**Risk modeling at the pre-investment phase of nuclear powerplant construction on the international market**

Involvement in the construction of nuclear power plants worldwide is a promising direction for developing the research and technological potential of engineering and general contracting companies in Russia. Nevertheless, Russian companies, involved in the construction of nuclear power plants (NPPs) abroad, need to adapt to foreign jurisdictions, their requirements and rules applied to the construction of hazardous industrial facilities, as well as unique social, economic and physical environments. In this regard, international activities, performed by Russian companies, are associated with uncertainty and risks that require the study and systematization of risk factors and development of risk management models.

The statistical data, covering the recent ten-year period, illustrates the level of uncertainty and problems arising in this area. Over 60% of nuclear reactors worldwide are built with a delay in construction. The consequences of such delays boost project costs. Major international corporations, implementing nuclear power plant construction projects abroad, consider the insufficient pre-project study of project organization and management issues at the stage of entering into an EPC (M) contract to be the risk factors arising in the pre-investment phase.

Risk management modeling is considered as the main element of the system designated for managing the organizational and economic reliability of the pre-investment phase of NPP construction in the international market. It includes: (a) structuring a multiparametric risk factor space based on four sources, including, on the part of the customer, the EPC (M) contractor, the contract and the external environment; (b) a pre-investment risk management model, applicable to NPP construction abroad, to be based on the overall project risk $P_r$; (c) a mathematical model for selecting a project implementation option based on the multi-criterial optimization of the future-oriented project plan-schedule.

**Keywords:** management and analysis of risks, construction of nuclear power plants abroad, pre-investment phase, life cycle of nuclear power plants

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**1. INTRODUCTION. PROBLEMS OF DEVELOPMENT OF THE INTERNATIONAL MARKET OF NPP CONSTRUCTION AND RELEVANCE OF MINIMIZATION OF RISKS IN THE PRE-INVESTMENT PHASE**

According to the 2020 results, the value of Russia’s portfolio of international NPP construction projects ranks first, since it has exceeded 130 billion USD for the ten-year period [1]. At the same time, an increase in the share of NPP construction in international markets is one of critical strategic directions of State Atomic Energy Corporation Rosatom. The compliance with deadlines and construction budgets, as well as the use of the Russian technology is a prerequisite for the Russian engineering companies acting as NPP suppliers. Actions, aimed at the continuous improvement of project management and operational processes, advanced information technologies and solutions, applied throughout the project life cycle, starting from the pre-contract efforts and ending with NPP commissioning, are taken to tackle these goals.

The participation of Russian companies in a large-scale international NPP construction project has several constituents, such as engineering services, construction and installation works, supply of materials and equipment, project design and management, as well as fundraising services.

As of 2020, Russian engineering companies construct nuclear power plants in Europe, Middle East, and North Africa, as well as in the Asia-Pacific region (Table 1).

The strength of Russia’s approach is the “turnkey” construction of a nuclear power plant. A Russian NPP supplier acts as an EPC (M) company responsible for supplying and integrating the technology, the final investment amount, and the contract implementation term. In addition, the Russian EPC (M) company fully designs, plans, builds and puts projects into operation, as well as manages NPPs in furtherance of the instructions issued by the owner [2].

Several studies, carried out by foreign and Russian researchers [3–5], have identified problems in NPP construction, such as regular failures to meet deadlines and project cost overruns that may reach up to several dozens or even hundreds of percent (Fig. 1).

One of the problems that accompanies the construction of a nuclear power facility is the assessment and sufficiently accurate projection of the overall project cost and timing, which implies that decision-makers obtain answers to such questions as “what is the probability of compliance with the project implementation schedule?”, “how can possible risks be...”

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Table 1. Ongoing international NPP construction projects using the Russian technology (as of December 31, 2020)

<table>
<thead>
<tr>
<th>Project country</th>
<th>Project name</th>
<th>Type of reactor</th>
<th>Main construction period</th>
<th>Investment amount, USD billion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belarus</td>
<td>Belarusian NPP</td>
<td>VVER-1200</td>
<td>2011–2020</td>
<td>11.0</td>
</tr>
<tr>
<td>Finland</td>
<td>Hanhikivi 1</td>
<td>VVER-1200</td>
<td>2016–2028</td>
<td>7.0–7.7</td>
</tr>
<tr>
<td>Hungary</td>
<td>Paks II</td>
<td>VVER-1200</td>
<td>2019–2031</td>
<td>14.0</td>
</tr>
<tr>
<td>Turkey</td>
<td>Akkuyu</td>
<td>VVER-1200</td>
<td>2010–2023</td>
<td>22.0</td>
</tr>
<tr>
<td>Iran</td>
<td>Bushehr — 2.3</td>
<td>VVER-1000</td>
<td>2016–2026</td>
<td>11.0</td>
</tr>
<tr>
<td>China</td>
<td>Tianwan — 7.8</td>
<td>VVER-1000 and VVER-1200</td>
<td>2011–2020</td>
<td>10.4 (6.1 and 4.3)</td>
</tr>
<tr>
<td>India</td>
<td>Kudankulam — 3.4</td>
<td>VVER-1000</td>
<td>2002–2025</td>
<td>9.5</td>
</tr>
<tr>
<td>India</td>
<td>Kudankulam — 5.6</td>
<td>VVER-1000</td>
<td>2002–2025</td>
<td>9.5</td>
</tr>
<tr>
<td>Egypt</td>
<td>Dabaa</td>
<td>VVER-1200</td>
<td>2015–2026</td>
<td>30</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>Rooppur</td>
<td>VVER-1200</td>
<td>2015–2024</td>
<td>13</td>
</tr>
<tr>
<td>TOTAL:</td>
<td></td>
<td></td>
<td></td>
<td>128.6</td>
</tr>
</tbody>
</table>

Fig. 1. The analysis of the international NPP construction market broken down by stages of construction and operation, including project delays (as of 31.01.2021)
minimized?”, and “how will possible deviations affect the total cost of the project?”.

Moreover, a substantial investment amount contributed to nuclear power plants, if compared to other types of power plants, makes them more sensitive to risks. Any delays and cost overruns have an immediate negative impact on economic performance and, as a result, on the ability to raise funding.

In this regard, a relevant task is to study management system elements in the pre-investment phase and to examine a methodological approach to assessing and reducing risks to ensure the timely completion of construction within initial budget limits to ensure the organizational and economic sustainability of NPP construction projects implemented worldwide.

2. MATERIALS. MODELING THE STRUCTURE OF THE NPP CONSTRUCTION LIFE CYCLE BROKEN DOWN BY STAGES, COSTS, DEADLINES, AND MANAGEMENT FEATURES

2.1. Structuring the life cycle of construction of a nuclear power plant abroad

An NPP construction project belongs to the category of large complex investment and construction projects (following the UNIDO rules), which are characterized by large-scale investments (up to 30 billion USD); long implementation periods (10–15 years to be spent to design, construct, and start up an NPP, that has a 60-year service life term); special attention to security issues throughout the entire life cycle.

An NPP construction project, implemented abroad, has several stages, clustered into the concepts of “a life cycle” and “an investment cycle” [7]:

- the life cycle (Fig. 2) includes the period from an investment project concept formulation to the decommissioning of a nuclear power plant;
- the investment cycle is an economic concept that covers the nuclear supply chain provided a consolidated structure of capital expenditures (Fig. 3) that also included labor, equipment and raw materials, and it requires the mobilization of a significant amount of labor resources, including the engineering personnel, and the availability of specialized construction and installation equipment. This leads to low adaptability to the changing design and, consequently, reduced productivity due to less rational use of personnel and the idle time of equipment. Furthermore, delays rise the overall cost of the power plant construction [8].

The consequences of overruns can seriously affect the profitability of an NPP construction project. For example, in case of a three-year delay, the breakeven point is reached in about ten years [5, 9]; since capital expenditures are primarily reflected in the final cost of electricity generation by new nuclear power plants, timely completion of construction is an effective means of limiting rising costs and risks in the course of constructing new nuclear facilities.

The 2016 report of the World Nuclear Association on the global nuclear supply chain provided a consolidated structure of capital expenditures (Fig. 3) that also included labor, equipment and raw material expenses (Fig. 4). It is noteworthy that in the Russian practice, the area of the general contractor’s responsibility for the construction of a nuclear power plant differs from the area of responsibility of an EPCM company worldwide. Russian engineering companies can enter into contracts at various stages of a project, and the scope of services and supplies within the framework of an NPP construction project may also vary [1].

2.2. Modeling the cost structure of NPP construction projects

The construction costs of nuclear power facilities are the key indicators, and the consequences of the schedule overruns affect the following two aspects:

1. Project financing. Additional costs, representing the interest amount, accumulated during the schedule overrun increases the overall financial burden, and boosts the risk assumed by the investors. Besides, cash inflows generated by the sale of electricity are delayed due to the construction schedule overrun.

2. Construction costs. The major portion of construction work is carried out on the construction site of the future nuclear power plant, and it requires the mobilization of a significant amount of labor resources, including the engineering personnel, and the availability of specialized construction and installation equipment. This leads to low adaptability to the changing design and, consequently, reduced productivity due to less rational use of personnel and the idle time of equipment. Furthermore, delays rise the overall cost of the power plant construction [8].

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**Structure of the pre-investment phase of the NPP construction project**

- Concept of future NPP
- Site selection and options consideration
- Obtaining licenses and permits
- Engineering survey
- NPP design
- Tender and EPC-contract conclusion

**NPP Construction:**
- Preparation and support objects
- “first concrete” for the reactor building
- Grid connection
- Modernization and extension of service life
- Decommission

*Fig. 2. Model of the life cycle of a nuclear power plant*
2.3. The analysis of terms of NPP construction projects

It should be noted that, according to the Russian technology (the “NPP-2006” project), the main target period of construction of each power unit is set by State Atomic Energy Corporation Rosatom for a maximum of 4.5 years (or 54 months)\(^1\).

The actual NPP project execution time includes construction work and lengthy licensing procedures, complex financial negotiations, site preparation, and infrastructure development. As the British Hinkley Point C project shows, a substantial share of investments had been made and a large amount of work had been completed long before the official construction phase began.

According to IAEA statistics\(^2, 3\), the average construction period of 63 units in nine countries (37 of them in China), launched in 2009–2019, reached 10 years. The analysis of the timelines of NPP construction projects, initiated between 2010 and 2019, illustrates the level of uncertainty and challenges associated with many of these projects, especially given that most of them were to have a five-year construction period (Table 2).

As of July 1, 2020, the average construction time was 7.3 years, exceeding the mid-2019 average by more than six months in terms of 52 reactors under construction.

In addition, all nuclear power plant units under construction in at least 10 out of 17 countries experienced an average delay of one year, and the completion dates for 33 (64 %) construction projects were postponed. Most of the NPP units, conventionally constructed on time, were started within the last three years or they have not yet reached the planned start-up dates, making it difficult to assess their compliance with the project schedule. There is still no certainty about the construction projects in the UK, Bangladesh, China and Russia.

According to IAEA, in most cases, additional licensing requirements, interference of the general public, problems with suppliers and financing, and improper construction management were the reasons for schedule overruns and rising costs\(^4, 5\)\(^[10]\).

2.4. Features of NPP construction project management outside of Russia

An NPP construction project, that employs the Russian technology, is a set of interrelated actions aimed at achieving the pre-set goals in a given time frame within a given budget. A set of interrelated elements and links between them, representing a “tree” of product-oriented components represented by equipment, work, services, and information, determines the project structure\(^[11]\).
Pursuant to the IAEA recommendations, in addition to ensuring the high quality of construction work according to the construction schedule, the project requirements, and the budget, the contractor (EPCM) responsible for the NPP construction outside of Russia, must prioritize the project work, ensure the availability of material resources and workforce, analyze and define risk management programs and solve any problems that delay the project implementation or threaten the quality of work performed.

NPP project management is the art of managing and coordinating human, financial, and material resources using modern management methods and techniques, organizational forms of production and construction to achieve the pre-set results in terms of the composition and scope of work, costs, timing, and quality to meet the goals pursued by the project participants.

NPP project functions are divided into project goal management (the subject area), time management, cost management, quality management, risk management, contract management, participant and personnel management, relationship management, and information flow management.

The management model of an investment project that entails the construction of a nuclear power plant on a foreign market involves planning a set of measures that ensure the project funding and management, the supply of technologies and engineering services, as well as construction, installation, and commissioning works. The development of project schedule options and the evaluation of investment performance are the strategic issues considered by decision makers at the pre-investment stage.

When choosing an organizational model for the implementation of an international project, it is recommended to take account of the following features of entry of foreign engineering and construction companies (of any level) to the market in the project implementation country [6]:

- a multi-stage system of obtaining licenses for the construction of particularly hazardous and technically complex facilities (for example, nuclear power facilities);
- tightened control and supervision over the project development by local self-government bodies;
- granting preferences to local service and equipment suppliers;
- the obligation to comply with the recommendations made by international organizations (for example, IAEA);
- immigration restrictions, including those issued due to the epidemiological situation in the country and difficulties with the employment of foreign engineering and technical personnel;
- conditions of certification and customs clearance for the import/export of materials or equipment.

### 3. METHODS. STRUCTURING THE FACTOR SPACE OF PRE-INVESTMENT RISKS THAT ACCOMPANY NPP CONSTRUCTION OUTSIDE OF RUSSIA

#### 3.1. Risk assessment of NPP construction abroad in the pre-investment phase

The mission of construction project risk management (according to the PMBOK® Knowledge Sets) is to increase the likelihood and impact of positive events or opportunities while reducing the likelihood and impact of negative events or threats that occur during the design and construction process. It includes risk management planning, identification, analysis, response planning, and project control applied throughout the project lifecycle.

The management of NPP construction projects, implemented outside of Russia, also means the identification, control, and management of characteristic risk factors [12, 13]. To solve this problem, the analysis of the main features of NPP construction projects, implemented outside of Russia, including the analysis of international experience, was carried out. As a result, an approach to assessing the organizational and economic sustainability of the pre-investment phase of NPP construction outside of Russia was formulated with account for the risk factors.

The study [14] examines the classification of risks and the management model applied to unique large-scale investment and construction projects (ISPs) outside of Russia. The cumulative risk of implementing a large complex ISP abroad is a set of causes of uncertainty as a result of the occurrence of random adverse events, the possibility of significant revenue shortfalls, and the loss of some resources by economic entities.

Largest international investment and construction groups (for example, VINCI, BOUYGUES, France) list the main risk factors that need to be taken into account in the pre-investment phase of an

### Table 2. 2010–2019 global nuclear reactor construction timelines

<table>
<thead>
<tr>
<th>Country</th>
<th>Total number of reactors</th>
<th>Construction period of 63 projects, years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>China</td>
<td>37</td>
<td>6.0</td>
</tr>
<tr>
<td>Russia</td>
<td>10</td>
<td>20.3</td>
</tr>
<tr>
<td>South Korea</td>
<td>6</td>
<td>6.0</td>
</tr>
<tr>
<td>India</td>
<td>4</td>
<td>10.4</td>
</tr>
<tr>
<td>Pakistan</td>
<td>3</td>
<td>5.4</td>
</tr>
<tr>
<td>Argentina</td>
<td>1</td>
<td>33.0</td>
</tr>
<tr>
<td>Iran</td>
<td>1</td>
<td>36.3</td>
</tr>
<tr>
<td>USA World</td>
<td>1</td>
<td>43.5</td>
</tr>
<tr>
<td>China</td>
<td>63</td>
<td>10.0</td>
</tr>
</tbody>
</table>
The disputes, broken down by their cause (which can be associated with the Owner, the Contractor, the Contract, and External Factors) are provided in Table 5 [15–17].

Each type of risk corresponds to unique factors (causes of occurrence), which can be used to simulate the probability of a risk and the degree of its impact on the course of construction of nuclear power plants, thereby providing information for decision makers.

Thus, the overall risk of implementing a nuclear power plant construction project abroad $P(r_i)$ can be defined as the sum of the probabilities of occurrence of negative events $P$, given the account is taken of their significance $w$:

$$P(r_i) = \sum_{j=1}^{n} P(r_j w_j)$$

where $q1$ — events; $r_j$ — factors (causes).

**Table 5. Multiparametric factor space of risks in the pre-investment phase of an NPP construction project outside of Russia**

<table>
<thead>
<tr>
<th>Risk Type $x$</th>
<th>Code</th>
<th>Negative risk factor or event $R$</th>
<th>Weight $w$</th>
<th>Probability $P$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project Owner (O)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O1</td>
<td>$O_1$</td>
<td>Late payment</td>
<td>$w_{o1}$</td>
<td>$P_{o1}$</td>
</tr>
<tr>
<td>O2</td>
<td>$O_2$</td>
<td>Schedule overrun caused by the Owner</td>
<td>$w_{o2}$</td>
<td>$P_{o2}$</td>
</tr>
<tr>
<td>O3</td>
<td>$O_3$</td>
<td>A change in the value of SMR during construction</td>
<td>$w_{o3}$</td>
<td>$P_{o3}$</td>
</tr>
<tr>
<td>O4</td>
<td>$O_4$</td>
<td>Design errors or low quality POI</td>
<td>$w_{o4}$</td>
<td>$P_{o4}$</td>
</tr>
<tr>
<td>O5</td>
<td>$O_5$</td>
<td>Provision of incorrect/incomplete information</td>
<td>$w_{o5}$</td>
<td>$P_{o5}$</td>
</tr>
<tr>
<td>O6</td>
<td>$O_6$</td>
<td>Late access to the construction site</td>
<td>$w_{o6}$</td>
<td>$P_{o6}$</td>
</tr>
<tr>
<td>O7</td>
<td>$O_7$</td>
<td>Unilateral refusal to accept the completed CMP</td>
<td>$w_{o7}$</td>
<td>$P_{o7}$</td>
</tr>
<tr>
<td><strong>EPCM-contractor (E)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>$E_1$</td>
<td>Unawareness of the geographical conditions of the project</td>
<td>$w_{e1}$</td>
<td>$P_{e1}$</td>
</tr>
<tr>
<td>E2</td>
<td>$E_2$</td>
<td>Work quality assurance problem</td>
<td>$w_{e2}$</td>
<td>$P_{e2}$</td>
</tr>
<tr>
<td>E3</td>
<td>$E_3$</td>
<td>Delays in the progress of construction and installation works</td>
<td>$w_{e3}$</td>
<td>$P_{e3}$</td>
</tr>
<tr>
<td>E4</td>
<td>$E_4$</td>
<td>Contractor’s financial problems</td>
<td>$w_{e4}$</td>
<td>$P_{e4}$</td>
</tr>
<tr>
<td>E5</td>
<td>$E_5$</td>
<td>Absence of written instructions from the customer</td>
<td>$w_{e5}$</td>
<td>$P_{e5}$</td>
</tr>
<tr>
<td>E6</td>
<td>$E_6$</td>
<td>Unclear local tender laws and regulations</td>
<td>$w_{e6}$</td>
<td>$P_{e6}$</td>
</tr>
<tr>
<td>E7</td>
<td>$E_7$</td>
<td>Different interpretations of the contract terms</td>
<td>$w_{e7}$</td>
<td>$P_{e7}$</td>
</tr>
<tr>
<td>E8</td>
<td>$E_8$</td>
<td>Unclear contract terms regarding the change of the contract price in relation to the preliminary amounts</td>
<td>$w_{e8}$</td>
<td>$P_{e8}$</td>
</tr>
<tr>
<td>E9</td>
<td>$E_9$</td>
<td>Unclear contract terms regarding the adjustment of approximate quantities</td>
<td>$w_{e9}$</td>
<td>$P_{e9}$</td>
</tr>
<tr>
<td>E10</td>
<td>$E_{10}$</td>
<td>Unclear terms of refunding withheld cash amounts</td>
<td>$w_{e10}$</td>
<td>$P_{e10}$</td>
</tr>
<tr>
<td>E11</td>
<td>$E_{11}$</td>
<td>An unclear way of reducing the damage caused by delays</td>
<td>$w_{e11}$</td>
<td>$P_{e11}$</td>
</tr>
<tr>
<td>E12</td>
<td>$E_{12}$</td>
<td>Unclear definition and types of defects</td>
<td>$w_{e12}$</td>
<td>$P_{e12}$</td>
</tr>
<tr>
<td>E13</td>
<td>$E_{13}$</td>
<td>Ungrounded distribution of risks in the contract</td>
<td>$w_{e13}$</td>
<td>$P_{e13}$</td>
</tr>
<tr>
<td>E14</td>
<td>$E_{14}$</td>
<td>Failure to account for or accurately calculate the additional cost of actual work at the time of the tender and the evaluation process</td>
<td>$w_{e14}$</td>
<td>$P_{e14}$</td>
</tr>
<tr>
<td>E15</td>
<td>$E_{15}$</td>
<td>Failure to examine the terms of the contract during the tender</td>
<td>$w_{e15}$</td>
<td>$P_{e15}$</td>
</tr>
<tr>
<td>E16</td>
<td>$E_{16}$</td>
<td>Ambiguous limit of liability for the use or storage of materials and equipment provided by the employer</td>
<td>$w_{e16}$</td>
<td>$P_{e16}$</td>
</tr>
<tr>
<td>E17</td>
<td>$E_{17}$</td>
<td>Disagreements over the amount of compensation for construction costs and time, in case a claim is filed</td>
<td>$w_{e17}$</td>
<td>$P_{e17}$</td>
</tr>
<tr>
<td>E18</td>
<td>$E_{18}$</td>
<td>Disagreements about the payment method caused by a change in the quantity</td>
<td>$w_{e18}$</td>
<td>$P_{e18}$</td>
</tr>
</tbody>
</table>
In addition, a similar method describes the risk of delayed construction of NPPs abroad $R_{(c1)}$, for example, a failure and/or a delay on the part of the Customer (O) (an energy company) to accept the work performed (events $O_i$) due to its incompliance with the local building codes ($E_2$), inconsistencies between the executive documentation and the Owner’s requirements and regulations issued by local regulatory agencies and ($E_6$), the availability of growing amounts of work and rising costs ($C_2$).

In this case, the cumulative risk that affects the $t_{cd}$ parameter, or “the forecasted duration of the project implementation option”, is determined as follows:

$$P(t_{cd}) = P(O_1, xw_{x1} + E_2, xw_{x2} + E_6, xw_{x6} + C_2, xw_{x2}). \quad (2)$$

4. RESULTS. PROPOSALS CONCERNING MODELING THE MANAGEMENT OF PRE-INVESTMENT RISKS OF NPP CONSTRUCTION PROJECTS BASED ON MULTI-CRITERIAL OPTIMIZATION OF FUTURE-ORIENTED SCHEDULES

Basic principles of multi-criterial optimization subsystems applicable to future-oriented project implementation plans at the pre-investment phase of NPP construction projects are formulated on the basis of the research works of Russian and foreign scientists and decision making frameworks. A mathematical model of multi-criterial optimization is one of basic components of this system [18].

The issue of multi-criterial formulation of the task of developing future-oriented project implementation plans is particularly relevant for large-scale investment and construction projects due to the large number of project participants (stakeholders) and differences in their interests and motivation [19]. For example, the criteria of optimality of future-oriented project implementation plans in the pre-investment phase of an NPP construction project can include:

1. On the side of the project initiator (an energy company) in the country of construction:
   - assurance of the proper level of safety and compliance with all international and local requirements applicable to the construction of nuclear energy facilities;
   - minimization of the construction period. In the case of a grave problem of electricity shortage in the region, this criterion may prevail over others;
   - completion of construction and installation works by a certain date. This criterion may be imposed by political factors (for example, it may be attached to the date of elections to government authorities).

2. On the side of the contractor, or the Russian EPC (M) company:
   - profit maximization;
   - assurance of high quality design, construction, installation and commissioning of unique NPP equipment in discharge of further operation obligations;
   - setting the stage for the regular and timely use of financing. The disbursement of funds designated for the design, construction and installation work may be limited to certain time periods (for example, years);
   - minimization of construction costs. This criterion can serve as the main one in the case of an EPC contract having a fixed amount specified;
   - setting the stage for the regular and timely use of resource, including highly skilled labor resources, special machinery and equipment. This issue may be relevant due to the contractor’s involvement in several projects at the same time.

The multi-criterial decision-making model can be formally presented as follows [20]:

$$G(T, K, X, S, F, P, R), \quad (3)$$
The efficiency coefficient of the dynamics of capital investments can be represented as follows:

\[ \alpha = \frac{\text{cost of building a facility or a group of facilities}}{\text{cost of building an equivalent facility without automation}} \]

where \( \alpha \) is the efficiency factor.

The efficiency factor is used to compare the cost of building a facility with and without automation. A higher efficiency factor indicates a more cost-effective solution.

### Additional Notes
- **Market aspects of construction activities**
  - The efficiency factor is used to compare the cost of building a facility with and without automation. A higher efficiency factor indicates a more cost-effective solution.
- **Limiting operator**
  - The limiting operator is used to establish the most significant criterion. The most significant criterion is the one that leads to the identification of the optimal solution. In particular, the project implementation schedule according to the most significant criterion is the optimal solution.
- **Formal heuristic algorithms**
  - Methods of sequential analysis of options for making a project schedule applicable for the implementation of an NPP project, for example, a formal heuristic algorithm designed for finding the optimal solution.
- **Sampling space**
  - The sampling space may contain the following mutually exclusive outcomes:
    - The technical support limit is not met (\( J_1 \)).
    - The time limit for the future-oriented project implementation schedule is not met (\( J_2 \)).
    - The material supply limit is not met (\( J_3 \)).
    - The option led to an improvement in the target function (\( J_4 \)).
    - The option led to the deterioration of the target function (\( J_5 \)).

The choice of the optimality criterion of future-oriented project implementation can be formulated as follows:

\[ \text{Optimality criterion} = \left\{ \begin{array}{ll}
J_1 & \text{when } a = 1, \text{ where } a \text{ is the number of the option, for which this limit is not met.} \\
J_2 & \text{when } a = 2, \text{ where } a \text{ is the number of the option, for which this limit is not met.} \\
J_3 & \text{when } a = 3, \text{ where } a \text{ is the number of the option, for which this limit is not met.} \\
J_4 & \text{when } a = 4, \text{ where } a \text{ is the number of the option, for which this limit is not met.} \\
J_5 & \text{when } a = 5, \text{ where } a \text{ is the number of the option, for which this limit is not met.}
\end{array} \right. \]
us to take account of a number of factors that are non-deterministic or not reflected in the selection of particular criteria by using informal decision making procedures [26].

As a result, one or more options of the future-oriented project implementation schedule of an NPP project, selected by decision makers, are, if necessary, handed over to an expert group for the detailed analysis, elaboration and further processing of results using the Fuzzy Logic approach [27].

5. CONCLUSIONS AND DISCUSSION

The international NPP construction market has a strong potential for Russian engineering (EPCM) suppliers whose objective is to increase the export potential of nuclear energy, with regard for the global situation, national competitiveness and the market positions. As the practice and research show, NPP construction organization and management outside of Russia represent more challenging tasks than projects implemented on the local market. The organizational and economic reliability in this environment implies special investment and construction project management processes and approaches to risk identification and management by the parties to the project.

Given the international and domestic research works, recommendations and practical experience, we propose to develop a model for managing the organizational and economic reliability of NPP construction outside of Russia as a combination of the following components:

1. The organizational and legal model of an NPP project with account for the features of the legal regulation of construction of nuclear power facilities in the country of project implementation, the available licenses authorizing the construction of nuclear power plants, and the recommendations of international organizations (IAEA).

2. The strategy for managing pre-investment risks based on the structured risk factor space for the construction of NPPs abroad. Provision of decision makers with data on the quantitative and qualitative analysis of project implementation risks, including possible deviations from the project schedules and costs, as well as mechanisms and/or recommendations aimed at their minimization.

3. Multi-criteria analysis and optimization of options of future-oriented project implementation schedules, including financing schedules and resource-focused requirements, using modern information technologies in project management.

The factor space of pre-investment risks that accompany the construction of NPPs abroad was structured and the mechanism of pre-investment risk assessment by using combined AHP-RII methods, which is implemented into the AHP-RII tool [27, 10]. The factor space of pre-investment risks that accompany the construction of NPPs abroad was structured and the mechanism of pre-investment risk assessment by using combined AHP-RII methods, which is implemented into the AHP-RII tool [27, 10].

We believe that the proposed methodology can be applied to other types of construction projects with a high proportion of foreign investment and technology, which is reflected in the business strategy of Russian nuclear enterprises.

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Моделирование управления рисками предынвестиционной фазы сооружения объектов атомной энергии на международном рынке строительства АЭС

Участие в зарубежных проектах атомного энергетического строительства является перспективным направлением развития научно-технического потенциала инжиниринговых и генподрядных компаний России. В то же время российским компаниям-участникам сооружения атомных электростанций (АЭС) за рубежом необходимо адаптироваться к иностранной юрисдикции, с приоритетом набором требований и приоритетам строительства опасных промышленных объектов, а также к уникальной социальной, экономической и физической среде. В связи с этим зарубежная деятельность российских компаний сопряжена с неопределенностью и рисками, которые требуют изучения и систематизации факторов риска и разработки моделей управления ими.

Статистика последних 10 лет иллюстрирует уровень неопределенности и проблем в этой области — более 60% атомных реакторов в мире сооружаются с задержкой сроков строительства, последствия которых приводят к увеличению затрат проекта. Крупнейшие международные корпорации, реализующие проекты строительства АЭС за рубежом, с факторами риска на предынвестиционной фазе сооружения АЭС на зарубежном рынке и включают в себя: а) структура многокритериального факторного пространства рисков по четырем источникам: со стороны заказчика, EPC(М)-подрядчика, контракта и внешней среды; b) модель управления предвыбующими рисками строительства АЭС за рубежом на основе совокупного риска проекта (р); c) математическую модель выбора варианта реализации проекта на основе многокритериальной оптимизации прогнозного плана-графика.

Ключевые слова: управление рисками, анализ, сооружение АЭС за рубежом, предынвестиционная фаза, жизненный цикл АЭС

ЛИТЕРАТУРА


Об авторах: Грабовый Петр Григорьевич — доктор экономических наук, профессор, заведующий кафедрой организации строительства и управления недвижимостью; Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ); 129337, г. Москва, Ярославское шоссе, д. 26; РИНЦ ID: 302471; osun_kaf@mgsu.ru;

Березка Виталий Викторович — преподаватель кафедры организации строительства и управления недвижимостью; Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ); 129337, г. Москва, Ярославское шоссе, д. 26; г. Москва, ул. Петровка; Scopus: 57205214283; v.berezka@hotmail.com.
