Capital construction projects management based on Bayesian networks integrated into the complexity model

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Abstract. This article presents the author’s results of the developments to assess the likelihood of problems when managing capital construction projects based on Bayesian networks. The research aim was to study the management decision-making procedure in framework the implementation of investment and construction projects, as complex models. The article relevance arises in connection with an increase in the percentage of capital projects that have not been fully implemented. As a rule, the main reasons for canceling or suspending construction projects are the lack of constant investment, delays in preparing design estimates, problems with connecting ready-to-use facilities to engineering systems, and the lack of a clear technology for developing and monitoring contracts. The article proposes an approach for occurrence probability predicting of problem situations in the framework of capital construction projects, based on the integration of the project complexity model and the method for assessing problem areas using Bayesian networks. The developed approach for analyzing the future project state on the basis available statistical data on analog facilities was tested on the example of construction a hotel chain.

1. Introduction
According to the online database "Investment Projects of Russia" [1], in 2017 in Russia more than 1,400 projects were implemented, broken down by industry:
1) industrial construction - 1008 projects,
2) civil engineering - 431 projects.
At the same time, the number of capital construction projects announced for implementation in 2017 exceeded this indicator of 2016 by 35%. In general, the picture has not changed over the past three years. Changes began to be observed in February 2020, when the number of projects at various development stages, on average, increased by 50-60%. At the moment, the base has at least 25,286 projects (Fig. 1).
It should be noted that projects in the early stages of implementation (planning, pre-design work, design) occupy more than 30% of the entire projects base that are at the active implementation stage. Its mainly include projects that are not identified or are in search of contractors. At least 23% of actively implemented projects are under construction (Fig. 1). But the fear is caused by canceled and suspended projects, which make up about 20% of the total number recorded on the portal. It is worth noting that, according to statistics [2], more than 50% of all constructed real estate in Russia for various reasons is rented out of time and costs. Moreover, this does not depend on the purpose of the
facility and the size of construction companies. Both large property developers and small developers are renting out the property with delays [3].

![Development dynamics of investment construction projects by stages for the period from June 2017 to February 2020](image)

**Figure 1.** Development dynamics of investment construction projects by stages for the period from June 2017 to February 2020 [2].

According to a study conducted in 2014 by Ernst & Young, the implementation of capital construction projects in 64% of cases occurs with budget overruns. Pre-agreed terms are violated in 73%, and actual costs are on average 59% of the planned. According to Bloomberg, only 20% of such projects are completed on time and do not require additional funding. About 75% of them go beyond the planned implementation period, and 60% do not fit into the planned expenses.

The main reasons list for this state of affairs includes mistakes made even at the stage of planning the capital construction project, such as impracticable schedules and estimates, not built relationships between its participants and problems with its financing. A huge role is also played by how well organized the work within the construction project framework is: technical design, the contractor selection and the involvement of the right specialists, making changes to the project and risk management.
According to 84% of respondents surveyed by AVEVA in conjunction with the International Association of Contract Management and Commercial Activities (IACCM), [3] a well-designed project should include a clearly defined scope of work. The success of its implementation, according to 56% of respondents, is facilitated by trusting relationships with the contractor and the effective management of changes in the contract (47%). The most common reasons for cost overruns and lagging behind the schedule are the inability to track changes in the terms of reference in accordance with the new requirements of the customer (64%), insufficiently effective control of changes (56%), ineffective control in the framework of contract management (38%).

Obviously, today, standard approaches to project management do not work - they do not have flexible enough functions to effectively handle the constant changes in capital construction projects. All this leads to the need to search or develop new approaches, the main task of which is to teach managers to make decisions that are most beneficial for projects.

2. Methods

To solve this situation, the professor of the Skolkovo business school, Pavel Aleksandrovich Alferov, developed a model for the complexity of the project. The following basic principles form the basis of this model [4]:

- focusing. It is necessary to focus on key aspects of complexity;
- adaptability. The model should be tailored to specific industries, organizations and types of projects;
- feedback. Supplements and clarification of all components of the model based on the results of its application are expected.

The model helps to assess the complexity of the project, identify the main problems and choose the right tools for working with them. The concept was based on the Goals and Methods Matrix (Turner & Cochrane, 1993), which allows us to assess the complexity of the project. According to this concept, the complexity of the project is determined by two main factors: product and technology (“what to do” and “how to do”), which are systematically presented in Fig. 2.

![Figure 2. «Product / Technology» Matrix [4].](image)

Based on this matrix and expert discussion, four types of project complexity were formed (Table 1) [4]:

1) the project scope,
2) high uncertainty of the requirements for the result,
3) high uncertainty of implementation technologies,
4) the critical influence of external factors.

Any combination of complexity types is permissible on a project: projects may have complexity in one of the types or in several at once.

The general logic for building the model is as follows. Types of complexity group the factors of complexity. For example, for the scale of the project, possible complexity factors will be the long project duration, the number of organizations involved in its implementation, etc. Now in the model 17 factors are identified for all four types of complexity. Complexity factors are measured by complexity assessment parameters, which may vary for different types of projects (table 1).

Table 1. Complexity factors in the “Project Complexity Model” by type of complexity.

| Types of difficulty | Difficulty factors |
|---------------------|--------------------|
| Scale (Fm)          | Long project duration |
|                     | Number of organizations participating in the project |
|                     | Budget and scope of contracting |
|                     | Number of management objects and scope of work |
|                     | Number of areas of professional competence |
| Result Requirements (Fr) | The presence in the project of informal requirements (expectations) |
|                     | A large number of parties determining the requirements |
|                     | Lack of customer expertise to formulate requirements |
|                     | Significant expected changes in requirements during project implementation |
| Realization technologies (Ft) | Novelty and low maturity of technologies used on the project |
|                     | A large number and the need to integrate the technologies used |
|                     | Novelty of technology for performers |
|                     | Possible replacement of key technologies during project implementation |
| The critical influence of external factors (Fc) | Territorial distribution and cultural differences of participants |
|                     | The special importance of the project for the involved organizations, government bodies and society as a whole |
|                     | Interdependence with other projects |
|                     | Existence of external barriers and restrictions |

Complexity factors determine the problems that a project will encounter. In particular, for a long-duration project, this is [4]:

- reducing interest in the project by the stakeholders,
- changing over the project period the composition of key decision-makers on the project,
- drop in team motivation,
- dismissal of key employees, the introduction of new project participants, etc.

Problems that complicate project management are solved through the implementation of certain actions (activities) that must be identified in accordance with the industry affiliation of the project. For example, to mitigate the risk of dismissal of key employees, this could be [4]:

- preparation of personal development plans for each key member of the project team for the long term (preferably until the end of the project),
- assessment of the team’s mood and regular (once a week, once a month, but at least once a quarter) summarizing the results of the assessment. Recommended tool - “teamwork barometer / survey of team satisfaction”,
- building a succession scheme (“right hand”, ready to replace in case of departure) for each key member of the project team and so on.

For more effective implementation of activities, there are a huge number of models, concepts, techniques and tools for project management. In this study, the author proposes to use Bayesian networks to describe the complexity of the project (problem areas). These networks are a directed
graph in which each vertex is marked with quantitative probabilistic information. And the total sum of the probabilities allows us to estimate the probability of the appearance of the problem that is being analyzed. To calculate the total sum of the probabilities the author suggests using equation (1).

Moreover, each element of the Bayesian network in a complete joint probability distribution can be calculated based on the information presented in this network. A universal element in a joint distribution is the probability of a conjunction of specific assignments of values of each variable, such as that presented in equation (1) [5, 6]:

\[ P(X_1 = x_1 \land X_2 = x_2 \land \ldots \land X_n = x_n). \]  

(1)

As an abbreviated notation for such a conjunction of the study's author uses the expression \( P(x_1, x_2, \ldots, x_n) \). The value of this element is given by the equation (2) [6]:

\[ P(x_1, x_2, \ldots, x_n) = \prod_{i=1}^{n} P \left( \frac{x_i}{\text{Parents}(X_i)} \right), \]  

(2)

where \( X_i \) is the top of the Bayesian network; \( \text{Parents}(X_i) \) denotes specific values of variables in the set of \( \text{Parents vertices} \) \( (X_i) \). Therefore, each element in the joint distribution is represented as the product corresponding elements in the conditional probability table of the Bayesian network. Moreover, conditional probability tables (hereinafter CPT) provide a distributed representation of the joint distribution. Thus, the author of the article proposes to quantitatively describe the total effect of project difficulties identified by the Skolkovo school staff on the project, using Bayesian networks and the conjunction equation (2).

3. Results

To apply the complexity model discussed above in the process of implementing capital construction projects with assessing the probability of difficulties by Bayesian chains, it is necessary to identify a list of problems (to create a knowledge base of problems - KBP) according to the main criteria of complexity [7, 8, 9].

For clarity, the analysis in this article will consider the construction project of the Hotel chain of apartments with a small business support center "F.R.E.S.H. City". This project was implemented by the investment and construction company "INVEST DEVELOPMENT GROUP" in 2016-2019 on Marshal Zhukov Avenue in the Strogino district of Moscow. Table 2 shows the knowledge base of problems for this project according to the types of complexity highlighted in table 1 [10, 11, 12, 13, 14, 15, 16].

| Types of difficulty | The main problems in the implementation of capital construction projects | Causes of problems |
|---------------------|------------------------------------------------------------------------|--------------------|
| \( F_{im} \)       | Changes in the work scope arising under the influence of any factors - from design plan explanations to unforeseen circumstances of force majeure | There is no detailed registration of all requests for changes, orders for additional work, approved transactions, sample accounts and applications for payment. The project manager does not have the ability to display the impact of all the specified data on the overall financial situation online. The technology for managing supply contracts also does not ensure the maintenance, within the framework of the approval process, of a complete journal of technical and commercial audit, in which all changes should be recorded |
| \( F_r \)          | Presence a small number of high-risk contracts with high risk          | There is no display of the financial condition of the contracts in real time |
| Types of difficulty | The main problems in the implementation of capital construction projects | Causes of problems |
|---------------------|-------------------------------------------------------------------------|-------------------|
|                      | profits                                                                  | There is no holistic tracking of data when exchanging it. A full audit log is not kept, in which all actual and even possible changes and amendments to the contract should be recorded, so that it is clear who is responsible for what and what exactly the changes will affect |
|                      | Active interaction between the operator and the contractor in connection with the terms of the contract, which may lead to claims | The contract administrator is not able to adjust the processing time for requests in accordance with the rules established for individual contracts |
|                      | Strict and pre-defined rules establishing the deadline for processing requests and claims of the contractor | Constantly it is necessary to check the fact that the relevant board directors’ members have been provided with accurate and complete documentation in accordance with the company’s transfer of authority policy. The project management system does not provide event management, does not notify relevant specialists of the need for action, and does not register all decisions made by them |
|                      | Total control by the board directors’ representatives. They control the lists of bidders, the approval of contracts and changes to them (including changes in the scope of work, budget and schedule of the project) | |
| \( F_c \)            | The presence of many phase during the construction and installation work stage: the project is never "static". Each project is implemented on the basis of its own unique strategy. A universal approach for all projects does not exist. Work on projects is distributed in separate blocks under the contract | Project managers are entitled to grant licenses for the implementation of various “blocks” or types of work only depending on the project stage. No flexibility is provided in this procedure. Planning for the project is carried out as part of one-time work units and within the contract terms, taking into account the resources available at the time of contract conclusion and the established goals |
|                      | Difficulties with connecting the capital to the communications.          | A monopoly has long been established in the market for the provision of such services. As a result, suppliers often do not cope with the flow of applications and therefore cannot connect the house to water and heat supply within the specified time. As a result, buyers do not receive the keys on time, although the developer completed all the work on schedule |
|                      | Difficulties in implementing the legislation when participating in the regional companies’ projects | Contract management technology does not measure the regional suppliers’ performance both within individual contracts and at all facilities as a whole. The selected technology does not verify all corporate framework agreements for the purpose of preliminary assessment and contractor’s selection in the project implementation country |
|                      | The development of new technologies is carried out in a | There is no organized comprehensive training program. Its must will be implemented by |
Types of difficulty | The main problems in the implementation of capital construction projects | Causes of problems
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very short time | \( H \) and lack of technology for managing supply contracts for the project (hereinafter referred to as O) [5,6]. | consultants and trainers who fully understand the specifics of contract risk management in the capital construction field
There is no constant monitoring of specialists working on projects. Their knowledge and experience can make a project successful or, conversely, impede its implementation | Even for similar objects, previous experience is not taken into account. Each new project manager has his own contract management strategy, which does not always correspond to the specifics of the project or the current situation on the project, if the specialist joined the work later than the initial stage

However, to solve the identified problems within the framework of the capital construction project implementation, they maximum systematization and structuring based on the project complexity model is absolutely insufficient. The neutralization of each problem is a separate management decision or an act of managerial influence in conditions of high uncertainty. Each problem is multi-criteria in nature. One part of the criteria is unknown and is probabilistic. The second part of the criteria is known, but may vary under the influence of various conditions. All criteria can be both discrete and continuous. Therefore, the most optimal management decision for these source data is to determine the likelihood of problems in the capital construction projects implementation.

To implement the proposed management decision, the author of the article suggests introducing a reasoning process (the executor is the project manager) into the procedure for solving identified problems based on various uncertainties. For example, the degree of confidence of the project manager in this or that information. In addition to applying the principles of odd logic, the task at hand can be solved using a statistical approach.

The Stanford solution method based on the expert confidence factor, as well as the idea of a statistical approach to describing uncertainty presented by the Bayesian model are most often considered as such an approach. In this study, the author uses Bayesian networks.

To use the Bayesian network, we fix the problem as a task in order to simplify the description of the decision-making procedure for it.

Let the project manager of the apartment’s hotel chain «F.R.E.S.H. City» use fix the construction and installation work on the project in the amount of Q for a period of time T. However, according to Table 2, it can be noted that the implementation of this plan can be stopped by: unforeseen force majeure circumstances (hereinafter referred to as H) and lack of technology for managing supply contracts for the project (hereinafter referred to as O) [5,6].

Next, we compile a table of conditional probabilities (hereinafter TCP) for the problem under consideration. Each line in the TCP contains the conditional probability of each vertex value for the problem in question, which determines the conditional probability. The statistics of projects on the construction of hotels in the framework of the construction of the Apartments Hotel Chain "F.R.E.S.H. City "in St. Petersburg, Rostov-on-Don, Samara, Yekaterinburg. Since to date, the investment and construction company INVEST DEVELOPMENT GROUP practice does not provide for the formation of technical and commercial audit bases, the statistics on problem situations in the framework of the projects was extremely limited. The main information that was obtained was related to the time frame for the implementation by he plan and the fact, as well as a description of the general procedures for implementing the project. In this regard, TCP is quite limited and allows you to determine the disruption probability of construction work on the project only taking into account the supply chain and the behavioral assumptions of the two direct participants in the project: the supplier’s counterparty and the project technical engineer [17, 18].

Figure 3 shows the Bayesian network, which is represented by the topology and conditional probability tables for all the variables considered, affecting the problem situation of the project.
The network topology for determining the probability of failure to perform construction and installation work on a project due to a violation of a supply contract or unforeseen circumstances shows that both reasons can lead to an undesirable event, but the messages that will come from the Counterparty and the Engineer will always be associated with a project non-fulfillment. Therefore, the Bayesian network confirms that the direct participants in the project, the Counterparty and the Engineer, cannot independently determine the reason for the failure to perform the construction and installation work and do not consult with each other before reporting the fail. There are no additional facts in this network that can describe in detail the conditions for the implementation of the project and the receipt of information by the Counterparty and the Engineer. Such a network structure is an example of a knowledge lack, because it would take too much working to find out why these facts may be more or less likely in each case.

Thus, the proposed Bayesian network is a complete description of the considered problem area.

Next, using equation (3), we calculate the probability of failure to perform construction and installation work on the project, taking into account the fact that not a single event occurred that was predicted by us within the framework of this task (neither a failure to fulfill the equipment supply contract or unforeseen force majeure circumstances), but the notorious human factor worked (“Reinsurance of agents”) both the Counterparty and the Engineer reported that the equipment will be delivered out of time:

\[
P(Π \land Q \land \bar{O} \land \bar{H}) = P(Π) P \left( \frac{H}{O} \right) P \left( \frac{Q}{O} \land \bar{H} \right) P(\bar{O}) P(\bar{H}) = 0.95 * 0.8 * 0.15 * 0.75 * 0.98 = 0.08379 \text{ или } 8.4%.
\]

The obtained value is quite impressive when compared with the average statistics for the construction industry [19]. The reliability deliveries coefficient of should not be lower than 95%. In our case, 91.6% [2, 20]. Moreover, this value is not associated with any objective reason, but takes into account only the human factor, or rather, the lack of trust among the participants in the situation in question to the information received.

4. Discussion
If all the available conditional probabilities, regardless of the nature of their representation (analytical or atomic), are combined into a common probability chain, then it will actually summarize a potentially infinite set of circumstances that can either cause disruptions in the implementation of the capital construction project, or cause the participants in the process will not be able to report this
problem. The project manager task, based on the available probabilistic data, is to simulate events occurring in the capital construction project problem area, at least approximately. The adequacy degree of the obtained probabilistic model can be increased as additional reliable information is introduced.

This probabilistic model can cause many criticisms, but it also has undeniable advantages:

1) it is very simple and transparent in its logic, which shows it well when solving real problems (tasks),
2) it allows the project manager to describe the relationship between several factors with one factor of trust in one rule,
3) this simple algebra reflects well the way of the project manager thinking or project analyst.

At first glance, the usefulness of the Bayesian rule is not very clear. Nevertheless, the rule finds wide application when, for example, probabilities estimates for several outcomes of a problem are known and it is necessary to calculate an estimate for another outcome. This is especially important in the tasks of projects’ financial diagnosis of projects, forecasting logistics activities, etc.

5. Conclusions

Thus, the Bayesian network serves as a representation of the joint probability distribution for the problem under consideration. It can be used to receive a response to any request about a problem area under consideration within the framework of an ongoing project.

Obviously, the management of capital construction projects, which are complex systems of the investment and construction complex, requires the formation of their own approaches and methods due to the specifics of industry knowledge about them. Problems that need to be solved must not only be classified, but also must be predicted considering the available statistics on projects already implemented in Russia and the World.

A reliable approach to the capital construction projects management of (along with the registration of all changes and amendments in real time, so that you can easily find out who and when made this or that decision) must fulfill a high predictive role. It must forecast problems and notify relevant specialists in advance so that measures can be taken in a timely manner and to avoid behind schedule. That approach should retain information on the basis on which this or that decision was made so that future projects deal not with uncertainty, but only with possible risks. And of course, all data and accompanying documentation should be stored in a reliable information bank, protected from changes, which, in the event of disputes or claims, will be the only source of reliable information about previous decisions and actions taken.

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