Assessment of uncertainties and risks related to implementation of infrastructure projects

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Abstract. The paper considers principles of assessing uncertainties and risks related to realization of infrastructure projects. The procedure for the examination of the proposed infrastructure project should use the methodological toolkit of risk theory, which was developed to assess safety of complex technical systems. A risk-based approach to the assessment of infrastructure projects involves a scenario assessment of the project, taking into account the influence of potential hazardous natural, technological, economic and socio-political factors that can significantly complicate the project implementation. A set of indexes allowing one to assess and compare different variants of the infrastructure project implementation is presented.

Key words: infrastructure project, uncertainty, risk, utility

1. Introduction

The concept of infrastructure project refers to long-term large-scale project that is focused on the development of infrastructure facilities and lifelines and is being carried out in accordance with the strategic plan of the social and economic development of the community, district or territory.

Planning and implementation of infrastructure projects is carried out in uncertain environment. Project uncertainties are related to: (a) random nature of various events and processes that develop at various stages of the project life cycle, and (b) lack of knowledge about many key phenomena that took place in the course of the project development. In some cases it is convenient to distinguish a certain group of uncertainties related to the possibility of occurrence of rare unexpected extreme events that cannot be foreseen at the design (panning) phase of the project. These uncertainties are actually a combination of uncertainties that belong to the first two groups but they are aggregated into the specific group in the view of tremendous influence that they have on the project implementation [1-4].

Due to the above listed uncertainties infrastructure projects should be described in the probabilistic formulation using branched scenario trees. These project uncertainties also cause a set of project risks that are inevitable when infrastructure projects are being developed. Project risks can be classified in accordance with the stage of the project as design, construction, maintenances and decommissioning risks. The following groups of project risks may be distinguished:
• Economic and financial risks include risks related to instant changes in taxes, interest rates, commodity prices, etc.
• Social and political risks may be caused by political conflicts, public unrest, etc.
• Organizational risks referred to human errors made at various stages of the project development.
• Risks of natural and manmade catastrophes include risks of extreme natural events, technological accidents, unauthorized impacts, etc.

One should note that the presence of uncertainties related to realization of infrastructure projects produce not only risks of various negative factors but also may create chances of some positive influences on the project (appearance of new technologies, improvement of business (economic) conditions, favorable environmental conditions, etc.).

2. Scenario assessment of infrastructure projects
Assessment of uncertainties is an important step of the process of making decisions regarding launching the infrastructure project and planning the schedule of its implementation. Due to the high level of uncertainty related to the project implementation its propagation is multivariate and should be characterized by a branched scenario trees that could be described by graphological models used for assessment of risks in complex engineering systems [4-8]. Each of the scenario $S^i$ ($i=1,2,...,k$) terminates with end state (outcome) $ES^i$ ($i=1,2,...,k$) of the project. Here each outcome $ES^i$ can be defined by a set of generalized parameters:

\[ ES^i = \left\{ P(S^i), \left[ C(S^{opt}), T(S^{opt}), X(S^{opt}) \right] \right\} \]

where $P(S^i)$ is the probability of the event $S^i$, $C(S^{opt})$ is the cost, $T(S^{opt})$ is the time, and $X(S^{opt})$ is the risk.

Figure 1. Scenario tree of the project

$S^{(b)}$ - base project scenario; $S^{(opt)}$ - optimistic project scenario; $S^{(pes)}$ - pessimistic project scenario; $H_i$ ($i=1,2,...,l$) - random factors (risk-factors) influencing the project.

• adjusted cost of the project implementation along scenario $S^i$ that is calculated through adjusting the flow of payments to a specific date (e.g. to the start of the project), $NPV^i$;
time of the project implementation along the specific scenario, $T^{(i)}$;

- an assemblage (aggregate) of the characteristics of the project outcome $X=(x_1, x_2, ..., x_n)$ that includes such parameters as cost of a unit of goods or services $Nc^{(i)}$, production rate $E^{(i)}$ of the facility (asset) constructed in the frame of the project, its reliability $Re^{(i)}$, service risk $R^{(i)}$, etc.

Each of the project outcomes (end states of the project) can thus be represented by a point in the project space of states $\Omega$: $ES^{(i)}(C^{(i)}, T^{(i)}, Nc^{(i)}, E^{(i)}, Re^{(i)}, R^{(i)}) \in \Omega$ (Figure 1) and this outcome can occur with a specific probability $P(ES^{(i)})$ that can be estimated using graphological models (event trees, fault trees, Bayesian nets, diagrams of influence, etc.).

Considering $m+2$ dimensional space of the project states and $\Omega(y_1, y_2, ..., y_{m+2})$, where $y_1=C$, $y_2=T$, $y_3=x_1$, $y_4=x_2$, $..., y_{m+2}=x_m$. A multiattribute utility function is introduced to compare various project outcomes that are characterized by a set of various parameters $(y_1, y_2, ..., y_{m+2})$. This function maps the points $ES^{(i)}$ of the project functional states $\Omega$ to the points $u^{(i)}$ of the axes $R^N$ of natural numbers:

$$ (y_1^{(i)}, y_2^{(i)}, ..., y_{m+2}^{(i)}) \rightarrow u^{(i)}, u^{(i)} \in R^N. $$

This mapping allows describing the preferences of the stakeholders regarding the outcome of the project. In other words the form of the function $u=u(y_1, y_2, ..., y_{m+2})$ is determined by the preferences of the stakeholders. It may form the basis for comparison of various scenarios and used in the criteria of the project success. When the whole scenario tree is assessed and the probabilistic distribution of the utility function for this specific variant of the project is obtained one may make judgments estimating the success of the project and compare different variants of the project implementation.

In the simplest formulation the linear utility function can be taken:

$$ U = \sum_{j=1}^{m+2} w_j y_j, $$

where $w_j$ are weighting coefficients that describe the importance of the factors $y_j$ in the eyes of the stakeholders. Weighting factors are constrained by a condition:

$$ \sum_{j=1}^{m+2} w_j = 1. $$

Then a specific value of the utility function will correspond to each project scenario $S^{(i)}$:

$$ U(S^{(i)}) = \sum_{j=1}^{m+2} w_j \cdot y_j(S^{(i)}) = w_1 \cdot C(S^{(i)}) + w_2 \cdot T(S^{(i)}) + \sum_{j=3}^{m+2} w_j \cdot x_{j-2}(S^{(i)}). $$

It is clear that the linear form of the utility function is oversimplified and does not allow assessing the interference between various factors and the preferences of the stakeholders to avoid scenarios with strong negative utility. Higher order polynomials should therefore be used for approximation of utility functions for real infrastructure projects.

Then using the project scenario graph all identified project scenarios are considered, and the values of probabilities $P(S^{(i)})$ and utilities $U(S^{(i)})$ for each of the scenario are estimated. Thus in the probabilistic formulation the infrastructure project can be described by a set of triplets:

$$ IP = \{S^{(i)}; P(S^{(i)}); U(S^{(i)})\}_{C}. $$

The subscript $C$ here refers to the complete set of project scenarios. This description of the project is quite similar to classical definition of risk introduced by Sten Caplan in [5]. The structure of triplets determines: (a) possible project scenarios, (b) probability of occurrence of the scenarios, and (c) values of the utility function that correspond to each of the scenario. The results of the scenario assessment are presented in a tabular form (Table 1).
Table 1. Listing of the project scenarios.

| Scenario | Probability | Utility |
|----------|-------------|---------|
| $S^{(b)}$ | $P(S^{(b)})$ | $U(S^{(b)})$ |
| $S^{(i)}$ | $P(S^{(i)})$ | $U(S^{(i)})$ |
| $S^{(2)}$ | $P(S^{(2)})$ | $U(S^{(2)})$ |
| ... | ... | ... |
| $S^{(k)}$ | $P(S^{(k)})$ | $U(S^{(k)})$ |

These data for the infrastructure project can be also presented in a graphical form by a set of points \{$(P(S^{(i)}), U(S^{(i)}))$\} at the “probability-utility” plane (Figure 2).

Figure 2. Presentation of the project outcomes by a set of points \{$(P(S^{(i)}), U(S^{(i)}))$\} that correspond to various project scenarios.

For the further consideration it will be more convenient to change the form of presenting data given in table 1. Here the scenarios $S^{(i)} (i=1,2,\ldots,k)$ that were initially numbered in an arbitrary order should be renumbered in such a way that the following conditions hold:

$$U(S^{(0)}) \leq U(S^{(i)}) \leq U(S^{(2)}) \leq \ldots \leq U(S^{(i)}) \leq \cdots \leq U(S^{(k)}) .$$

Besides the scenario table will be supplemented with an additional column containing the values of cumulative probabilities $F(S^{(i)}) = P(U \geq U(S^{(i)}))$ for each of the scenario $S^{(i)}$ that equal to the probability that the random value of the project utility $U$ will be higher than the value of utility $U(S^{(i)})$ corresponding to the scenario $S^{(i)}$.

Then the outcome of the scenario assessment of the infrastructure project can be presented in the following triplet form:

$$IP = \{< S^{(i)}; F(S^{(i)}); U(S^{(i)}) > | c_i (i = 0,1,2,\ldots,k) \}$$

(4)

Thus each of the scenario can be represented by a point \{$(F(S^{(i)}), U(S^{(i)}))$\} on the plane “cumulative probability-utility”. Connecting these points sequentially one can get a stepwise line $F(U)$ (Figure 3, line 1). This probabilistic distribution of the random value $U$ is called a utility profile of the infrastructure project and can be considered as a general characteristic of the project uncertainties [2].

It should be noted that if a more detailed assessment of the project scenario tree is carried out, each of the scenarios $S^{(i)}$ should be considered as a union of several very similar to each other subscenarios...
the difference between which were previously considered to be negligible. It means that if the scenario
assessment was conducted in a more detailed way the stepwise line of the project utility profile would
tend to a smooth curve (Figure 3, curve 2). In this case the discrete random variable
\( U \)

\[ \text{can be considered as a continuous variable } u \]

and described by a probability density function \( f_U(u) \), probability
distribution function \( \Phi_U(u) = P(U < u) \) and the project utility profile \( F(u) = P(U > u) = 1 - \Phi_U(u) \).

| Table 2. Supplemented listing of the project scenarios. |
|------------------------------------------------------|
| Scenario     | Probability | Utility | Cumulative probability    |
|--------------|-------------|---------|--------------------------|
| \( S^{(0)} \) | \( P(S^{(0)}) \) | \( U(S^{(0)}) \) | \( F(S^{(0)}) = 1 \) |
| \( S^{(1)} \) | \( P(S^{(1)}) \) | \( U(S^{(1)}) \) | \( F(S^{(1)}) = F(S^{(2)}) + P(S^{(1)}) \) |
| \( S^{(2)} \) | \( P(S^{(2)}) \) | \( U(S^{(2)}) \) | \( F(S^{(2)}) = F(S^{(3)}) + P(S^{(2)}) \) |
| \( \ldots \) | \( \ldots \)   | \( \ldots \)  | \( \ldots \) |
| \( S^{(k)} \) | \( P(S^{(k)}) \) | \( U(S^{(k)}) \) | \( F(S^{(k)}) = F(S^{(k+1)}) + P(S^{(k)}) \) |
| \( \ldots \) | \( \ldots \)   | \( \ldots \)  | \( \ldots \) |

3. Indexes of the infrastructure project utility

The procedure described in the p.2 allows one to create utility profile for the infrastructure project. This profile is the most general characteristics of uncertainties, risks and chances related to implementation of the infrastructure project [2]. However when the comparison assessment of different variants of the project should be carried out it is desirable to have a set of quantitative measures (indexes) of the project utility. These indexes can then be compared with some references or alternative variants of investments. To this end it is desirable to develop some indexes of the infrastructure project utility that would allow one to conduct comparative assessments of different variants of the project and to select the optimal one with accounting for the utility function and the preferences of the stakeholders.

The mathematical mean of the random variable \( u \) is one of its most simple and understandable characteristics. It can be referred to as integral index of the project utility:

\[
I_E = E\{U\} = \sum_{j=1}^{n} P(S^{(j)}) U(S^{(j)}) = \int_{0}^{\infty} u \cdot f_U(u) \cdot du .
\]

It can be showed that the area \( S_{E} \) under the utility profile \( F(u) \) equals to the mathematical mean of the random variable \( U \):

\[
S_{E} = \int_{0}^{\infty} F(u) du = \int_{0}^{\infty} (1 - \Phi_U(u)) du = \int_{0}^{\infty} f_U(x) dxdu = \int_{0}^{\infty} f_U(x) du dx = \int_{0}^{\infty} x f_U(x) dx = E\{U\} .
\]

In the ideal deterministic case when there is no uncertainties in the course of the project realization
the project can be described by a single stepwise line (line 1, Figure 4) that bounds the rectangle and
corresponds to baseline scenario of the project realization that occurs with the probability \( P(S^{(b)})=1 \)
and whose utility \( U(S^{(b)})=u_b \). When the project is assessed in a probabilistic formulation the project
utility profile would be presented by a curve 2 (Figure 4). The position of the curve 2 with respect to line 1 is determined by the following conditions:

- The influence of the negative random factors causes the occurrence of a number of pessimistic scenarios whose utility is lower than the utility of the baseline scenario $u < u_b$. Therefore the utility profile 2 will go below the stepwise line 1.
- The influence of the positive random factors may trigger the development of some optimistic project scenarios with utility $u > u_b$. That is why the maximum values of the utility profile $u_{\text{max}}$ will exceed the value of $u_b$.

The area of the curvilinear triangle $ABC$ (Figure 5) characterizes the decrease of the project utility ($\Delta U$) due to the influence of negative (unfavorable) random factors. The area of the curvilinear triangle $CDE$ will on the contrary define the increase of the expected utility of the project ($\Delta U_+$) due to the influence of the positive (favorable) random factors. Comparing the areas under the line 1 ($A_{OABD}$) and line 2 ($A_{OAE}$) one can estimate the decrease (in some cases increase) of the expected project utility when the project is considered in a probabilistic formulation and project uncertainties are taken into account. This value can be considered as another index of the project utility:

$$R_{pw} = A_{OABD} - A_{OAE}.$$

Figure 4. Project utility profiles in case of deterministic (line 1) and probabilistic (line 2) assessment of the infrastructure project utility.

Figure 5. The influence of positive and negative random factors.

Figure 6. Assessment of the effectiveness of additional measures 1- initial utility profile of the project, 2- utility profile of the project after realization of additional measures.

Figure 7. Determination of the integral utility of the project in the presence of scenarios with negative utility.

Assessment of utility profiles allows assessing the efficiency of measures to reduce the cost of project, cut the time of construction or increase safety and security of the project. If the area under the
utility profile increases after realization of additional measures than these measures should be considered effective.

It should be noted that in the general case given a certain method of choosing a utility function, unfavorable project scenarios may have a negative utility (Figure 7). In this case, the integral utility of the project will be the difference between the absolute values of positive utility $U_+$ and negative one $U_-$. 

$$U = |U_+| - |U_-|.$$  (6)

The utility profile built for the infrastructure project under consideration is a fairly complete representation of the uncertainties and risks that may occur at different stages of the project life cycle. The utility profile corresponds to the triplet representation of the project uncertainties (4) and makes it possible to assess the feasibility of the project.

Through utility profiles one can judge the effectiveness of various kinds of measures aimed at reducing the cost of work, reducing the project implementation timeframe, increasing safety of the facility being created, and reducing the risks of its operation. If, taking into account the additional costs of the protection measures, the area under the utility curve increases (Figure 6), then the additional measures should be considered justified in terms of the utility criteria of the stakeholders.

The advantage of this approach is that it allows one to conduct quantitative estimates and take into account the non-monetary characteristics of the project.

The use of utility profiles also makes it possible to compare different projects. Evaluating the area under the utility profiles of three projects, which are presented in Figure 7, it can be concluded that the project variant 1 is the most preferable.

![Figure 8. Comparison of various projects $E\{U_1\} > E\{U_2\} > E\{U_3\}$.](image)

![Figure 9. Probability density functions of utilities of various projects $E\{U_1\} = E\{U_2\}$, $\sigma\{U_1\} < \sigma\{U_2\}$.](image)

However, a comparison of the mathematical expectations of the project utility for different variants of the project often does not allow choosing the more preferable one (for example, in cases when the utility profiles overlap and have approximately equal areas). A simple comparison of the mathematical expectations of the project utility for cases 1 and 2 (Figure 8) can be insufficient to make a decision which variant is better. Mathematical mean of the project utility is not a complete and comprehensive characteristic of the project as it does not allow describing the aversion of project variants with large scatter of utility values for various scenarios (Figure 9). Bearing this in mind in addition to integral project risk index a ratio of the mathematical mean $E\{U\}$ and standard deviation $\sigma\{U\}$ of the random utility value $U$ can be used as an additional project risk index:

$$I_p = \frac{E\{U\}}{\sigma\{U\}}.$$  (7)

Another utility index that allows assessing the utility of the project on the bases of its probability distribution is its fractile index:
\[ I_p = u_p = \Phi^{-1}(P), \quad (8) \]

where \( \Phi^{-1}(P) \) is the so-called quantile function which is an inverse function of the function \( \Phi_U(u) \).

This index determines the value of utility \( u_p \) which with a given probability \( P \) will not be exceeded in the case of implementation of the project.

In particular, when assessing the utility of projects, 5% and 95% quantiles can be used: \( I_{0.05} \) and \( I_{0.95} \) that represent levels \( U \) that will not be exceeded with a probability of 5% and 95%, respectively.

Derivative indices of the project utility (with respect to \( I_p \)) are the mathematical expectations of the left and right tails of the distribution of the magnitude \( U \):

\[ I_{LT} = E(U \mid U < I_{0.05}), \quad (9) \]
\[ I_{RT} = E(U \mid U > I_{0.95}). \quad (10) \]

The issue of development normative values for utility indexes for projects of various types as well as the type of utility function remains largely open now and requires further consideration.

4. Conclusions

1. When planning and implementing infrastructure projects, one encounters two types of uncertainties: (a) uncertainties stemming from the natural variability of conditions and factors affecting the progress of the project; and (b) uncertainties caused by limited knowledge about the processes occurring at different stages of the project development.

2. Scenario analysis of the infrastructure project allows obtaining the so-called profile of the project utility which is the most complete characteristic of uncertainties, risks and chances that accompany its implementation.

3. The proposed set of infrastructure project utility indexes can be used as a basis for making a comparative assessment of various project implementation options.

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