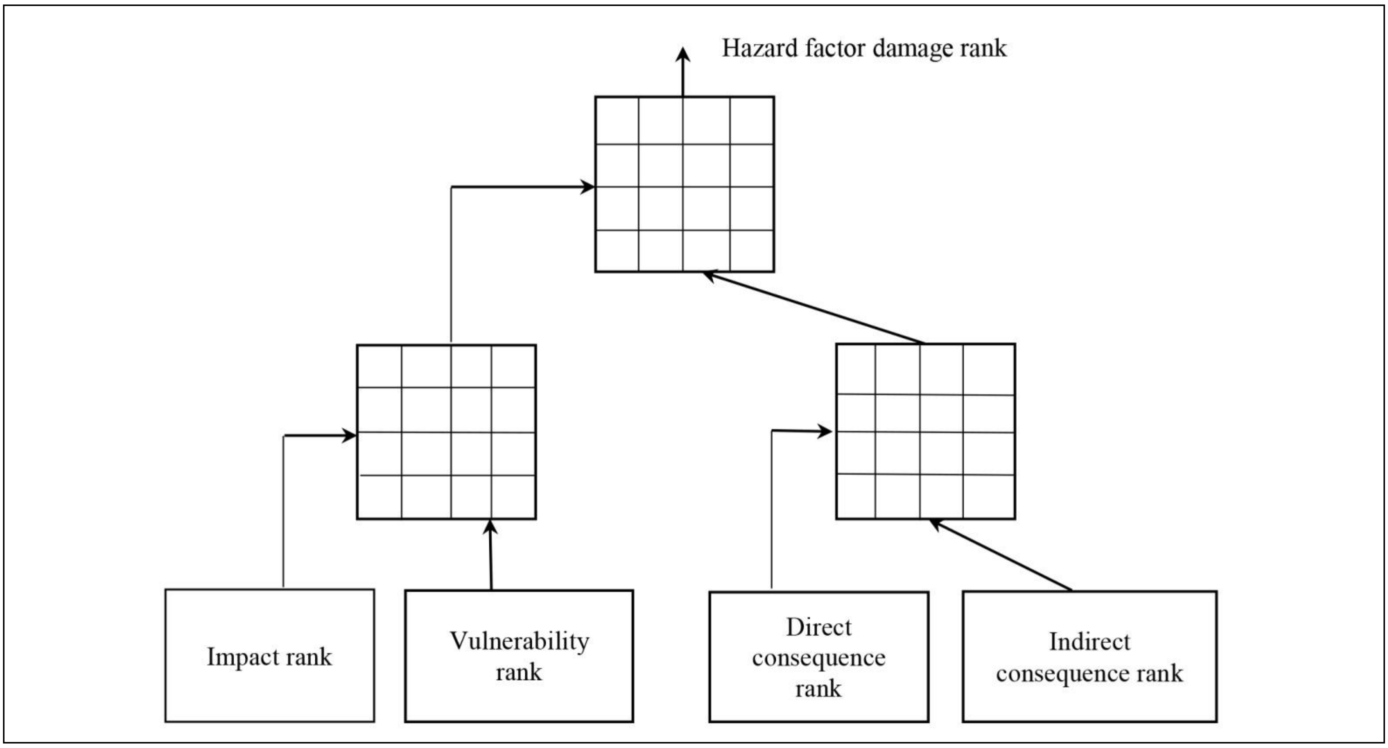


Fig. 4. Calculating hazard factor damage ranks.

Table 1

Indicator scales for calculating hazard factor damage ranks

Rank	Damage characteristics for IFs			
	Impact	Vulnerability	Direct consequences	Indirect consequences
1	Minor	Absent	Absent	Absent
2	Weak	Weak	Acceptable	Acceptable
3	Restrictive	Medium	Costly	Costly
4	Blocking	High	Critical	Critical

Table 2

The convolution matrix for impact and vulnerability ranks

	Vulnerability			
Impact	1	1	1	2
	1	2	2	3
	1	2	3	4
	1	3	4	4

Table 3

The convolution matrix for direct and indirect consequence ranks

	Indirect consequences			
Direct consequences	1	1	2	3
	1	2	3	3
	3	3	4	4
	4	4	4	4

When calculating convolutions using these matrices, the row with the first indicator's rank and the column with the second indicator's rank are selected. For example, in the first convolution, the third row and the fourth column are selected for the impact rank equal to 3 and the vulnerability rank equal to 4. At their intersection we obtain a convolution of the indicators equal to 4. The resulting convolution is the first input indicator for calculating the hazard rank of the facility (i.e., it determines the row of the final convolution matrix, see Table 3). The assessment by the indicators of direct and indirect consequences is the second input indicator (the column number in the final convolution matrix).

Table 4

The final matrix for determining the damage rank of IF by a hazard factor

	Rank of the second convolution			
Rank of the first convolution	1	1	2	2
	1	2	3	3
	2	3	4	4
	3	4	4	4

Thus, the hierarchical system of matrix convolutions in Fig. 4 allows estimating the damage ranks for a selected hazard factor of the IF. The results of these calculations are the input indicators for determining the final integrated risk assessment for the IF under consideration; see Fig. 5.

The convolution matrices for hazard factor ranks and damage ranks (Fig. 5) are formed using expert opinions similar to the matrices in Tables 1–4.

The integrated assessments of the IFs obtained by this scheme are used to select the most hazard-prone facilities. Let the IFs under consideration be arranged

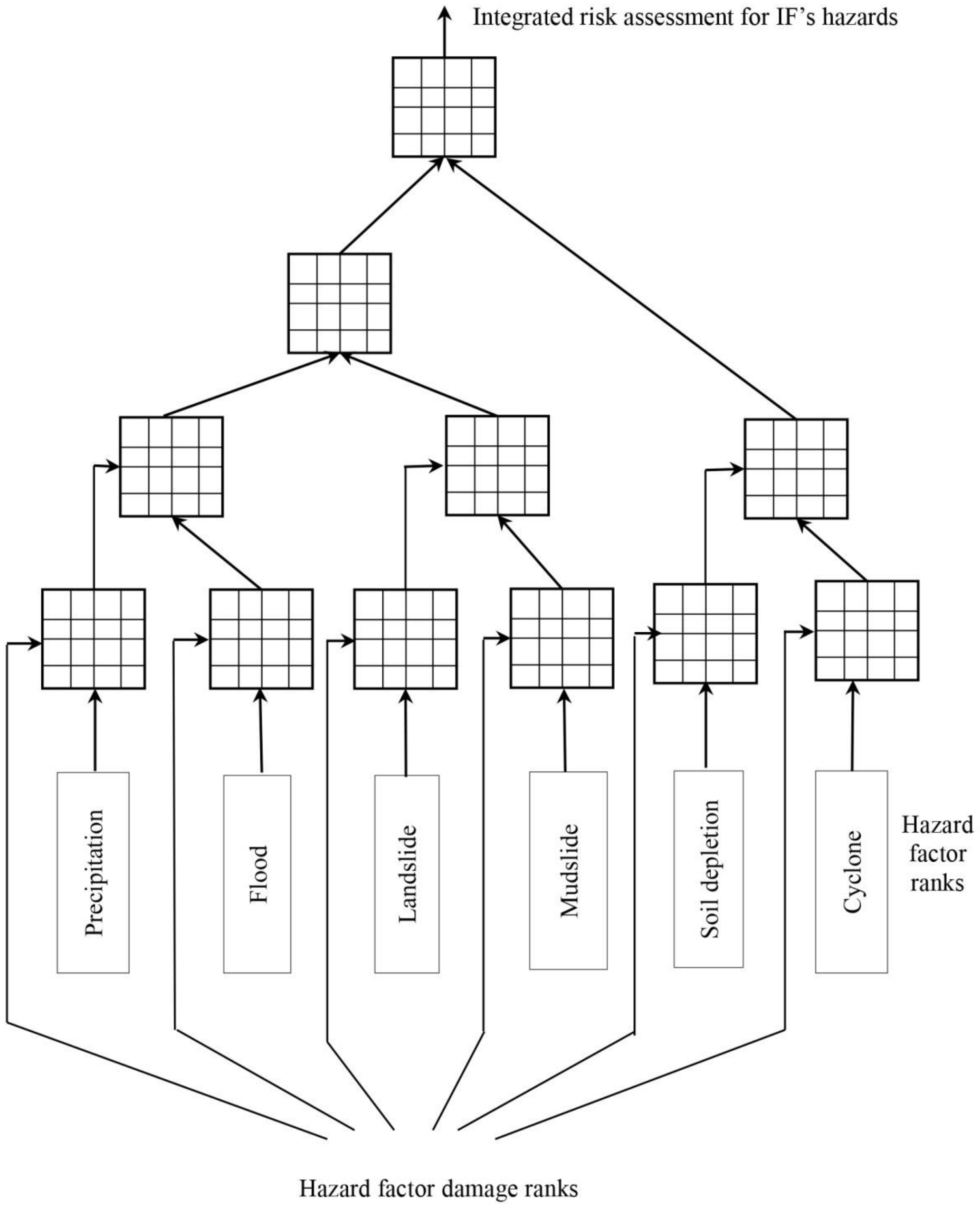


Fig. 5. The integrated risk assessment procedure for IFs.

in descending order of the integrated assessment rank. In this way, we find the groups of IFs prone to different degrees of hazard. The facilities with integrated assessment ranks 4 and 3 should be further examined. They are candidates to receive investment funds for adaptation measures, i.e., form the preliminary portfolio (Fig. 2).

The integrated assessment procedure for projects (including all stages and numerical characteristics of the initial, intermediate, and final indicators), as well as a justification for using ranking scales and an interpretation of their values, was described in detail in [18].

3. INVESTMENTS IN CLIMATE CHANGE ADAPTATION AND FINANCING OF ADAPTATION MEASURES

3.1. An Investment Allocation Mechanism

Following the procedure presented above, we select a preliminary portfolio of infrastructure facilities for further examination in terms of the necessity and feasibility of adaptation measures. For the facilities from this portfolio, more accurate risk assessments and required adaptation funding are determined based on their examination in situ. If adaptation measures cannot be implemented in full on all the facilities from the preliminary portfolio due to the limited investment fund, we propose to apply an allocation mechanism based on the risk assessment–costs method, ideologically similar to the greedy algorithm for solving the knapsack problem [22]. According to this method, facilities are sequentially selected (and necessary resources are allocated to them from the available investment fund) in descending order of the value w_i/u_i, where w_i and u_i denote the risk assessment and required investments of facility i, respectively. Generally speaking, the greedy algorithm is not optimal [22]. However, in practice, the investment fund is often not rigidly fixed. In the case of an insignificant shortage of investments, as a rule, the investment fund can be increased to include one more facility in the portfolio. In this case, the greedy algorithm becomes optimal.

When forming an investment portfolio for adaptation measures, the inclusion of a facility in the portfolio may require the inclusion of one or more other facilities due to the existing technological links to the former facility. In a system of interconnected facilities, investments can be allocated by the algorithms described in [23].

3.2. A Model for Adaptation Planning and Financing

After the preliminary allocation of funds among the IFs for their adaptation, the next problem is to plan and finance the corresponding measures depending on their volume within the available funds.

The planning of adaptation measures and their financial support at the sectoral level can be performed by environmental and safety departments as well as by the departments responsible for infrastructure development and maintenance. For example, in the railway industry of Russia, these tasks are assigned to the Departments of Technical Policy, Ecology, and Technosphere Safety and the Central Infrastructure Directorate. In what follows, the authority responsible for planning and financial support will be conventionally called the control authority (CA).

For planning, the CA uses information received from the executors of adaptation measures. In the case under consideration, this information is the data reported by the staff responsible for carrying out measures on a particular IF. By assumption, the staff is informed about the IF’s vulnerability and the possible impact on the facility due to climatic factors, unlike the CA. However, there exists the problem of strategic behavior (data manipulability) since the facility’s staff may have private interests in funding and the adaptation plan. In this case, the facility’s staff may try to influence the plan and funding by distorting the data reported. We introduce an abstract model describing this problem, which may arise at real facilities when managing adaptation measures. The approach discussed below is based on the theory of active systems and organizational control considering the specifics of IFs; for example, see [19, 20, 24, 25].

Let y be the amount of damage due to the impact of CCs and g be the investment fund allocated for the IF under study. The system consists of the CA, which carries out planning and funding, and the Agent (a representative of the facility’s staff), see Fig. 6. We denote by ξ the impact of CCs on the facility and by r the parameter characterizing the facility’s vulnerability, where $\xi_1 \le \xi \le \xi_2$ and $r_1 \le r \le r_2$.

By assumption, unlike the Agent, the CA does not know the exact values of the parameters ξ and r. Let the CA be aware of the possible bounds of these parameters: $\eta_1 \le \xi \le \eta_2$ and $s_1 \le r \le s_2$, where $\eta_1 \le \xi_1$, $\xi_2 \le \eta_2$, $s_1 \le r_1$, and $r_2 \le s_2$.

The CA–Agent system has the following sequence of moves [19, 20, 24, 25].

Making the first move, the CA establishes a mechanism consisting of:

- an adaptation planning procedure $x = \pi(\eta, s)$, where x is the plan of adaptation measures, η is information on the impact parameter of the facility, and s is information on the vulnerability parameter;
- a financing (incentive) scheme $\sigma(x)$ for adaptation measures, where $\sigma(x) \le \tau g$, g is the investment

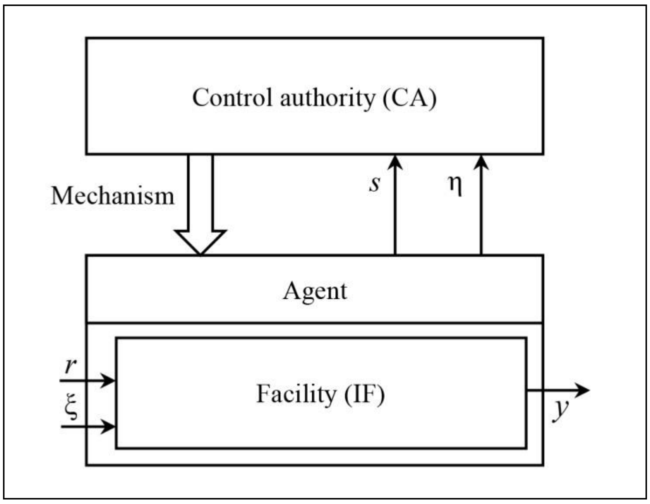


Fig. 6. The interaction between the CA and the Agent.

fund for these measures and $0<\tau<1$ is the share of the fund allocated for incentives;

- a penalty function $\chi(x, z)$ for a deviation *z* of the factual volume of adaptation measures from the plan, with the properties $\chi(x, z)\geq 0$ and $\chi(z, z)=0$.

Let $x, z\in X(x^0, \xi, r)\in X^0=[0, x^0]$, where x^0 is the maximum volume of adaptation measures required to mitigate the climate impacts on the facility under the maximum impact and vulnerability.

Note that the CA does not know the future progress of adaptation measures. Nevertheless, the CA chooses the penalty rule for the non-fulfillment of the plan as part of the mechanism for the Agent.

The second move belongs to the Agent. The Agent reports the estimates η (the impact on the facility) and *s* (the facility's vulnerability). After that, in accordance with the established mechanism, the Agent knows the adaptation plan $x=\pi(\eta, s)$ and the amount of funding $\sigma(x)$ if the plan is fulfilled.

Suppose that the damage from CCs is described by $y=y(z, \xi, r)$, i.e., the damage depends on the volume of adaptation measures *z*, the impact ξ, and the vulnerability *r*. By a natural assumption, the function $y(z, \xi, r)$ is non-increasing in *z* and non-decreasing in ξ and *r*.

Let the Agent's goal function be $f(x, z, \xi, r)$ $=\sigma(z)-\zeta(z, \xi, r)-\chi(x, z)$, where $\zeta(z, \xi, r)$ denotes the Agent's cost function for implementing the volume of measures *z*. Assume that $\zeta(z, \xi, r)\geq 0$, $\zeta(0, \xi, r)=0$, the function $\zeta(z)$ is twice differentiable, and the mixed derivatives exist.

We write the CA's goal function in the form $\Phi(y, g)=F(y)+\lambda g$, where $F(y)$ is an increasing function and the parameter λ determines the value of the allocated funds *g* for the CA.

When choosing the reported estimates and the volume of measures, the Agent seeks to maximize its goal function. When choosing the mechanism, the CA seeks to minimize its goal function $\Phi(y, g)$.

The Agent chooses its actions and reports the estimates as follows. According to the Agent's behavioral principle (maximization of the goal function), we have

$$\varphi(x, \xi, r)=\sigma(z^*)-\zeta(z^*, \xi, r)-\chi(x, z^*)$$
$$=\max_{z\in X}[\sigma(z)-\zeta(z, \xi, r)-\chi(x, z)].$$

The Agent's estimates are determined from the condition $\varphi(\pi(\eta^*, s^*), \xi, r)=\max_{\substack{\eta_1\leq\eta\leq\eta_2\\ s_1\leq s\leq s_2}}\varphi(\pi(\eta, s), \xi, r)$.

In other words, when reporting the information, the Agent seeks for a plan maximizing its goal function.

Suppose that the components of the Agent's goal function are such that the corresponding maxima exist.

Problem statements

A) It is required to find a mechanism that ensures strategy-proofness, i.e., the Agent's interest in reporting the reliable estimates of the impact and vulnerability parameters, $\eta^*=\xi$ and $s^*=r$, to the CA and fulfilling the plan, $z^*=x$.

B) It is required to find an optimal mechanism on the set *M* of admissible mechanisms:

$$\Phi(y, g)=F(y(z^*, \xi, r))+\lambda g$$
$$=F(y(z^*(\pi(\eta^*, s^*), \xi, r))+\lambda g \underset{m\in M}{\to}\min.$$

Now we further specify this general model. Assume that the impact and vulnerability parameters are measured in relative units: $\xi\in[0, 1]$ and $r\in[0, 1]$. This means that for $\xi=0$, there is no impact on the facility; for $\xi=1$, the impact achieves maximum. Accordingly, for $r=0$, the facility is completely invulnerable to the impact; for $r=1$, the vulnerability achieves maximum (the operation of the facility is terminated).

Let $y=b(x^0p-z)$, where x^0 is the maximum volume of adaptation measures under the maximum impact and vulnerability, $p=\xi r$, and $b>0$ is a given parameter. In addition, the cost function has the form $\zeta(z, \xi, r)=\zeta(z, px^0)=\dfrac{\beta px^0}{px^0-z}$, where $\beta>0$. The cost function is proportional to the impact and vulnerability of the facility and inversely proportional to the damage. The inverse proportionality means that the Agent incurs greater costs for actions to reduce the damage. The cost function is chosen based on these considerations. Generally speaking, another cost function can be used in the model. Note that the following properties must hold for its derivatives [26]: $\zeta'_z(z, p) > 0$, $\zeta''_{zz}(z, p) > 0$, $\zeta'_p(z, p) < 0$, and $\zeta''_{zp}(z, p) < 0$.

From $\eta_1 \le \xi \le \eta_2$ and $s_1 \le r \le s_2$ it follows that $q_1 = \eta_1 s_1 \le q = \eta s \le \eta_2 s_2 = q_2$, where q is the Agent's estimate of the parameter p reported to the CA.

We select the penalty function

$$\chi(x, z) = \begin{cases} v \text{ if } & x \ne z \\ 0 \text{ if } & x = z, \end{cases}$$

where $v > 0$.

Let $F(y) = By$, where the parameter $B > 0$ denotes the amount of damage in monetary terms, to be compared with the value λg of the investment fund g.

Note that $y \ge 0$ and, accordingly, $z \in X(p) = [0, x^0 p] \in X^0 = [0, x^0]$.

Under these assumptions about their components, the goal functions of the CA and Agent take the form

$$\Phi(y, g) = By + \lambda g = Bb(x^0 p - z) + \lambda g,$$

$$f(x, z, \xi, r) = \sigma(z) - \frac{\beta p x^0}{p x^0 - z} - \chi(x, z). \tag{1}$$

3.3. Strategy-Proofness and Plan Fulfillment by the Agent

Let the incentive scheme $\sigma(z)$ be given. To establish the condition of reporting reliable data (strategy-proofness) and plan fulfillment, we will use previous results [26, 27].

Consider the set $P(p) = \{u \mid \sigma(u) - \zeta(u) \ge \sigma(z) - \zeta(z, p)) - \chi(x, z),\ u \in X,\ z \in X\}$. This set defines all plans that are beneficial for the Agent. Substituting formula (1) into the expression for $P(p)$ yields

$$P(p) = \{u \mid \sigma(u) - \frac{\beta p x^0}{p x^0 - u}$$

$$\ge \sigma(z) - \frac{\beta p x^0}{p x^0 - z} - v,\ (u, z) \in [0, p x^0]\}.$$

If the plan is fulfilled, the Agent's goal function takes the form $\varphi(x, p) = f(x, x, p) = \sigma(x) - \dfrac{\beta p x^0}{p x^0 - x}$.

By [27, Theorem 1], under the planning procedure $\pi^*(\eta, s) = \pi^*(q)$, where $q = \eta s$, the Agent will report reliable data about the impact and vulnerability parameters and fulfill the plan if, for any admissible estimates (η, s), $0 \le \eta \le 1$, $0 \le s \le 1$, there exist restrictive sets for ensuring incentive-compatibility, denoted by X^c, $X^c \cap P(q) \ne \varnothing$, such that

$$\varphi(\pi^*(q), q) = \max_{x \in X^c \cap P(q)} \varphi(x, q),$$

or

$$\sigma(\pi^*(q)) - \frac{\beta q x^0}{q x^0 - \pi^*(q)} = \max_{x \in X^c \cap P(q)} [\sigma(x) - \frac{\beta q x^0}{q x^0 - x}], \tag{2}$$

Example. Let the incentive scheme be linear, $\sigma(x) = kx$, $X^c = [0, x^0]$, $v \ge k x^0$, and $\alpha = 0$. From formula (2) we obtain the planning procedure $\pi^*(q) = q x^0 - \sqrt{\beta q x^0 / k}$, which ensures the reliable estimates $\eta = \xi$, $s = r$.

Condition (2) defines the solution of problem A) on the strategy-proofness of the mechanism.

3.4 An Optimal Financing Mechanism for Adaptation Measures

To find the optimal mechanism, we will use the methodology described in [26]. Note that the CA's goal function achieves its minimum λg in the variable z at $z = x^0 p$ and its maximum $Bbx^0 p + \lambda g$ at $z = 0$: $\lambda g \le \Phi(y, g) \le Bbx^0 p + \lambda g$. We introduce the parameter γ as the maximum required value of the CA's goal function, i.e., $\lambda g \le \Phi(y, g) \le \gamma$. The parameter γ takes a value on the interval [λg, $Bbx^0 p + \lambda g$]. Under a fixed value of the parameter γ, we consider the set of pairs (p, z) such that

$$Bb(x^0 p - z) + \lambda g \le \gamma. \tag{3}$$

Let this set be denoted by $Q_\gamma = \{(p, z) \mid Bb(x^0 p - z) + \lambda g \le \gamma\} = \{(p, z) \mid z \ge p x^0 - \dfrac{\gamma - \lambda g}{Bb}\}$. Consider the planning procedures whose argument and corresponding value belong to the set Q_γ and, in addition, that satisfy condition (2). If the Agent reports reliable information, these planning procedures will ensure a value of the CA's goal function not greater than γ.

Inequality (3) can be written as $z \ge px^0 - \frac{\gamma - \lambda g}{Bb}$. Hence, the lower bound of the set Q_γ becomes $z = px^0 - \frac{\gamma - \lambda g}{Bb}$.

For simplicity, we study the case of strong penalties [24], when the penalty value *v* is sufficiently high, e.g., $\sigma(z) - \frac{\beta q x^0}{q x^0 - z} < v$ for any admissible *z*. Under such a penalty, the Agent's choice of the volume of measures *z* coincides with the plan: $z = x$.

According to formula (1), the first-order necessary optimality conditions for the Agent's goal function $f'_x(x, x, \xi, r) = 0$ are given by

$$\sigma'(x) = \frac{\beta x^0 p}{(x^0 p - x)^2}. \tag{4}$$

We find an incentive scheme ensuring these optimality conditions at the lower bound of the set Q_γ, i.e., at $x = x^0 p - \frac{\gamma - \lambda g}{Bb}$. This equality can be written as $p = [x + \frac{\gamma - \lambda g}{Bb}] / x^0$. Substituting it into formula (4) yields the equation

$$\sigma'(x) = \beta \frac{(Bb)^2}{(\gamma - \lambda g)^2} x + \beta \frac{Bb}{\gamma - \lambda g}.$$

Therefore, the incentive scheme maximizing the Agent's goal function on the bound of the set *Q* is given by

$$\begin{aligned}\sigma(x) &= \beta \int_0^x \Big[\frac{(Bb)^2}{(\gamma - \lambda g)^2} t + \frac{Bb}{\gamma - \lambda g}\Big] dt \\ &= \beta \frac{(Bb)^2}{2(\gamma - \lambda g)^2} x^2 + \beta \frac{Bb}{\gamma - \lambda g} x.\end{aligned} \tag{5}$$

The incentive scheme (5) and the planning procedure

$$\pi^*(q) = x^0 q - \frac{\gamma - \lambda g}{Bb} \tag{6}$$

describe the structure of the optimal mechanism and ensure a value of the CA's goal function not greater than γ. Now we estimate the minimum value of the parameter γ to find the optimal mechanism. The plan and the amount of investments for the worst-case estimate $q = q_2$ are

$$x_2 = \pi^*(q_2) = x^0 q_2 - \frac{\gamma - \lambda g}{Bb},$$

$$\sigma(x_2) = \beta \frac{(Bb)^2}{2(\gamma - \lambda g)^2} x_2^{\,2} + \beta \frac{Bb}{\gamma - \lambda g} x_2.$$

The minimum value γ = γ* can be determined from the full use of the investments τg to stimulate adaptation measures. For this purpose, it suffices to solve the equation

$$\sigma(x_2) = \beta\Big[\frac{(Bb)^2}{2(\gamma - \lambda g)^2} x_2^{\,2} + \frac{Bb}{\gamma - \lambda g} x_2\Big] = \tau g \tag{7}$$

for γ on the interval $[\lambda g, Bbx^0 q_2 + \lambda g]$.

By substituting the expression for x_2 and reducing similar terms, we write equation (7) as

$$\frac{(Bb)^2}{(\gamma - \lambda g)^2} (x^0 q_2)^2 = \frac{2\tau g}{\beta}.$$

Hence,

$$\gamma^* = \gamma = \lambda g + \begin{cases} Bbx^0 q_2 \sqrt{\dfrac{\beta}{2\tau g}} & \text{if} \quad \dfrac{\beta}{2\tau g} \le 1 \\ Bbx^0 q_2 & \text{if} \quad \dfrac{\beta}{2\tau g} > 1. \end{cases}$$

Formulas (5) and (6) with $\gamma = \gamma^*$ provide the solution of problems A) and B).

On the one hand, this adaptation planning and financing model is a detailed version of the model discussed in [26], which includes the impact and vulnerability parameters. On the other hand, the former model extends the latter one: the CA's goal function depends on the investment fund. For the more general cost function considered in [26], the equations cannot be solved in explicit form to obtain the optimal incentive scheme and planning procedure that ensure the reporting of reliable data to the CA (strategy-proofness). At the same time, for the cost function introduced above, the optimal solution has been found analytically. Note that the previous results of [24, 25] were developed in [26]: the optimal mechanism (the planning procedure, the incentive scheme, and the penalty function) was designed under the CA's incomplete awareness.

CONCLUSIONS

Due to large-scale infrastructure, multifactor uncertainty, and the need to make urgent decisions, there are significant difficulties in forming an adaptation program as well as in determining and implementing engineering solutions.

In these conditions, boundedly rational decisions become justified. This is especially true at the initial stages preceding a more detailed examination of infrastructure facilities (IFs): such an examination requires significant time and financial resources for diagnosing IFs and refining climate change (CC) forecasts considering the local landscape, the upper layer of the Earth's surface, and the wear and tear of IFs.

In this paper, we have proposed three possibilities for applying boundedly rational decisions.

The first possibility is to identify, in the first stage, a preliminary portfolio of IFs for adaptation measures using the integrated assessment procedure based on expert opinions.

The second possibility is to examine the IFs from this preliminary portfolio, refine risk assessments for the adverse impact of climate changes on IFs, and determine the investments required for IFs. These assessments are used to form the final portfolio of IFs. For this purpose, the idea is to allocate the available investment fund sequentially to IFs in descending order of their risk indicators. This indicator equals the ratio of the facility's risk assessment to the amount of investments required for the facility's adaptation measures.

The third possibility is to design and apply an incentive mechanism for adaptation measures that ensures reliable data from the IF's staff and the rational use of investments.

In the future, the possibility of refining CC forecasts during the implementation of adaptation measures rationalizes the use of roadmaps considering the development of technology and infrastructure and different CC scenarios. In this case, a roadmap describes planned trajectories for implementing measures to mitigate the adverse impacts of CCs and shifts the adaptation paradigm from responding to the occurred natural disasters to the proactive approach to disaster risk reduction based on meteorological, hydrological, and climate monitoring and forecasts. From the time point of view, a roadmap defines a possible sequence of implementing adaptation measures under different scenarios of CC forecasts and infrastructure development. For example, in the railway industry, it includes the development of railroads, rolling stock, and the types of fuel and energy used for trains, as well as traffic control systems and automation and remote control devices. A roadmap rests on long-term climate and infrastructure development forecasts and is periodically updated depending on changes in the forecasts and the results of meteorological, hydrological, and climate monitoring (e.g., every 5 years).

In the future, it is also necessary to create a unified climate change forecasting system based on artificial intelligence and current monitoring systems, as well as digital twins of IFs, in order to analyze climate change and the vulnerability of IFs and assess the risks of adverse impacts.

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