1. Introduction

The development of scenario prediction led to the development of two basic instrumental methods. They are a tree of objectives and a prediction graph. The objective of the methods is analysis of complex systems or processes, where allocation of many structural or hierarchical levels is possible. We build a tree of objectives based on formation of the main objective and various sub-objectives, which lie at the less significant levels of the hierarchy.

The base of the methodology of construction of a prediction graph is initial implementation of sub-objectives and events, which lie at lower levels of the hierarchy with a final exit to a main objective. In other words, we build a tree of objectives based on the «top-down» principle and we build a tree of events, which lie at lower levels of the hierarchy with a final exit to a main objective. In other words, we build a tree of events, which lie at lower levels of the hierarchy with a final exit to a main objective. The prediction graph is initial implementation of sub-objectives and various sub-objectives, which lie at the less significant levels of the hierarchy.

The analysis of scenario prediction methods presented by «tree» graphs shows that the above principle is not taken into consideration at performing of several interconnected problems of scenario prediction. However, there is a «bow-tie» method based on the methods of a fault tree and a tree of consequences, which gives possibility to investigate causes of occurrence of risk events and to analyze their possible consequences in a simple graphical way. This method gives possibility to establish a connection between causes and consequences of dangerous (risk) events for development of a set of measures aimed at prevention and/or reduction of their consequences. However, the method performs analysis of complex situations in a rather simplified form and does not give possibility to assess adequately probability of occurrence of a combination of factors, which lead to negative consequences,
especially if they are dependent. It also does not make it possible to reflect a set of reasons that arise simultaneously and cause negative consequences (emergencies).

The solution of this problem lies in the integrated application of existing methods and means of scenario prediction aimed at identification of causes of emergence of risk factors and prediction of possible scenarios of development of their consequences. In this context, the combined use of methods aimed at identification of causes of negative events and probabilistic methods is expedient. This, in turn, makes possible to model complex uncertain situations (consequences of negative events), generate and assess possible scenarios for their development.

For example, we should pay special attention to the risk management process when implementing software (SW) development projects. It is necessary to be able to identify, analyze and predict possible consequences at each stage of the software development process in accordance with the chosen software development methodology for effective program risk management.

There are formal methods of analysis of failure risk widely used to predict risks associated with possible programming errors that result in software failure. The most common of them are Event Tree Analysis (ETA), Fault Tree Analysis (FTA), and Failure Modes and Effects Analysis (FMEA) methods. In particular, we can consider programming errors as causes, and software failure as a consequence when applying the FTA method. A software failure can cause a number of negative consequences (risks of software projects), for example, additional software development costs, violation of terms of delivery to a customer, etc. It is possible to perform an analysis of such effects using a probability tree.

We can use a fault tree method as an approach that gives possibility to analyze a cause of a risk factor.


Work [10] proposes an approach based on construction and analysis of a fault tree. It makes possible to perform computer and mathematical modeling of a risk of a technological process. This approach gives possibility to identify weak spots of a system (an object under study), to identify the most likely events and system parameters, which lead to negative events.

For today, a fault tree is an effective tool for risk analysis of software failures. It gives possibility to analyze causes of failures (hardware, software) and their consequences. Work [11] proposes the method of qualitative risk analysis of software development based on the complex use of the fault tree method and the method of assessment of the indicator of the net reduced cost of a software development project. Author of paper [12] uses the method of a fault tree to analyze types and consequences of failures of options of structures of information processing systems on the example of analysis of duplicate structures with the version-time redundancy.

There is a reverse trend in works [7–12]. There is analysis of causes of emergence of risk situations conducted, but the task of analysis and prediction of possible ways (scenarios) to overcome or reduce risks remains unresolved.

Works [5–12] consider the methods of scenario analysis and prediction autonomously, without taking into consideration their combined application for cases with interconnection of problems, which require solution. Only paper [13] investigates possibility of integrated application of formal methods of specification requirements and reliability analysis. It considers the method of analysis of types and consequences of critical failures and the method of a fault tree analysis on the example of a computer control system of motor traffic control. However, outstanding issues related to estimation of probability of occurrence of emergencies in the absence of accumulated accident statistics (emergencies) with a use of a tree failure method remain unresolved. As well as determination of probability of the most critical failures in construction of a critical matrix by the method of analysis of types and consequences of critical failures.

Authors of paper [14] use the «bow-tie» method to analyze possible causes and consequences of implementation of risks. In particular, paper [15] proposes modification of the «bow-tie» method and methodology of partial quantitative risk assessment method. Authors applied and tested it in the shipbuilding industry. However, this methodology does not make it possible to assess probability of implementation and possible combinations of risk factors, which lead to negative consequences.

Consequently, all of the foregoing confirm the expiry of a study devoted to the search for approaches that
make it possible timely detection and analysis of risk factors, which lead to possible negative consequences and provide a mathematical apparatus for modeling and assessment of an impact of adverse events (risks), prediction of possible scenarios for development of risk events and study of possible consequences.

3. The aim and objectives of the study

The aim of this study is to construct a method for the integrated application of formal methods of scenario prediction represented by graph models of the hierarchical structure on the example of the integrated application of a fault tree and a probability tree.

We set the following tasks to achieve the objective:
– to develop a procedure for aggregation of individual expert assessments of possibility of manifestation of a negative (risk) event in solution of probabilistic inference problems based on scenarios constructed using probability trees;
– to investigate a possibility for an integrated application of a fault tree and a probability tree on the example of generation of sequence of scenarios of occurrence of risk events caused by failures of software and analysis of their consequences;
– to run a computational experiment and analyze the results obtained.

4. Materials and methods to study the problem on integrated application of methods of scenario prediction

A fault tree is a deductive logical-and-graphical method, which serves to identify possible ways that lead to an undesirable event (for example, a failure of a system or a failure of its individual blocks). The key theoretical foundation of the FTA is the assumption that system components operate successfully or fail completely [16, 17].

We use a basic set of symbolic images for a graphic representation of the simplest fault tree (Fig. 1).

![Fig. 1. Basic set of FTA symbols: a – input event; b – interim event; c – resultant event; d – «and» condition; e – «or» condition; f – priority «yes»; g – exclusive «or»; h – condition of the majority rule «m» with «n»)](image)

Fig. 2 shows the example of a simple fault tree.

The fault tree (Probability Tree Analysis, PTA) serves to analyze a sequence of scenarios (options) for further development of events. They may be the result of manifestation of possible system failures with the use of the fault tree [18–20]. We form a set of system of random events and probabilities of their implementation for this purpose.

![Fig. 2. Fault tree](image)

Each branch of the tree displays a one-incident event from each system of random events (in this case, the system of random events consists of two events) and the probability \( P_i \) of their implementation. We obtain combinations of such trees by their integration, which lead to formation of a probability tree (Fig. 3), which is a tree-like graph.

Each node (vertex) of such a graph relates to one complete system of random events. A tree branch coming from the corresponding node represents each event and probability of its implementation. Each path from the root node to the final position on the tree reflects one of the possible combinations of events called the scenario.

![Fig. 3. Probability tree](image)

We can calculate the total number of scenarios before building a probability tree:

\[ N = \prod_{i=1}^{z} n_i, \]  

where \( n_i \) is the number of events in the \( i \)-th system of random events; \( z \) is the total number of such systems.

5. Procedure for determination of aggregated expert assessments of the implementation of a risk event when solving problems on probabilistic inference

We can use the probability tree as an effective graphical tool for risk analysis of software projects. There are two main approaches to obtaining of probability of occurrence of a risk event. They are an objective approach and a subjective approach. The basis of the objective method for determination of probability of occurrence of a negative (risk) event is accumulated statistical data based on calculation of the frequency
of occurrence of risk events. If sufficient statistical information is absent, it is necessary to use the subjective method to determine probability of occurrence of risk. Its basis is methods of expert assessment. In this case, we assess possibility of occurrence of an adverse situation (risk) based on considerations and personal experience of a specialist (an expert).

We can engage several experts (a group of experts) to obtain more accurate assessment of possibility of occurrence of a risk event. In this case, the task of obtaining of aggregated expert assessments arises.

Let us consider the procedure of aggregation of individual probabilistic assessments of experts in solution of problems of probabilistic inference on probability trees.

Let us assume that there is a set of experts given $E = \{E_i \mid i \in I \}$, and a set of risk events $R = \{ r_j \mid j \in J \}$. We assume that $R$ represents a set of independent events. Each expert should assess the probability (probability) of a risk event $r_j \in R$ on a scale from 0 to 1. Or, based on their knowledge and experience, experts can present their assessments of the implementation of a risk event within a given scale of expert measurement.

We can represent the results of an expert survey in the form of a set of individual expert assessments as a matrix of $I \times k$ dimension:

$$ A = \begin{pmatrix} a_{i1} & a_{i2} & \cdots & a_{ik} \\ a_{i1} & a_{i2} & \cdots & a_{ik} \\ \vdots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{ik} \end{pmatrix}, \quad (2) $$

where $a_{ij}$ is the possibility (probability) of occurrence of $r_j$ risk event, which is formed by the $i$-th expert.

We get a set $B = \{ b_i \mid i \in I \}$. Its each component is a vector of assessments of $E_i$ expert: $b_i = \{ p_{ij} \mid j \in J \}$, where $p_{ij}$ is the possibility (probability) of the occurrence of risk $r_j$.

Thus, it is possible to construct $k$-systems of random events for each expert. It is possible to represent them graphically as a distribution tree. Each branch of the tree reflects probability of occurrence of the analyzed risk event.

We assume that we have the given basis for the analysis $\Omega = \{ \omega_1, \omega_2 \}$, where $\omega_1$ is $r_j$ risk, which is realized; $\omega_2$ is $r_j$ risk, which is considered as non-essential (absent) one. If $m(\omega_1)$ is probability of occurrence of $r_j$ risk, we can express the probability of its absence as $m(\omega_2) = 1 - m(\omega_1)$.

Thus, for each $r_j$ risk, we obtain $M_r = \{ m(\omega_i) \mid i = I \}$ vector, where $m(\omega_i) = \{ m(\omega_1), m(\omega_2) \}$ is a vector of probabilistic assessments of $r_j$ event formed based on the individual $E_i$ expert assessments.

We use a mathematical apparatus of the theory of evidence to obtain aggregated assessments [21–23].

The aggregation of individual expert benefits occurs by combination of the obtained major probability masses for each $r_j$ risk event by all experts $m(\omega_i) = m^{(1)} \oplus m^{(2)} \oplus \ldots m^{(k)}$. Authors of papers [22, 23] recommend using one of the proportional conflict redistribution rules (PCR rules) for the aggregation of expert assessments.

As a result, for each given $r_j$ risk, we obtain a vector of probabilistic assessments of its implementation $m^{(1)}(\omega_i) = \{ (m(\omega_1), m(\omega_2)) \}$.

Next, we analyze and calculate the obtained probability tree for independent systems of random events with corresponding probabilistic assessments of occurrence $m^{(1)}(\omega_i) \in m^{(i)}$ and non-occurrence (absence) $m^{(1)}(\omega_i) \in m^{(1)}$ of $r_j$ negative event.

Authors of [24–26] propose to determine the order of combination of expert evidences, for example, taking into consideration a degree of difference and structure of expert evidences to improve the quality of combination results when constructing aggregate assessments.

6. Procedure for integrated application of scenario prediction methods

Let us consider an example of the integrated application of a fault tree and a probability tree in scenario prediction of possible software failures and their consequences.

We assume that a number of systems of random events is $z = 3$, and a number of events in each of the systems is $n = 2$. Then the number of the obtained scenarios is:

$$ N = \prod_{i=1}^{3} 2 = 2 \cdot 2 \cdot 2 = 8. $$

Here are schemes of formation of all scenarios:

(1): $P_1 \rightarrow P_3 \rightarrow P_7$;

(2): $P_1 \rightarrow P_3 \rightarrow P_5$;

(3): $P_1 \rightarrow P_4 \rightarrow P_9$;

(4): $P_1 \rightarrow P_4 \rightarrow P_{10}$;

(5): $P_2 \rightarrow P_5 \rightarrow P_1$;

(6): $P_2 \rightarrow P_5 \rightarrow P_{12}$;

(7): $P_2 \rightarrow P_6 \rightarrow P_{15}$;

(8): $P_2 \rightarrow P_6 \rightarrow P_{14}$.

Let us consider three typical project risks: $R = \{ r_j \mid j = 1, k \}$, $k = 3$: $r_1$ – additional software development costs (risk to exceed project cost); $r_2$ – violation of terms of delivery of software to a customer (risk to exceed terms of performance of works); $r_3$ – staff turnover (staff provision risk).

We propose to assess a probability (probability) of occurrence of each risk within the given scale of assessments to the group of experts of 5 people $E = \{ E_i \mid i = I \}$, $l = 5$. Experts express their judgments on a scale from 0 to 1: no risk (0); risk is insignificant – insignificant probability of implementation of a risk event (0.1); low probability of implementation of a risk event (0.3); it is not possible to say anything about possibility of implementation of a risk event (0.5); high probability of implementation of a risk event (0.7); critical probability of implementation of a risk event (0.9); it is clear that the risk situation will come (1). Values 0.2; 0.4; 0.6; 0.8 correspond to interim judgments between each gradation. Table 1 shows the results of the expert survey.

We use PCR5 rule of combination to obtain an aggregated (collective) assessment [22]. We calculate $m_{PCR5(C)}$ combined belief assignment in accordance with proportional conflict redistribution rule PCR5 based on the expression:
where $m_{12}(C)$ is the combined belief assignment for $C=X\cap Y$ subset calculated based on the conjunctive consensus.

**Table 1**

<table>
<thead>
<tr>
<th>$r_i$</th>
<th>$m(\omega_i)$</th>
<th>$E_1$</th>
<th>$E_2$</th>
<th>$E_3$</th>
<th>$E_4$</th>
<th>$E_5$</th>
<th>$m_{12345}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_1$</td>
<td>$m(\omega_1)$</td>
<td>0.4</td>
<td>0.3</td>
<td>0.5</td>
<td>0.2</td>
<td>0.6</td>
<td>0.34</td>
</tr>
<tr>
<td>$r_1$</td>
<td>$m(\omega_2)$</td>
<td>0.6</td>
<td>0.7</td>
<td>0.5</td>
<td>0.8</td>
<td>0.4</td>
<td>0.66</td>
</tr>
<tr>
<td>$r_2$</td>
<td>$m(\omega_3)$</td>
<td>0.2</td>
<td>0.4</td>
<td>0.7</td>
<td>0.3</td>
<td>0.4</td>
<td>0.29</td>
</tr>
<tr>
<td>$r_2$</td>
<td>$m(\omega_4)$</td>
<td>0.8</td>
<td>0.6</td>
<td>0.3</td>
<td>0.7</td>
<td>0.6</td>
<td>0.71</td>
</tr>
<tr>
<td>$r_3$</td>
<td>$m(\omega_5)$</td>
<td>0.7</td>
<td>0.5</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
<td>0.78</td>
</tr>
<tr>
<td>$r_3$</td>
<td>$m(\omega_6)$</td>
<td>0.3</td>
<td>0.5</td>
<td>0.6</td>
<td>0.4</td>
<td>0.2</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Fig. 4 shows the distribution trees based on aggregated expert assessments. Each of them reflects probability of occurrence of a negative event (risk) $r_j \in R$, which may affect implementation of the project.

![Fig. 4. Trees of distribution of systems of random risk events](image)

Not only individual risks can affect the successful implementation of the project, but also their possible combinations.

Fig. 5 presents integrated application of the fault tree and probability tree for scenario prediction of possible software failures and subsequent events, which can lead to negative consequences.

There are the following notations adopted on the fault tree [27]: 1 – errors in the specification; 2 – errors in output data; 3 – deviation from the specification; 4 – false logic or sequence of operations; 5 – lack of time for decisions; 6 – lack of data; 7 – deviation from the specification; 4 – false logic or sequence of operations; 8 – inaccurate registration; 9 – distortion of programming rules.

*An* logical operations form respectively:
- and, $1 \land 2 \land 3 \rightarrow 10$ – errors when setting a problem;
- and, $4 \land 5 \land 6 \rightarrow 11$ – algorithmizing errors;
- and, $7 \land 8 \land 9 \rightarrow 12$ – programming errors.

*Or* logical operation $(1 \lor 2 \lor 3) \lor (4 \lor 5 \lor 6) \lor (7 \lor 8 \lor 9) = 10 \lor 11 \lor 12$ – may lead to a failure of software. We consider this as a manifestation of a certain set of programming errors on the fault tree.

At the same time, we can consider software failure as a cause, which can lead to a number of events reflected in the probability tree.

The considered example implies that all random risk events are probabilistically independent (the order of passing of nodes on a probability tree is arbitrary), Fig. 5.

![Fig. 5. Integrated application of scenario prediction methods: $a$ – a fault tree; $b$ – a probability tree](image)

The considered probability tree gives us a possibility to form 8 scenarios with the following probabilities of their implementation:

$P_{(1)}=P_1P_2P_3=0.340.290.78=0.077$;

$P_{(2)}=P_1P_2P_3=0.340.290.22=0.022$;

$P_{(3)}=P_1P_2P_3=0.340.710.78=0.188$;

$P_{(4)}=P_1P_2P_10=0.340.710.22=0.053$;

$P_{(5)}=P_2P_2P_11=0.660.290.78=0.149$;

$P_{(6)}=P_2P_2P_12=0.660.290.22=0.042$;

$P_{(7)}=P_2P_2P_13=0.660.710.78=0.366$;

$P_{(8)}=P_2P_2P_14=0.660.710.22=0.103$.

$P = \sum_{i=1}^{8} P(y_i) = 0.077 + 0.022 + 0.188 + 0.053 + 0.149 + 0.042 + 0.366 + 0.103 = 1$.

Given the results obtained, we can choose the scenario with the highest probability of its occurrence (scenario 7 with $P_{(7)}=0.366$), that is, the probability of implementation
of scenario 7 is 36.6%. The scenario (2) has a minimal probability of its implementation under conditions of accepted indicators of risk events.

We convert the tree under condition of the independence of random events and cause a new redistribution of probabilistic assessments between events. This makes possible to analyze and determine probability of implementation of each of possible scenarios formed with different combinations of random risk events.

It is necessary to determine a priori probabilities of implementation of risk events and conditional probabilities of occurrence of events in case of existence of the dependence between risk events. We should use the methodology proposed in [28] for assessment of conditional probabilities based on the expert assessment procedure.

### 7. Discussion of results of studying the integrated application of methods of scenario prediction

There are a number of instrumental methods of scenario analysis and prediction created for now. Various tree-like graphs represent them. The objective of each of these methods is solution of a specific prediction problem and it does not take into consideration possible presence of several interrelated problems, which determine a general problem. The studied approach of integrated application of scenario prediction methods gives possibility to perform deeper analysis of systems and objects under study.

The integrated use of the fault tree method and the probability tree method is an effective tool for analysis of possible scenarios for further development of events, which are consequences of failure of a software system. Such failures are reasons for violation of functionality and security of implementation of the main functions of a software system. The scenarios built in this way give possibility to identify possible risk events caused by system failures, which can lead to catastrophic consequences with significant damage in real complex software systems. The advantage of the proposed methodology is the ability to determine probability of implementation of a scenario based on a group expert assessment. The peculiarity of the approach lies in the fact that it makes possible to process experts’ assessments generated under uncertainty (for example, an expert cannot assess possibility of occurrence of a risk), as well as contradictory and inconsistent expert judgments. The use of the combination mechanism for aggregation of individual expert assessments based on the mathematical apparatus of the theory of evidences and the theory of plausible and paradoxical reasoning makes possible to achieve such advantages.

We should note limitations imposed on a number of systems of random events analyzed when constructing a probability tree as a disadvantage. There is an exponential increase in its size and, consequently, in a series of possible scenarios with an increase in a number of analyzed systems of random events, especially if a number of events in such systems are significant. It is advisable to use a probability tree if a series of random events do not exceed 4.

It is possible to use the proposed approach as an add-on to existing methods of risk analysis for software projects, where the main cause of risks are defects in hardware and software, data or computing processes.

For example, we assess possibility of implementation of an adverse event (risk) and its impact on a project in the process of qualitative risk analysis. As a result, we get a list of risks ranked by a degree of their impact on a project and a risk map. It is possible to perform the risk ranking based on «probability/consequence» matrix analysis, according to the PMBOK standard. If a group of experts of the corresponding profile determines possibility of risk implementation based on subjective probabilities, we can form the collective assessment based on the proposed procedure of aggregation of individual probabilistic expert assessments.

Another example is a common sharing of the proposed methodology for generation of a succession of negative event scenarios and analysis of sensitivity of individual risk factors to deviations of system parameters. The approach makes possible identification of risk factors, which have the greatest impact on project implementation.

It is possible to apply the offered methodology under conditions of use of modern flexible methods of software development. The development of technology management software projects led to emergence of flexible and adaptive software development methodologies. The objective of the most of them is minimization of risks by reduction of development to a certain number of short iteration cycles, each of which should end with generation of the next interim version of software. Speaking about the class of iterative software development models, we can note that it is possible to apply the proposed approach at the stage of testing of current prototype software. This application will give possibility to analyze an impact of risks of possible failures (identification of their causes and consequences) on the state of a software development process.

The possible objective for further research is development of methods for improvement of the quality of the obtained expert information and exploring the possibility of using of Bayesian networks to analyze a sequence of scenarios for development of a negative event.

### 8. Conclusions

1. We have proposed in this study to use the combination mechanism based on one of the rules from the theory of evidence or the theory of plausible and paradoxical reasoning for the aggregation of individual expert assessments of a possibility of the occurrence of a risk event. We determined that we could obtain more effective results of combination if we use conflict redistribution rules. The establishment of the order of combination of expert evidences gave possibility to improve the quality and accuracy of the combination results. The approach makes it possible not to ignore and not to lose expert information obtained based on non-coincident and contradictory expert evidences.

2. We investigated the possibility of integrated application of formal methods of scenario prediction, namely a fault tree and a probability tree. The proposed method of integrated application of a fault tree and a probability tree gives a possibility to analyze sequences of scenarios of manifestation of a risk event caused by accidental negative influences of possible failures of functioning of a technical, software system, or its individual elements. It enables to identify risks in advance and to predict consequences of their impact on safe operation of a system, to offer effective and timely mechanisms for their management and to improve control and monitoring of possible threats. This, in turn, gives a possibility to improve performance and quality of operation of
technical and software systems and to reduce the potential financial loss associated with implementation of a risk event.

3. We presented the examples of practical implementation of the proposed methodology for the integrated application of a fault tree and a probability tree on the example of solution of the problem of risk analysis of software projects caused by failures in functioning of software and systems. The obtained practical results are intended to identify and analyze potentially possible defects in programs and data in a timely manner at the stages of design and implementation or in case of violation of the technology of implementation of a program project. Their application gives possibility to correct prediction of occurrence of a risk event associated with possible software failures promptly in order to apply effective methods and means to reduce risks and minimize the associated effects of their negative impact on all stages of the life cycle of software systems. This, in turn, helps to increase reliability of software systems due to identification of hidden errors and defects and analysis of possible scenarios of their impact on the quality of a product.

References

At the present stage of development of automated control systems for large industrial facilities, aspects of management in crisis situations with a lack of time are of particular importance. These situations are usually called crisis due to the significant amount of damage that occurs in a very limited period of time. In this regard, the period of time for making