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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 $P(r_{it})$; (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

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 services¹.

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)².

The strength of Russia's approach is the "turn-key" 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)³.

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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² Official website of the ASE Engineering Division of the Rosatom State Corporation. URL: <https://www.ase-ec.ru/> (accessed: January 1, 2021).

³ World Nuclear Industry Status Report, report on the current status of the nuclear industry in the world for 2020. URL: <https://www.worldnuclearreport.org/IMG/pdf/wnisr2019-v2-hr.pdf> <http://www.rusatom-overseas.com/> (accessed: January 1, 2021).

¹ Official website of the State Corporation "Rosatom". URL: <https://rosatom.ru/production/design/stroyashchiesya-aes/> (accessed: January 1, 2021).

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

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

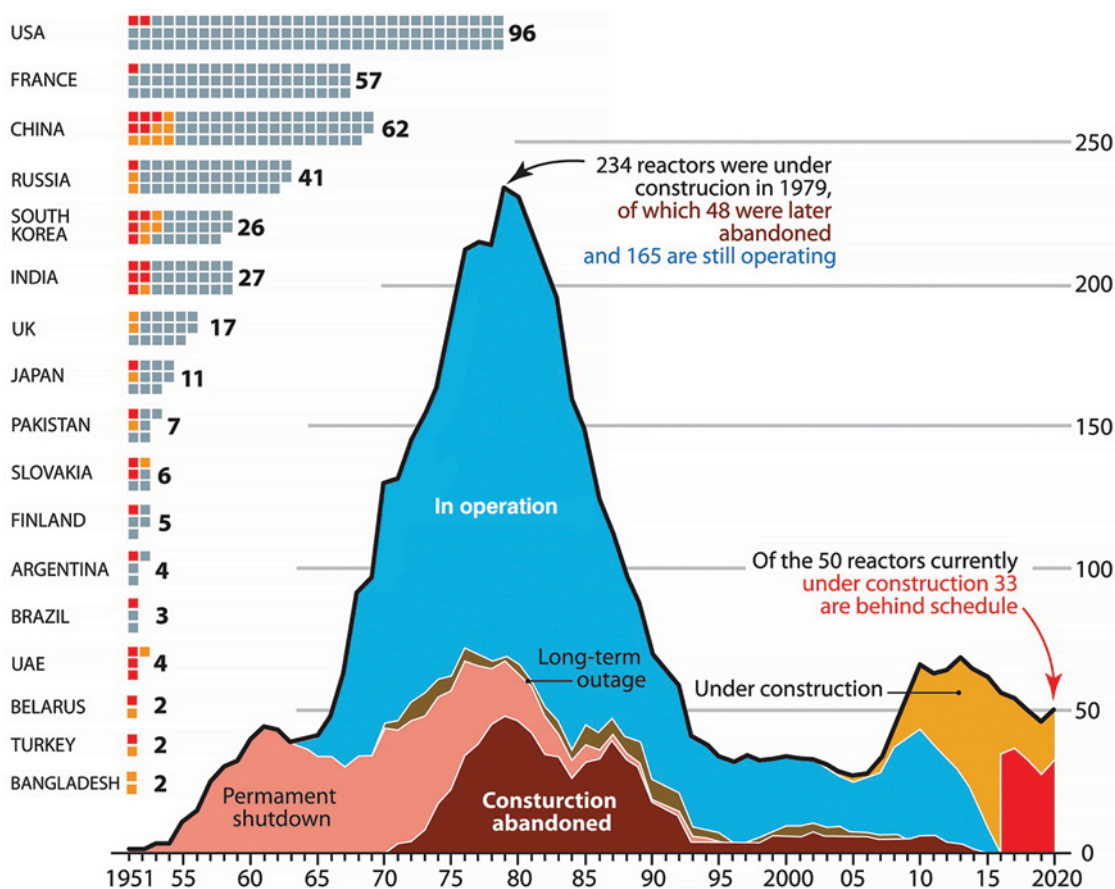
Nuclear reactors under construction globally

by countries (only countries with active projects)

— under construction

— operational

— behind schedule



Source: World Nuclear Industry Status Report, Global Nuclear Power Database

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 plants⁴, 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 by⁵ [6]:

- 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 NPP lifecycle during which initial investments are made. It lasts 8–12 years on average.

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 vary¹.

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 aspects⁶:

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 the 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 Association⁷ 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).

4 International Energy Agency, Nuclear Power in a Clean Energy System, report — May 2019. URL: <https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system> (accessed: January 1, 2021).

5 Information on the status of the nuclear industry from the International Atomic Energy Agency (IAEA). URL: <https://www.iaea.org/topics/nuclear-power-plant-life-cycle> (accessed: January 1, 2021).

6 Unlocking Reductions in the Costs of Nuclear Construction — A Practical Guide for Stakeholders, the report of the nuclear energy Agency of the Organization for economic co-operation and development, 2020. URL: https://www.oecd-neo.org/jcms/pl_30653/unlocking-reductions-in-the-construction-costs-of-nuclear (accessed: January 1, 2021).

7 Economics of Nuclear Power (updated in March 2020). URL: <https://www.world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx> (accessed: January 1, 2021).

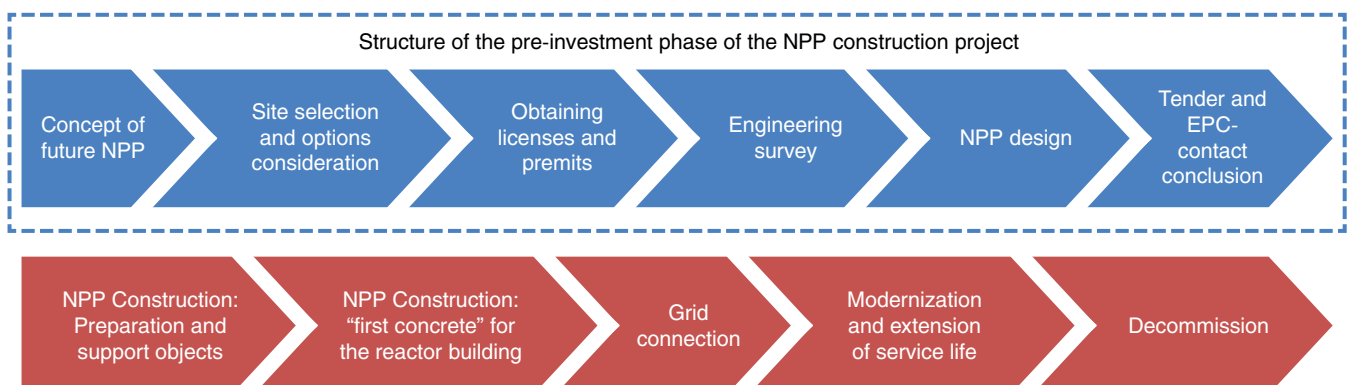


Fig. 2. Model of the life cycle of a nuclear power plant

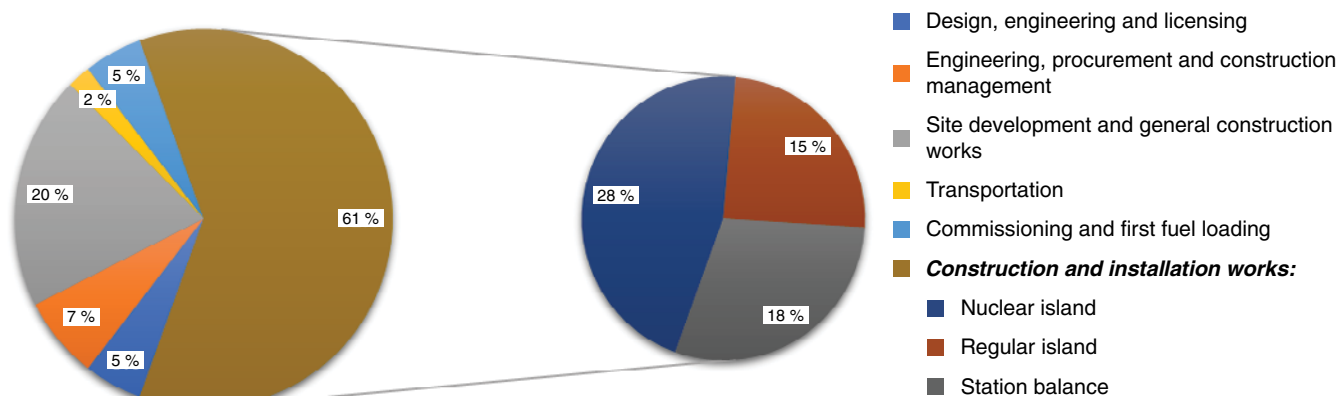


Fig. 3. Consolidated structure of capital expenditures for the construction of nuclear power plants

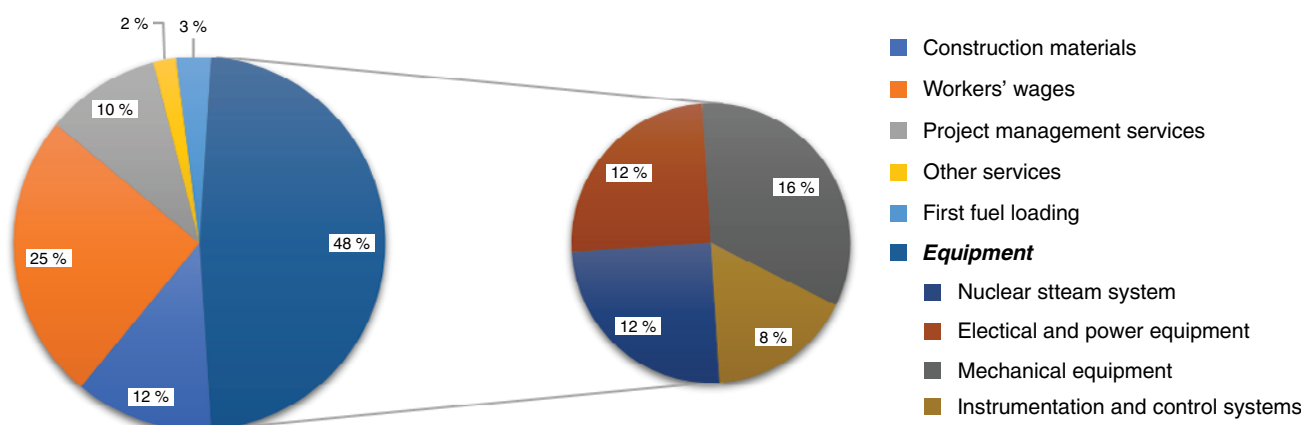


Fig. 4. Breakdown of the cost of construction of nuclear power plants in the context of labor remuneration, cost of equipment and materials

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 the IAEA statistics^{8, 9}, 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^{8, 9} [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].

⁸ IAEA s NUCLEUS information resource, International Atomic Energy Agency. International Atomic Energy Agency, Project Management in Nuclear Power Plant Construction: Guidelines and Experience, Nuclear Energy Series No. NP-T-2.7, IAEA, Vienna, 2012. URL: <https://www.iaea.org> (accessed: January 1, 2021)

⁹ International Atomic Energy Agency, Project Management in Nuclear Power Plant Construction: Guidelines and Experience, Nuclear Energy Series. No. NP-T-2.7, IAEA, Vienna, 2012.

Table 2. 2010–2019 global nuclear reactor construction timelines

Country	Total number of reactors	Construction period of 63 projects, years		
		Average	Min	Max
China	37	6.0	4.1	11.2
Russia	10	20.3	8.1	35.1
South Korea	6	6.0	4.1	9.6
India	4	10.4	7.2	14.2
Pakistan	3	5.4	5.2	5.6
Argentina	1	33.0	33.0	
Iran	1	36.3	36.3	
USA World	1	43.5	43.5	
China	63	10.0	4.1	43.5

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, France¹⁰) list the main risk factors that need to be taken into account in the pre-investment phase of an

¹⁰ Annual report of the VINCI Group for 2019. URL: <https://www.vinci.com/publi/vinci/2019-vinci-annual-report.pdf> (accessed: January 1, 2021).

► international project, such as: (a) difficulties in the facility design and analysis caused by the underestimation of the amount of work or the overestimation of the expected profitability; (b) errors in the analysis of the terms of the tender documentation and the contract proposed by the customer, or (c) errors in the analysis of technical and legal norms of the country of the project implementation. In addition, the following specific factors are identified [15] in relation to the construction of nuclear power plants abroad:

- **Insufficient qualification** of local subcontractors due to the lack of experience in the implementation of technologically complex large-scale projects, such as the construction of nuclear power plants;
- **Supply delays** due to the global shortage of skilled manufacturers of special equipment for nuclear power plants and its late delivery to construction sites for installation. In addition, there may arise problems with the purchase of bulk materials (concrete, rebar, crushed stone, metal, etc.) due to large amounts of purchases and their unavailability on local or global markets;

- **Lack of qualified labor resources.** Delayed construction, installation and commissioning due to the lack of experienced technical specialists and/or the need to do the work once again due to quality control errors in the course of production and construction.

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 $P(r_{it})$ can be defined as the sum of the probabilities of occurrence of negative events P , given the account is taken of their significance w :

$$P(r_{it}) = \sum_{j=1}^{q1} P(r_{ij} \cdot xw_{qi}), \quad (1)$$

where $q1$ — events; r_{ij} — factors (causes).

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

Risk Type x	Code	Negative risk factor or event R	Weight w	Probability P
Project Owner (O)	O ₁	Late payment	w_{01}	P_{01}
	O ₂	Schedule overrun caused by the Owner	w_{02}	P_{02}
	O ₃	A change in the value of SMR during construction	w_{03}	P_{03}
	O ₄	Design errors or low quality POI	w_{04}	P_{04}
	O ₅	Provision of incorrect/incomplete information	w_{05}	P_{05}
	O ₆	Late access to the construction site	w_{06}	P_{06}
	O ₇	Unilateral refusal to accept the completed CMP	w_{07}	P_{07}
EPCM-contractor (E)	E ₁	Unawareness of the geographical conditions of the project	w_{e1}	P_{e1}
	E ₂	Work quality assurance problem	w_{e2}	P_{e2}
	E ₃	Delays in the progress of construction and installation works	w_{e3}	P_{e3}
	E ₄	Contractor's financial problems	w_{e4}	P_{e4}
	E ₅	Absence of written instructions from the customer	w_{e5}	P_{e5}
	E ₆	Unclear local tender laws and regulations	w_{e6}	P_{e6}
	E ₇	Different interpretations of the contract terms	w_{e7}	P_{e7}
	E ₈	Unclear contract terms regarding the change of the contract price in relation to the preliminary amounts	w_{e8}	P_{e8}
	E ₉	Unclear contract terms regarding the adjustment of approximate quantities	w_{e9}	P_{e9}
	E ₁₀	Unclear terms of refunding withheld cash amounts	w_{e10}	P_{e10}
	E ₁₁	An unclear way of reducing the damage caused by delays	w_{e11}	P_{e11}
	E ₁₂	Unclear definition and types of defects	w_{e12}	P_{e12}
	E ₁₃	Ungrounded distribution of risks in the contract	w_{e13}	P_{e13}
	E ₁₄	Failure to account for or accurately calculate the additional cost of actual work at the time of the tender and the evaluation process	w_{e14}	P_{e14}
	E ₁₅	Failure to examine the terms of the contract during the tender	w_{e15}	P_{e15}
	E ₁₆	Ambiguous limit of liability for the use or storage of materials and equipment provided by the employer	w_{e16}	P_{e16}
	E ₁₇	Disagreements over the amount of compensation for construction costs and time, in case a claim is filed	w_{e17}	P_{e17}
	E ₁₈	Disagreements about the payment method caused by a change in the quantity	w_{e18}	P_{e18}

End of Table 5

Risk Type x	Code	Negative risk factor or event R	Weight w	Probability P
Contract (C)	C ₁	Different interpretations of the contract terms	w _{c1}	P _{c1}
	C ₂	Unclear contract terms concerning approximate calculations	w _{c2}	P _{c2}
	C ₃	Unclear definition of defects	w _{c3}	P _{c3}
	C ₄	Ungrounded distribution of risks in the contract	w _{c4}	P _{c4}
	C ₅	Ambiguous limit of liability for the use or storage of materials and equipment provided by the employer	w _{c5}	P _{c5}
	C ₆	Disagreements over the amount of compensation of costs in the event of a claim and the method of payment for changes in amounts	w _{c6}	P _{c6}
	C ₇	Differences in construction standards and methods of organization and production of works	w _{c7}	P _{c7}
External factors (X)	X ₁	Currency exchange rate fluctuations	w _{x1}	P _{x1}
	X ₂	Economic fluctuations and changes in tax rates	w _{x2}	P _{x2}
	X ₃	Changes in laws and regulations	w _{x3}	P _{x3}
	X ₄	Language barriers, different cultural and religious traditions	w _{x4}	P _{x4}
	X ₅	Force majeure, such as weather disasters, war, revolution, and civil unrest	w _{x5}	P _{x5}
	X ₆	Differences in construction standards and methods of organization and production of works	w _{x6}	P _{x6}
	X ₇	Tougher immigration rules governing the stay of SMEs	w _{x7}	P _{x7}

In addition, a similar method describes the risk of delayed construction of NPPs abroad $P(r_{d1})$, 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_7) 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_{fdi} parameter, or "the forecasted duration of the project implementation option", is determined as follows:

$$P(r_{fd1}) = P(O_7 x w_{o7} + E_2 x w_{e2} + E_6 x w_{e6} + C_2 x w_{c2}). \quad (2)$$

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 resources,** 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]:

$$G(T, K, X, S, F, P, R), \quad (3)$$

► where T is the problem formulation; K — the set of criteria; X — the set of scales; S — the set of alternatives; F — the mapping of a set of alternatives onto the set of assessments; P — the system of preferences of a decision-maker; R — the decision rule.

Scientists and specialists offer different types of criteria depending on problem solving conditions. For example, the main (most significant) criteria include the net present value (NPV), the profitability index (PI), the internal rate of return (IRR) [21], income maximization, expected risk minimization [22], project implementation time (P), social effect, etc.

The choice of the optimality criterion of future-oriented schedules in the pre-investment phase depends on specific conditions of the construction process and activities of the organization, the interests of the investor and the contractor. It is proposed to optimize the project implementation schedule according to the most significant criterion, the is, the identification of the optimal solution. In particular, the most significant criterion is the efficiency of the dynamics of capital investments, proposed by V.A. Afanasyev [23], who analyzed the market aspects of construction activities as early as in the days of the USSR. The efficiency coefficient of the dynamics of capital investments can be represented as follows:

$$K_{IO} = \frac{K(\alpha^T - 1) + \sum_{i=1}^n K_i (2 - \beta^i) - \alpha^{T-t_i}}{K(\alpha^T - \beta^T)}, \quad (4)$$

where K is the total amount of capital investments (the estimated cost of building a facility or a group of facilities); K_i is the i -th capital investment at time t_i ; T is the duration of the entire set of works; α is the coefficient of reduction of the i -th capital investment to term $t_i + 1$, equal to $1 + E_n$; β is the coefficient of reduction of the i -th capital investment to term $t_i - 1$, equal to $1/(1 + E_n)$; E_n is the standard efficiency factor.

These principles serve as the basis for the developed set of **formal heuristic algorithms designated for finding the optimal option of future-oriented project implementation schedules in the pre-investment phase**. Methods of sequential analysis of options [24] and direct search [25] were used to develop formal heuristic algorithms.

The optimization algorithm, based on the most significant criterion, can be specified as follows: there is an ordered set of $S = \{S_n\}$ options for making a future-oriented project implementation schedule that meets regulatory requirements ($S \subset D$); $P = \{P_k\}$ is a set of alternative future-oriented schedules taking account of a specific facility, material, technical, human and financial resources.

For each P_k option, the set of outcomes $J = \{J_m\}$ and the transition vector on set S are defined: $R_n[a_{1k-1}e_1, a_{2k-1}e_2, a_{3k-1}e_3]$, where e_i ($i = 1, 2, 3$) is the unit transition vector parallel to the axis.

$$e_i = \begin{cases} 1 & \text{during transition to } S_k : a_{ik} a_{ik} - 1; \\ 0 & \text{during transition to } S_k : a_{ik} = a_{ik} - 1; \\ -1 & \text{during transition to } S_k : a_{ik} a_{ik} - 1. \end{cases} \quad (5)$$

Limiting operator $O(J)$ of search domain D is defined for set J . It corresponds to each outcome with subset $S_{k+1} = O(J_k)S_k = S_k \setminus C$, containing the optimal version of the future-oriented schedule at $D \neq \emptyset$.

The sampling space may, for example, contain the following mutually exclusive outcomes:

- the time limit for the future-oriented schedule is not met ($J_k = 1$);
- the construction and installation work funding limit is not met ($J_k = 2$);
- the material supply limit is not met ($J_k = 3$);
- the human resources use limit is not met ($J_k = 4$);

- the technical support limit is not met ($J_k = 5$);
- the option led to an improvement in the target function ($J_k = 6$);
- the option led to the deterioration of the target function ($J_k = 7$).

The transition to experience is characterized by the following operations:

- when $J_k - 1 = 1$:
 $e_{ik} = -1$, where i is the number of any options;
 $e_{ik} = 0$ for $i \neq i$;
 $\forall S_n [a_{in} \geq a_{ik-1} \rightarrow S_n \subset C]$;
 $S_k = S_{k-1} \setminus C$;
- when $J_{k-1} = 2$:
 $e_{3k} = 1$; $e_{2k} = e_{1k} = 0$;
 $\forall S_n [a_{3n} \leq a_{3k-1}; a_{1n} = a_{1k-1}; a_{2n} = a_{2k-1} \rightarrow S_n \subset C]$;
 $S_k = S_{k-1} \setminus C$;
- when $J_{k-1} = 3$:
 $e_{ik} = 1$, where i is the number of the option, for which this limit is

not met;

- when $J_{k-1} = 4$:
 $e_{ik} = 1$, where i is the number of the option, for which this limit is

not met;

- when $J_{k-1} = 5$:
 $e_{ik} = -1$, where i is the number of the option, for which this limit is

not met;

- when $J_{k-1} = 6$:
 $R_n = R_n$;
 $\forall S_n [a_{in} \leq a_{ik-1}; e_{ik-1} = 1; J_{k-2} = 6 \cup J_{k-2} = 7 \rightarrow S_n \subset C]$;
 $(\forall S_n [a_{in} \geq a_{ik-1}; e_{ik-1} = -1; J_{k-2} = 6 \cup J_{k-2} = 7 \rightarrow S_n \subset C])$;
 $S_k = S_{k-1} \setminus C$;

- when $J_{k-1} = 7$:
 $R_n = R_{k-1}e$, where $[-1, -1, -1]$ — unit vector;
 $\forall S_n [a_{in} \geq a_{ik-1}; e_{ik-1} = 1; J_{k-2} = 6 \cup J_{k-2} = 7 \rightarrow S_n \subset C]$;
 $(\forall S_n [a_{in} \geq a_{ik-1}; e_{ik-1} = -1; J_{k-2} = 6 \cup J_{k-2} = 7 \rightarrow S_n \subset C])$;
 $S_k = S_{k-1} \setminus C$.

The research continues as long as set $S \neq \emptyset$.

Formal heuristic algorithms allow to reduce the time of the optimization process by 2.5–3 times compared to the iteration of future-oriented schedule options and guarantee to find the extremum of the target function at $D \neq \emptyset$.

The decision making process in the multi-criterial conditions is reduced to finding such an alternative option from the set of acceptable ones, which may not be optimal for any of the criteria q_i , but which turns out to be acceptable for the entire vector of criteria $Q = \{q_1, q_2, q_3, \dots, q_n\}$, i.e. finding a compromise alternative [24]. The real facility will always represent some compromise combination of required qualities. This problem can be solved by introducing an additive criterion, for example, reduced costs.

Thus, it is possible to obtain an option of the future-oriented schedule applicable to the implementation of an NPP project, for which the relative level of all particular criteria is not worse than a certain limit value of $q_i^* + \Delta q_i$ with the value of the additive criterion Q_{Σ} sufficiently close to optimal Q_{Σ}^* . In addition, this approach allows

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-criterial 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 finding the optimal future-oriented schedule was modeled on the basis of multi-criterial optimization performed within the framework of an integrated organizational/economic reliability management system. The described formal algorithm allows us to take account of a number of factors that are non-deterministic or not specified in the process of selecting partial criteria of optimality.

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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 присущим ей набором требований и правил 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 модели 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, к факторам риска на предынвестиционной фазе относят недостаточную предпроектную проработку вопросов организации и управления проектом на этапе заключения EPC(M)-контракта (engineering, procurement, construction, management — управление проектированием, поставками и строительством).

Моделирование управления рисками рассматривается в качестве основного элемента системы управления организационно-экономической надежностью предынвестиционной фазы сооружения АЭС на зарубежном рынке и включает в себя: а — структуризацию многопараметрического факторного пространства рисков по четырем источникам: со стороны заказчика, EPC(M)-подрядчика, контракта и внешней среды; б — модель управления предынвестиционными рисками строительства АЭС за рубежом на основе совокупного риска проекта $P(r_{11})$; в — математическую модель выбора варианта реализации проекта на основе многокритериальной оптимизации прогнозного плана-графика.

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

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