Organizing Industrial Construction of Nuclear Power Facilities in the Global Nuclear Power Markets taking into account Reliability Simulations from Pre-Investment Stages

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Abstract. This article considers the problem of ensuring the growth of export capacities of the industrial construction of nuclear power facilities in the global markets through the simulation and management of the organizational reliability during the pre-investment stage. This research is made relevant by a high level of uncertainty in the implementation of international investment projects for nuclear power when over 60% of the world’s nuclear reactors are constructed with delays and at increasing costs. The purpose of this research is to develop methodological approaches and practical recommendations on the modeling and complex management of organizational reliability indicators for the industrial construction of nuclear power facilities in the global markets during the pre-investment stages. This article presents the following results: the simulation procedure for the organizational reliability and life cycles of the industrial construction of nuclear power facilities developed by the authors, development specifics and trends for this type of industrial construction, recommendations concerning the organization of industrial construction to improve the reliability of nuclear power facility construction based on a managed factor space and multi-criterion optimization of calendar schedules. The conceptual approach to modeling and management of the organizational reliability of nuclear power industrial construction and operation life cycles in question can be determined as a promising market tool that can be used to regulate the increase of the competitive abilities of the Russian branches of Rosatom State Corporation. This stipulates facilitating the growth of the industrial construction of nuclear power facilities in the global market from the current share of Rosatom State Corporation of 26% (120 billion USD) to 40-50% before 2035 through the improvement of the organizational reliability of the implementation of this type of investment projects.

1. Introduction
Participating in the international market of industrial construction of nuclear power facilities is a promising development area of Russian nuclear power companies. Increasing the export capacities of the industrial construction of nuclear power facilities is hindered by the insufficient reliability of their implementation due to the delays in nuclear power facility construction and the increase in the contract
value, which can often be attributed to high organizational risks that were not considered during the pre-construction stage.

Thus, we deem it relevant to develop the methods that could increase the share of Russian investment projects in the global market of industrial nuclear power construction. These projects shall have a high competitive ability through the improvement of the organizational reliability of this type of investment projects formed during the pre-investment stage.

This research focuses on the industrial construction associated with large and complex nuclear power investment megaprojects of Rosatom State Corporation in the global nuclear power construction market, as well as similar projects of other developers in different countries.

Currently, the nuclear power industry is one of the largest sectors. In the recent decade, the global market of nuclear power plant construction shifted towards third-world countries [1]. Developing countries generally face a lack of capital available for the construction of nuclear power generation units [2].

The history of international nuclear power plant construction is traditionally divided into three waves of nuclear technology developing countries [1]. The first wave includes the countries that began developing the peaceful atom industry in the 1950es-1960es. These are the USA, the UK, the USSR, and Canada. Later they were complemented with the second-wave countries, such as Germany, Japan, France, Sweden, Czech Republic, and Italy. Over the last fifteen years, new nuclear technology importers appeared: South Korea and China (the third wave) [3].

The implementation of nuclear power facility construction projects abroad are classified as large and complex investment and construction projects [4]: large-scale investment (up to 30 billion USD); long implementation times (10-15 years for designing, construction, and commissioning, and 60 years of operation).

N. Ya. Leontyev in his thesis [5] studies the competitive ability of engineering companies operating in the nuclear facility construction sector. Besides, improving the efficiency and the quality of service is a key condition for the promotion of Russian-made nuclear power equipment in the global market [6]. Improving export capacities of the nuclear power sector is set as a purpose in the documents of the Ministry of Economic Development and Trade [7] and the Energy Strategy of Russia both the current one spanning up to 2030 [8] and the developed draft spanning up to 2035.

Some of the works by Russian researchers [9] identified the problems with the implementation of the industrial construction projects for nuclear power facilities (regular delays in construction and investment increases reaching up to several dozens or even hundreds of percent). We must note that, in Russian practices, the scope of responsibilities of the key contractor for the nuclear power plant construction differs from the scope of responsibilities typical of foreign EPCM companies [10].

We established that international construction projects are more prone to cause disputes due to such factors as differences in the legal regulation of contracts, cultural specifics, language barriers, and technical standards [11]. Risks associated with this type of industrial construction always lead to disputes and conflicts [12] that manifest themselves in different ways.

The article by A.P. Solovyova, V.V. Kharitonov, and O.G. Shmakov [13] presents the author's calculation model for the efficiency of nuclear power facility investments under commissioning delays. Muhammed Mufazzal Hossen, Sangku Kang, and Chongyun Kim [14] developed an assessment procedure for the organizational risk associated with the delays in nuclear facility construction and assessed this kind of risk for international turnkey nuclear projects. The analysis shows that construction delays may be unacceptable in terms of foregone earnings and capital costs interest [15].

Budget overrun and delays in industrial construction projects for new generation nuclear facilities in recent years have made it clear that the nuclear industry still uses unsuccessful and obsolete management and construction control methods in nuclear projects [16]. If project completion is put off by a year, the levelized cost of electricity increases by approximately 8-10% [17].

Some of the works carried out by the authors of this article demonstrated the importance of the formalization of simulation and management processes for the organizational risks during the pre-
investment stage of nuclear facility construction in the global market [18-20]. The structure of Russian sales strategies for nuclear projects in the global market [21], as well as the analysis of the project and risk management specifics for the industrial construction in foreign countries, are of key importance [22].

The assessment of the life cycle costs for capital construction projects from the viewpoint of the cost of ownership for the ultimate consumer is also a promising area of research [23,24]. Using this principle for the assessment of the cost of ownership for the life cycles of a nuclear power plant must include the development stage and the operation state, taking into account the specifics of nuclear facility construction abroad [22]. The analysis [25] showed that the formation of innovative sales strategies for nuclear facility investment and construction projects for global markets in Russia is a priority in the organization of efficient industrial construction.

2. Methods

Expert research found that the key organizational reliability criteria for the industrial nuclear power construction projects include the efficiency of organizational decisions related to nuclear projects in terms of construction times and costs identified at the early pre-investment stage of the life cycle (LC).

Developing methods requires the priority of the organizational reliability control for industrial construction according to reliability indicators based on the fulfillment of construction terms and costs. The simultaneous consideration of these two efficiency factors is referred to as the construction intensity in this research work. Thus, it is necessary to simulate reliability as organizational reliability (ORN) using the construction work intensity (CWI) criterion.

To understand ORN as the efficiency of industrial construction during LC states i-j, we must view it as the compatibility of reliability criteria with a reference point equal to one that dissipates due to subsequent organizational failures.

The standard procedure for the formalization of OR_{i-j} against LC_{i-j} stages may look as follows with goal function minimizing the deviations of \Delta OR_{i-j}:

\[
ORN_{0}^{i}[LC_{0}^{i}] \rightarrow ORN_{i+1}[LC_{i+1}] \rightarrow ORN_{i+2}[LC_{i+2}] \rightarrow \ldots ORN_{i-j}[LC_{i-j}] \rightarrow \Delta OR_{i-j} \text{(min)}
\]  

We must note that according to the UNIDO procedures, documents like the preliminary feasibility reports, feasibility reports, and the calculations of contract terms and costs at the pre-investment stages contain preliminary data that shall be clarified at the contract award stage and the project development and approval stage within the construction method statement. Therefore, the calculation model for OR_{i-j} across LC_{i-j} stages may look as follows:

\[
ORN_{\text{typo}}[LC_{i-j}^{\text{typo}}] \rightarrow ORN_{0}^{i}[LC_{0}^{i}] \rightarrow ORN_{i+1}[LC_{i+1}] \rightarrow \ldots ORN_{i-j}[LC_{i-j}] \rightarrow \Delta OR_{i-j} \text{(min)}
\]

The developed procedure aims to simulate the OER_{i-j} indicator based on the intensity criterion through two basic components.

Firstly, it is the organizational reliability of the first type (OR_{i-j}(I)) related to the fulfillment of the set construction schedule (T_{0}^{\text{typo}}) within nuclear facility construction life cycles as the compatibility of the decisions made on T_{0} to later LC stages compared to the early LC stages. Any positive or negative deviation from the construction terms results in a reduced OR_{i-j}.

We suggest using the data on the proportion of nuclear power generation units built without delays (N^{'}) and their total number (N_{0}) at the set calculation period and date as an additional organizational reliability index. In this case, OR_{n} is determined as follows:

\[
OR_{n} = N^{'} / N_{0}
\]
This type of OR describes the probability of fault-free construction of nuclear power generation units. It does not reflect the deviation from the schedule and only indicates instances of failures. This indicator can be used due to the complication with the collection of statistics.

Secondly, it is the organizational reliability of the second type (OR_{ij}(2)) related to the fulfillment of the set construction costs (S^i_j) within nuclear facility construction life cycles as the compatibility of the decisions made on S^i at later LC stages compared to the early LC stages.

This theoretical approach can be illustrated with the following formula:

\[
ORN_{ij} = OR_{ij}(1) \times OR_{ij}(2)
\]

where

\[
OR_{ij}(1) = \frac{1}{T_{ij}} \times (\frac{1}{T_{ij}} + \Delta T_{fail})
\]

\[
OR_{ij}(2) = \frac{S^i}{S^i + \Delta S_{fail}} = \frac{1}{\frac{1}{S^i} + \Delta S_{fail} / S^i}
\]

where

\[
S_i = S^i = S^i_{pl}
\]

The OR (2)_{ij} formula can be used when S^i is over or equal to S^i_{pl}.

| Stage | Construction schedule |
|-------|------------------------|
| i     | \(T_{ij} = T_{ij}^{pl}\) |
|       | \(\Delta T_{fail} = T_{ij} - T_{ij}^{pl}\) |
| j     | \(\Delta T_{fail} = T_{ij} - T_{ij}^{pl}\) |
|       | \(T_{ij}^{pl}\) |

**Figure 1.** The calculation model to determine the parameters of organizational reliability OR_{ij}(1) across the stages of LC_{ij} based on the identification of construction terms failures.

3. Results

The analysis of problems associated with the organizational reliability of industrial construction for nuclear power projects in the global market using the lagging criterion for scheduled construction terms showed that 33 out of 52 or 63.5% of the nuclear power generation units were built with delays as of 01.07.2020.

Researching the organizational reliability using the delay criterion for the scheduled commissioning of nuclear power generation units showed that the branches of Rosatom State Corporation can boast high fulfillment reliability for the construction schedules prepared earlier. In this research, we used the data from the International Energy Agency (IEA), the International Atomic
Energy Agency (IAEA), the World Nuclear Association, and the Atomic Energy Agency (OECD). Thus, the organizational reliability $PR_n$ of power generation units in Russia is 0.67. As of 01.07.2020, only the UK and Bangladesh exceed Russia in this standalone index. The organizational stability of China is 0.6, and it is 0.5 for Turkey and Pakistan, and 0.29 for India. Countries like South Korea, UAE, Belarus, Slovakia, the USA, Argentina, Iran, and Japan feature low organizational reliabilities because all of their power generation units are built with delays.

The indicator of $OR_n$ makes up a specific local picture of organizational discipline in nuclear facility construction but it cannot be seen as unique and it requires additional parameters for complex analysis.

The analysis of the open data from the IAEA\(^1\) showed that the average construction terms for nuclear power generation units from 2009 to 2019 are ten years judging by 63 nuclear facilities under construction. The minimum term for South Korea and China is 4.1 years, and for Pakistan, it is 5.2 years. For Russia, these indicators are 20.3 years on average, 8.1 years at the minimum, and 35.1 at the maximum. The USA deal with long construction terms (43.5 years).

There is a clear global trend for the increase in nuclear facility construction terms due to the safety restrictions. In the 1980es-1990es, the average construction term was 8 years. The average value for the recent years is 10 years and it can vary.

Nine power generation units competed by Chinese nuclear companies in 2018-2019 took 7.6 years to construct on average. At the same time, five Russian projects took 16 years on average from project launch to grid connection. The Rostov-4 project took 35 years from the start of construction to power production. The analysis of construction term fulfillment showed that the average delay is at least 50\% of the planned values. We can claim that the rapid construction of nuclear facilities is exceptional.

The unitary cost interval of capital (overnight) costs in the foreign nuclear construction market is within the range of 6500-12250 USD per 1 kW of installed nuclear capacity. It varies across countries and tends to decrease because it has to compete with alternative energy sources.

Since the information of scheduled and actual construction costs and terms for nuclear facilities is restricted or classified in different countries, it causes difficulties with testing the $ORN$ methods suggested previously. Thus, the authors develop a radial expert analysis model for the $ORN$ graph.

It was established that all the market segments can be divided into 3 groups: A – highly reliable construction projects with $ORN_{1.3}$ between 10 and 0.9. As a rule, the organizational reliability $OR(1)_{1.3}$ for these projects can be fulfilled with a single indicator, and $OR(2)_{1.3}$ is the value of cost failures up to 20\%. Thus, the average $ORN_{1.3}$ remains within 80\% or 0.8; B – reliable projects with $ORN_{1.3}$ ranging from 0.79 to 0.50; C – low-reliability projects with $ORN_{1.3}$ ranging from 0.49 to 0.20; D – critical reliability projects with $ORN$ lower than 0.20.

The analysis of $OR(2)_{1.3}$ values showed that their averages change even under high organizational reliability indices. Thus, for highly reliable group A projects where $OR(1)_{1.2}$ = 1.0, project costs can change due to inflation and unaccounted cost factors at the very least.

$ORN$ calculations for some of the nuclear power plants built during the Soviet period showed that Zaporizhzhia and Balakovo nuclear power plants had the best construction indices within group A. We calculated the final $ORN_{1.3}$ for them, which equaled 0.60. This indicator for the second group of nuclear power plants (in Kalinin, Khmelnitsky, Rostov, and Yuzhnoukrainsk) equaled 0.34. The obtained change graphs for these indicators show a significant dissipation of single basic indicators to unsatisfactory reliability zones.

In today's global nuclear construction market, we can assess $ORN$ using only local organizational reliability indicators like $OR_n$ calculated before and the average index of $OR(2)_{1.3}$ of 0.8. This produced the following organizational reliability groups of customer countries in the global market. The data is presented as of 01.07.2020 and in descending order: The UK and Bangladesh - 0.8 (group A – highly reliable projects); Russia, China – 0.5 (group B – reliable projects); Turkey, Pakistan – 0.4 (group C - low-reliability projects).

\(^{1}\)https://prisweb.iaea.org/Home/Pris.asp
This procedure was tested in experiments due to the problems with data collection. The interpretation of the results and the procedure itself require creative development and cannot be deemed finalized.

4. Discussion

The production of an intensity-based organizational reliability indicator for industrial construction as a compatibility system for the decisions made during the life cycle of nuclear facilities using the local criteria of implementation terms and costs is interesting in theoretical and practical terms. At the same time, this problem raises a number of controversial issues. Firstly, if you integrate ORN and terms and costs fulfillment, it would be desirable to analyze correlations between cost and term fulfillment indicators as well. It might be necessary to include them in the final ORN indicator as different-weight correlation indicators or use other types of economic and mathematical correlations between specific reliability indicators. Secondly, the ORN procedure presented is generic and requires adjustments accounting for the corporate standards of a specific operator or a customer country.

The controversial issues mentioned above should be seen as development prospects rather than the drawbacks of the procedure in question.

5. Conclusions

The performed research confirms the relevance of the research area selected by the authors and the development of methodological approaches and practical recommendations for the modeling and complex management during the pre-investment stages using the integrated indicators of organizational reliability of the industrial construction of nuclear facilities.

The problem of increasing the competitive ability of the construction departments of Rosatom Russian State Corporation abroad requires the growth of its share from the current 26% (130 billion USD) to 40-50% over the period until 2035. The concepts and procedures that would help improve the organizational reliability of the industrial construction of nuclear facilities through its costs and terms are the key elements in the formation of these competitive advantages.

The problem in question is important for the Russian economy is confirmed by the fact that the current Russian portfolio of nuclear facility construction orders in the global market is very large. It is 2.5 times bigger than a similar export order portfolio for the products of the Russian defense industry sector ($53.8 billion in 2020).

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