AN ALGORITHM FOR IDENTIFYING THE DICHOTOMOUS CONVOLUTION GRAPH OF RISK COMPONENTS IN COMPLEX ORGANIZATIONAL SYSTEMS BASED ON ITS EXPERT-DEFINED HIERARCHICAL DECOMPOSITION

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Abstract. Most well-known methods and algorithms for assessing the risks of complex organizational systems are based on the independence assumption of aggregate risk components. At the same time, in practice, risks are often interrelated, i.e., a change in one risk entails a change in others. Therefore, when assessing the aggregate risk of organizational systems, their complexity—the presence of numerous interrelated risks—should be taken into account. This can be done using the integrated rating mechanism as a multicriteria assessment method. In the classical version, its components—the binary trees of criteria and the logical convolution matrices of their values—are set by experts. However, in many cases, experts cannot agree on the structure of the integrated rating tree. In such practical situations, formal methods for synthesizing the tree structure considering the system specifics are in demand. Even if a method yields a nonunique solution, it will ensure the latter's logical validity, and the results can be used in practical tasks. In this paper, the mechanism is extended by replacing the binary integrated rating tree with the dichotomous convolution of aggregate risk components of complex organizational systems, based on its expert-defined decomposition. An algorithm for identifying the dichotomous convolution graph of risk components is proposed, including construction rules and verification criteria. The theoretical results are applied to construct a system for assessing the risk of an aviation accident.

Keywords: risk assessment, aggregate risk, integrated rating, binary tree, dichotomous convolution, hierarchical risk decomposition, risk of an aviation accident.

INTRODUCTION

The existing methods and approaches widely used for risk management in organizational systems include the following main tasks of the decision-maker (DM): the identification of risks, their analysis and assessment, the search for control actions, and the solution of optimization problems [1]. At the same time, there are both formal statements of risk assessment problems with a well-developed mathematical framework (typically in publications related to mathematical control theory; for example, see [2–4]) and weakly formalized ones, characteristic of works in the field of management [5–7].

The vast majority of research devoted to methods and algorithms for assessing risks in complex systems, including organizational ones, can be attributed to one of the two approaches. Adhering to the first approach, authors assess separate risks to rank or compare them with threshold values, often neglecting their interrelations, and do not calculate the aggregate risk [8–11] (also called overall or integral risk in the literature). The second approach is to calculate an aggregate risk assessment of a system by summing local risks [12–16] or, within a scenario-based framework, by summing risk values for each scenario [17]. In this case, as in the first, the mutual influence of risks is often not considered or discussed.

From the perspective of decomposing aggregate risk, studies on the risk assessment of organizational systems often feature classification diagrams [18] and cause-and-effect (causal) diagrams [19], where aggregate risk is either split into local risks [20] or represented as various factors [21] and other characteristic components. Such diagrams, compiled by experts, can be treated as a hierarchical decomposition of risk, i.e., a structure describing the system's aggregate risk.

In separate publications (for example, see [22, 23]), the structure of interrelations between local risks is represented as a weighted directed graph. Experiments with triggering a pulse process in such structures demonstrate how a change in the value of separate local risks entails a change in the related local risks and, consequently, a change in the value of the system's aggregate risk.

Thus, the desire to consider risks comprehensively, taking their mutual influence into account, is natural despite the significantly growing complexity of the risk model. This paper addresses the issue of obtaining an aggregate risk assessment not as a simple sum of the values of identified local risks, but as their integrated rating based on expert knowledge regarding the mutual influence of aggregate risk components.

The integrated rating mechanism (IRM) is widely used in practice to assess the risks of complex organizational systems. Here, our aim is to extend the IRM by creating a formal algorithm for transforming an expert-defined hierarchical decomposition of aggregate risk into a dichotomous convolution of its components (i.e., a directed graph where each vertex has either two or zero incoming arcs). On the one hand, such a convolution allows using typical IRM operations (the dichotomous convolution of risk component assessments) to construct a comprehensive assessment; and on the other hand, it directly accounts for the mutual influence of risk components since the number of outgoing arcs from a specific vertex is unlimited. (In the classical version, a tree is often used, i.e., at most one outgoing arc for each vertex.)

The remainder of this paper is organized as follows. Section 1 reviews works on both the IRM and known algorithms for identifying an integrated rating (IR) tree. In Section 2, the problem of identifying the dichotomous convolution of risk components is formulated and solved; also, we present an algorithm for constructing a dichotomous convolution based on a given hierarchical decomposition and provide a numerical example. In Section 3, initial data are described for the expert construction of a hierarchical decomposition of the risk of an aviation accident; we consider in detail the process of identifying a dichotomous convolution based on the expert-defined hierarchical decomposition of this risk and specify the corresponding extended IRM for this risk.

1. ALGORITHMS FOR IDENTIFYING INTEGRATED RATING TREES: A REVIEW OF RESEARCH

The integrated rating mechanism is a multicriteria assessment method for objects [24]; it is used as a control mechanism in organizational and production systems to assess and rank complex objects [25]. The IRM components include the assessment criteria, the binary trees constructed upon them, and the logical convolution matrices, defined by experts [26, 27]. Initially, the IRM was developed as a control mechanism in the electronics industry [28].

Owing to its much broader capabilities, revealed subsequently, this mechanism is used, e.g., to manage ecological-economic systems when assessing environmental risks [29], to estimate the potential of projects or select the most effective projects [30], to evaluate and achieve targets and implement tasks of regional development programs [31], and to assess the effectiveness of real estate management [32]. Thus, the IRM is versatile, and we will apply it for risk assessment in the aviation industry.

Assessment criteria in the IRM are convoluted in pairs to obtain aggregated scores. In turn, the latter are also convoluted in pairs until forming the tree's root, referred to as the integrated rating. (When assessing the risks of a certain complex system, the value at the tree's root can be interpreted as the aggregate risk.) The order of criteria convolution is generally not deterministic and, within the classical approach, is defined by experts based on general beliefs regarding the importance of criteria or expert preferences. It is therefore quite natural to formalize or even automate this process somehow.

One method for identifying the structure of an IR tree is to use training sets with an appropriate transformation of truth tables [33, 34]. In [26, 35–37], the IRM was represented as a unitary vector for neural network-based identification and design of such mechanisms. The structures were pre-generated by various methods [38, 39] and then used to predict which of the possible IR trees should be taken. In the above series of papers, an algorithm was proposed to obtain equivalence groups (a table of branches, a list of structures). Analysis of these groups allows excluding unfeasible structures (i.e., the equivalence groups exceeding given scales) and mirror structures.

In the absence of a complete training set, the above authors proposed a decomposition method for splitting the sets of tree leaves until obtaining subgroups for all feasible sets [40]. As a result, entire families of branches can be excluded. Despite the thorough elaboration of this approach, according to the authors, the challenge of selecting the structure of binary trees remains unsettled [26].

Another well-known method is binary composition, which works as follows. First, experts identify and rank the assessment criteria by the degree of importance. Then, based on a given preference function, the DM combines adjacent criteria into a dichotomous structure. One advantage is that this method preserves the monotonicity of the DM's preference function at all levels of the decision tree [41]. However, it does not ensure tree construction; in particular, if the assessment criteria are not comparable, an expert will be unable to rank them reasonably. For example, when assessing the quality of a regional healthcare system, the criteria are the median qualification of the medical staff and the average period of hospitalization. An attempt to compare their importance directly, without considering the specifics of the healthcare system, will fail.

Sequential dichotomy is an alternative method for constructing IR trees. Here, the final (general) assessment formulation of an object or system is divided into two specific, mutually complementary formulations. In doing so, one shall preserve completeness, consistency, and causal relations. This process continues for the child formulations until objective, measurable criteria emerge [42]. Note that there may be several ways to divide a general formulation into two specific ones. Furthermore, it may prove impossible (more precisely, impractical due to computational intensiveness) to obtain the values of some objective measurable criteria derived at the lower levels of the tree. For example, an objective criterion describing the demand for a higher education program is the average salary of graduates. However, universities have no mechanisms to acquire such data, so this criterion is not applied.

Owing to the construction rules, the IRM can be used to assess risks considering the mutual influence of risk components. In many studies, aggregate risks were assessed on a dichotomous structure [17, 29, 43, 44]. Within the classical IRM approach to risk assessment, risk characteristics are categorized by experts into those that can/cannot be precisely calculated [45].

If the initially specified structure of risk characteristics is not a tree, experts may encounter difficulties in obtaining a logical dichotomous structure from the decomposition. To address this problem, we extend the IRM by proposing an algorithm for identifying the dichotomous convolution graph of risk components based on an expert-defined hierarchical risk decomposition.

Note that a dichotomous convolution can always be represented as a tree by splitting vertices that influence more than one vertex in the preceding level (also called a layer or tier in the literature). However, certain difficulties may arise when, e.g., minimizing the necessary budget to reduce the risk value to a specified threshold: the dichotomous programming method always yields an optimal solution on a tree, but in the case of a dichotomous structure, only a lower bound of the solution can be derived. Such problems on trees and dichotomous structures, as well as methods for passing from a lower bound to an exact solution, were discussed, e.g., in [46, 47].

We consider hierarchical risk structures defined by experts. These structures may be of various natures, e.g., causal or classificatory. We impose the following requirements on the structure of risk components:

- The top layer of the hierarchy has exactly one vertex (the root, representing the risk under study); by assumption, the layers of the remaining vertices are numbered by the path length from them to the root.
- The subgraphs formed by the subsets of adjacent-layer vertices (with the layer numbers differing by one) and the edges connecting them are bipartite.

Note that an original algorithm for identifying the structure of an IR tree was developed by the authors to assess risks in an IoT system [48]. The modified algorithm proposed below is demonstrated on an example of the threat of an aviation accident as a most dangerous one for airlines.

Our approach can be linked to the concept of critical event combinations, where a graph is constructed for each accident combination to reflect the structure of its occurrence. Based on these structures, differential equations are compiled to determine the probability of accidents and disasters [49].

In contrast to probabilistic safety analysis (for example, see [50–52]), which also considers the interrelation of risks, the method proposed below can be used to calculate the risk value under limited statistical data, adapting to real-time conditions. Although probabilistic safety analysis is a conventional tool for quantitative risk assessment based on failure statistics, a comprehensive assessment using the identification algorithm of dichotomous convolution graphs takes into account weakly formalized and qualitative indicators without the need to introduce coefficients with a high degree of uncertainty.

The functions of airlines include organizing and carrying out the transportation of passengers, baggage, and cargo; performing aircraft maintenance; and conducting commercial activities such as ticket sales and route planning. The following large groups of risks for airlines are often identified in the literature: the industry risk, associated with the nature of air transportation operations; the regional risk, dependent on the political and economic situation; and the legal risk, due to changes in legislation [53]. Nevertheless, preventing threats to air transportation safety is a top priority for any airline. Clearly, safety violations entail significant related risks for the airline (financial, operational, commercial, and reputational).

Increasing the volumes of air traffic and passenger transportation requires improving the approaches of airlines to safety assurance, particularly refining methods for predicting and assessing risks, as well as ways to mitigate them. According to the report of the International Aviation Committee (IAC) released in May

2025 [54], in 2024 as compared to 2023, the number of aviation accidents grew from 26 to 46, and the number of accidents with fatalities reached 65 vs. 31 in the previous year. According to the global data for 2024 from the International Air Transport Association [55], the number of fatalities due to aviation disasters increased to 244 vs. 72 in 2023.

An aviation accident—a disaster or a failure—is an event possibly causing loss of life (fatal injury), damage to or destruction of an aircraft, or its disappearance [56, 57]. Therefore, we will consider the risk of an aviation accident as the most critical and dangerous aviation event. Aviation accidents are classified in regulatory documents; for example, see [58]. Categories of high-risk accidents include: the collision of a serviceable aircraft with the ground, the unauthorized departure beyond the boundaries of a runway, the loss of control in flight, and mid-air collision. This paper will deal with one such high-risk event [59].

2. IDENTIFICATION OF A DICHOTOMOUS CONVOLUTION GRAPH BASED ON A GIVEN HIERARCHICAL DECOMPOSITION

2.1. The Problem of Identifying the Convolution Graph of Risk Components: Mathematical Formulation

Consider a system with a given hierarchical decomposition of its aggregate risk in the form of a directed graph $G=(V, E)$ of a layer-parallel structure. The vertex corresponding to the aggregate risk is the only one in the graph with an in-degree of 0. For convenience, it will be denoted by $v_0 \in V$. The other vertices have an in-degree of 1 or greater.

Recall that, in essence, such a decomposition reflects the mutual influence of risk components and their causal relations. Therefore, in this model, it is possible to assess directly only the components for which the corresponding vertices in the graph G have an in-degree of 0. (In a special case where G is a tree, such vertices are called leaves.) The scores of the other components in each layer of the hierarchical decomposition can be obtained by aggregating the scores of the components in the next layer.

The convolution procedure of graph vertices is to aggregate sequentially the scores for the criteria in the lower layer into a generalized (aggregated) score for the criterion in the higher layer. If the graph is a tree, this procedure is implemented by moving from the leaves to the root, where each vertex is assigned an aggregation rule (a convolution matrix). This matrix determines how a combination of scores of lower-layer vertices is transformed into the score of a higher-layer vertex.

Formally, this definition can be written as follows. Let S_{v_0} be the set of scores for criteria, and let K_{v_0} be their integrated rating, which is determined at the vertex v_0. If l_1^1 and l_1^2 are the tree vertices immediately preceding the vertex v_0, then $S_{v_0}=S_{l_1^1}\cup S_{l_1^2}$, and the integrated rating K_{v_0} is obtained based on the matrix convolution of the generalized scores $K_{l_1^1}$ and $K_{l_1^2}$ [60].

The procedure for convoluting criteria values using the IRM involves the pairwise convolution of components. At the same time, if some risk components have three or more subcomponents, the question arises regarding the order to aggregate their scores. Precisely this problem—the selection of an appropriate order to aggregate risk components in intermediate layers of the hierarchical decomposition—will be addressed below.

Formally, the problem is to find a mapping

$$\mathfrak{F}:\ G(V, E)\rightarrow G'(V', E'),\ V\subseteq V',$$

such that any of the vertices $v\in V'$ has an in-degree of either 2 or 0. Note that there is no requirement for an in-degree of 1 for all vertices, with the exception of v_0. Thus, formally, $G'(V', E')$ is not necessarily a binary tree, which is the most common condition for implementing the classical IRM. Therefore, in this case, we speak of its modification.

2.2. An Algorithm for Identifying the Dichotomous Convolution Graph of Risk Components

Let $n\in\mathbb{N}$ be the number of layers in the directed graph of the hierarchical decomposition of the system's aggregate risk. We denote by $L_i\subset V$, $1<i\le n$, the vertex subset in the i th layer of the decomposition $G=(V, E)$.

Definition 1. Vertex subsets $V_i\subseteq L_i$ and $V_{i-1}\subseteq L_{i-1}$, L_i, $L_{i-1}\subset V$ of the graph $G=(V, E)$ are said to be strongly adjacent if $\forall u\in V_i$ $\forall v\in V_{i-1}$ $\exists(u, v)\in E$, i.e., each vertex in the set V_{i-1} has an incoming edge from each vertex in the set V_i.

Definition 2. Vertex subsets $V_i\subseteq L_i$ and $V_{i-1}\subseteq L_{i-1}$, L_i, $L_{i-1}\subset V$ of the graph $G=(V, E)$ are said to be weakly adjacent if $\forall u\in V_i$

$\exists v \in V_{i-1}\ \exists (u, v) \in E$, i.e., each vertex in the set V_{i-1} has an incoming edge from at least one vertex in the set V_i. ♦

Note that strongly adjacent subsets are always weakly adjacent. The converse is generally false, so the number of weakly adjacent subsets cannot be less than that of strongly adjacent ones.

The algorithm consists of the following sequence of actions.

Step 1. Let $i = n+1$.

Step 2. Extend the hierarchical decomposition $G(V, E)$ with a "fictitious" layer L_i such that $\forall v \in L_i\ \exists! u \in L_{i-1} : (u, v) \in E$.

Step 3. For the vertices of the ith and $(i-1)$th layers, construct binary matrices B_i and D_i of dimensions at most $\left|2^{|L_i|-1}\right| \times \left|2^{|L_{i-1}|-1}\right|$ so that their rows and columns are complementary to all non-empty feasible vertex subsets of the ith and (i – 1)th layers, respectively. (Some combinations may be prohibited due to the impossibility of corresponding pairs.) Set the matrix elements corresponding to adjacent vertices (or vertex subsets) equal to one, and the rest equal to zero.

Step 4. Compute the vector sums $\vec{S}(B_i) = \left(b_i^1, \ldots, b_i^{i-1}\right)$ and $\vec{S}(D_i) = \left(d_i^1, \ldots, d_i^{i-1}\right)$, where b_i^j and d_i^j are the sums of the jth columns of the matrices B_i and D_i, respectively.

Step 5. For each pair of non-empty adjacent vertex subsets $V_{i-1}^k \subseteq L_{i-1}$ and $V_i^k \subseteq L_i$, compute

$$\vec{Y}_{i-1} = \frac{\vec{S}(B_i)}{\vec{S}(D_i)},$$

which will be called the vector of the *interrelation indices* of the subsets. Note that the vectors $\vec{S}(B_i)$ and $\vec{S}(D_i)$ are divided elementwise. By Definitions 1 and 2 and the construction of $\vec{Y}_{i-1}$, the value $y_{i-1}^k \in \vec{Y}_{i-1}$ of the interrelation index will be greater for a smaller cardinality of the set V_{i-1}^k, all other parameters being fixed.

Step 6. Sequentially convolute the pairs of vertices of the (i – 1)th layer and (at successive substeps) their subsets $V_{i-1}^k, V_{i-1}^m \subseteq L_{i-1}, k \neq m,$ with the maximum values of the interrelation indices among all previously unconvoluted vertices or their subsets, thereby forming a dichotomous hierarchical risk assessment structure. At each substep, add the vertices (or vertex subsets) being convoluted to the hierarchy if they have not been included previously, and a new vertex representing their union; connect this vertex by two arcs to the vertices being convoluted at the current substep. Vertices (or vertex subsets) are considered unconvoluted if, in the new hierarchy, they have no corresponding vertex or its in-degree is 0.

Step 7. If $i > 1$, then set $i = i-1$ and get back to Step 3; otherwise, terminate the algorithm.

This algorithm outputs a dichotomous hierarchy $G'(V', E')$ where the zero layer is the vertex v_0 (the integrated rating of the components of the (i – 1)th layer in the hierarchical decomposition of the system's aggregate risk), and the set of its hanging vertices coincides with that of the original hierarchical decomposition $G(V, E)$.

Since the order of aggregating the vertices of the (i – 1)th layer is determined by their connections to the vertices of the ith layer, the algorithm creates an additional layer to convolute the hanging vertices of the hierarchical decomposition. In the purely mathematical formulation of the problem, this layer is fictitious, but when solving particular problems, it shall take on a meaningful role; for example, one can perform a detailed risk decomposition (at a deeper level than required for decision-making), or reflect in the additional layer the established interrelation of directly measurable risk components.

To make the algorithm implementable, it is also necessary to select a pair of vertices (vertex subsets) L_{i-1} for convolution at the current substep of Step 6 if the interrelation index achieves maximum on three or more unconvoluted vertices (their subsets), or (which essentially leads to the same situation) if the maximum is reached on one subset, and the second-highest value is reached on two or more candidates for convolution.

At the current—formal—stage, it seems impossible to propose a constructive criterion for the solution's uniqueness. Nevertheless, when applying this algorithm in practice, one can consider the specifics of a complex organizational system and introduce additional criteria for prioritizing convolution (e.g., the importance of a risk component or the frequency of a factor). This will be demonstrated in subsection 3.1 for an organizational system of a particular industry (an airline).

2.3. A Numerical Example to Illustrate the Algorithm

Consider the following example to illustrate the above algorithm for identifying the dichotomous convolution graph of risk components. Let the hierarchical decomposition of the aggregate risk of a complex organizational system be represented as a directed graph $G = (V, E)$ with $n = 2$ layers, where $|V| = 8, |L_1| = 3, |L_2| = 4,$ and $\{v_0\} \cup L_1 \cup L_2 = V$ (Fig. 1).

For a detailed analysis, we take one iteration of the algorithm in which the layer 1 vertices of the hierarchical decomposition are convoluted, based on their interrelation, through the vertices of the next layer (layer 2). The algorithm will begin Step 3 and $i = 2$.

Step 3. For the vertices of layers 2 and 1, we construct the binary matrices B_2 (the elements corresponding to strongly adjacent vertex subsets are set to 1, and the other elements to 0; see Table 1) and D_2 (the elements corresponding to weakly adjacent vertex subsets are set to 1; see Table 2). Both matrices will have dimensions 7×15. For ease of understanding, the matrices are transposed here.

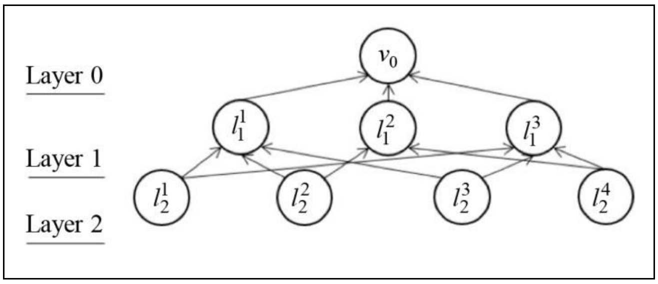

Fig. 1. The hierarchical decomposition of aggregate risk: an example.

Step 4. We compute the vector sums $\vec{S}(B_2) = (b_2^1, \ldots, b_2^{1,2,3}) = (7, 3, 7, 1, 3, 1, 0)$ and $\vec{S}(D_2) = (d_2^1, \ldots, d_2^{1,2,3}) = (7, 3, 7, 9, 11, 9, 12)$.

Table 1

The matrix of strongly adjacent vertex subsets in layers 1 and 2 (transposed)

	l_1^1	l_1^2	l_1^3	l_1^1, l_1^2	l_1^1, l_1^3	l_1^2, l_1^3	l_1^1, l_1^2, l_1^3
l_2^1	1	0	1	0	1	0	0
l_2^2	1	1	0	1	0	0	0
l_2^3	1	0	1	0	1	0	0
l_2^4	0	1	1	0	0	1	0
l_2^1, l_2^2	1	0	0	0	0	0	0
l_2^1, l_2^3	1	0	1	0	1	0	0
l_2^1, l_2^4	0	0	1	0	0	0	0
l_2^1, l_2^4	1	0	0	0	0	0	0
l_2^2, l_2^4	0	1	0	0	0	0	0
l_2^3, l_2^4	0	0	1	0	0	0	0
l_2^1, l_2^2, l_2^3	1	0	0	0	0	0	0
l_2^1, l_2^2, l_2^4	0	0	0	0	0	0	0
l_2^1, l_2^3, l_2^4	0	0	1	0	0	0	0
l_2^2, l_2^3, l_2^4	0	0	0	0	0	0	0
$l_2^1, l_2^2, l_2^3, l_2^4$	0	0	0	0	0	0	0

Table 2

The matrix of weakly adjacent vertex subsets in layers 1 and 2 (transposed)

	l_1^1	l_1^2	l_1^3	l_1^1, l_1^2	l_1^1, l_1^3	l_1^2, l_1^3	l_1^1, l_1^2, l_1^3
l_2^1	1	0	1	1	1	1	1
l_2^2	1	1	0	1	1	1	1
l_2^3	1	0	1	1	1	1	1
l_2^4	0	1	1	1	1	1	1
l_2^1, l_2^2	1	0	0	1	1	0	1
l_2^1, l_2^3	1	0	1	1	1	1	1
l_2^1, l_2^4	0	0	1	0	1	1	1
l_2^1, l_2^4	1	0	0	1	1	0	1
l_2^2, l_2^4	0	1	0	1	0	1	1
l_2^3, l_2^4	0	0	1	0	1	1	1
l_2^1, l_2^2, l_2^3	1	0	0	1	1	0	1
l_2^1, l_2^2, l_2^4	0	0	0	0	0	0	0
l_2^1, l_2^3, l_2^4	0	0	1	0	1	1	1
l_2^2, l_2^3, l_2^4	0	0	0	0	0	0	0
$l_2^1, l_2^2, l_2^3, l_2^4$	0	0	0	0	0	0	0

Step 5. We compute the vector $\vec{Y}_1$. The computation results are shown in Table 3, with rounding to two decimal places.

Table 3

The values of the interrelation indices for adjacent vertex subsets in layers 1 and 2

Index	l_1^1, l_1^2	l_1^1, l_1^3	l_1^2, l_1^3	l_1^1, l_1^2, l_1^3
$\vec{S}(B_2)$	1	3	1	0
$\vec{S}(D_2)$	9	11	9	12
$\vec{Y}_1$	0.11	0.27	0.11	0

Step 6. According to Table 3, among all vertex subsets, the maximum value (0.27) of the interrelation index is observed for the subsets l_1^1, l_1^3. Hence, at the first substep, the vertices l_1^1 and l_1^3 shall be convoluted, and at the second substep, the unconvoluted vertex l_1^2 shall be added to their convolution. The resulting dichotomous convolution (in this case, a tree) reflects the comprehensive assessment (integrated rating) of the layer 1 components in the hierarchical decomposition of the aggregate risk (Fig. 2).

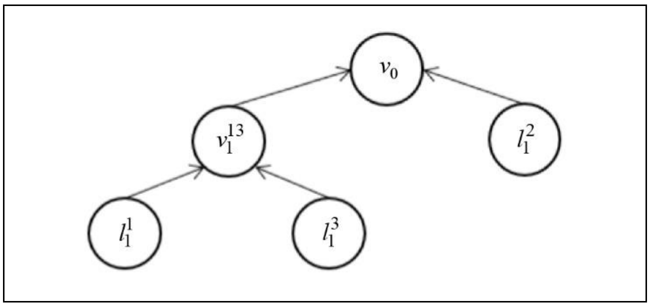

Fig. 2. The dichotomous structure of the integrated rating procedure.

3. CONSTRUCTING THE DICHOTOMOUS CONVOLUTION OF THE RISK OF AN AVIATION INCIDENT BASED ON ITS HIERARCHICAL DECOMPOSITION

3.1. The Hierarchical Decomposition of the Risk of an Aviation Accident

To illustrate the effectiveness of the algorithm for identifying the dichotomous convolution graph of risk components in complex organizational systems based on an expert-defined hierarchical decomposition, we choose the risk of a most dangerous aviation accident, namely, *Controlled Flight Into Terrain* (CFIT). The occurrence of such an accident depends on numerous contributing factors and potential events. They include challenging environmental conditions, pilot disorientation, errors in the design of diagrams and documentation, automation errors, and operational workload [58].

The factors and their interrelations characterizing aviation accident situations are structured based on the identification of factors and causal relations through the analysis of documents such as international standards and guidelines from the International Civil Aviation Organization (ICAO) [58, 61–67], industry standards and guidelines from the International Air Transport Association (IATA) [68, 69], guidelines and tools from the Flight Safety Foundation [70], the Air Code of the Russian Federation [71], the Rules for the Use of the Airspace of the Russian Federation [72, 73], orders of the Ministry of Transport of the Russian Federation [74, 75], official letters and documents from the Federal Air Transport Agency [76], and databases on investigations of aviation accidents, failures, and disasters [77, 78].

The structuring methodology is based on the application of causal models for representing situational knowledge, derived from qualitative and quantitative information [79]. A causal relation, confirmed by an expert through references, establishes partial order relations on the set of factors influencing aviation events. By using transformation algorithms for the resulting causal graphs, one can construct a hierarchical decomposition of factors as the foundation for a comprehensive assessment model of events defined by the state of aviation accident factors.

For aviation safety as an example, experts structured the factors and their interrelations influencing aviation accidents; based on the expert appraisals, we constructed a hierarchical decomposition of the risk of an aviation accident in the form of a three-layer $(n=3)$ directed graph (Fig. 3).

The hierarchical decomposition of the CFIT risk is shown in Fig. 4. Dashed arrows indicate the vertices (factors) acting only in combination with others. The incoming arcs of each vertex are colored uniformly.

Table 4–6 lists the vertices of each layer in the graph, along with their explanation and references to the source documents defining the causal relation.

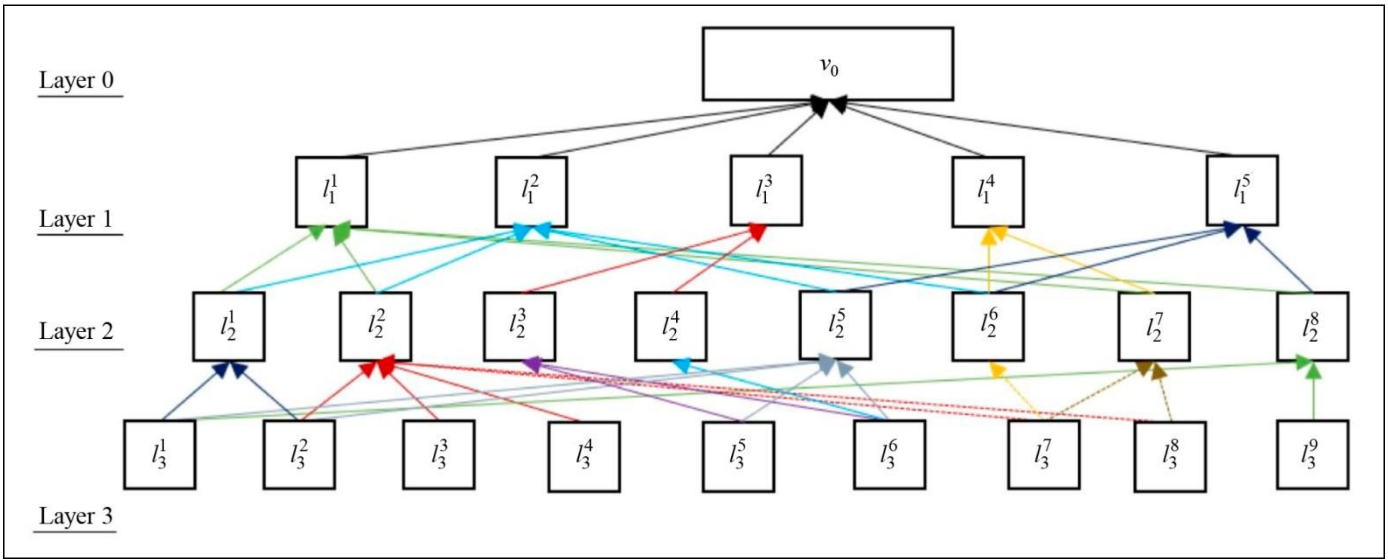

Fig. 3. The hierarchical decomposition of the CFIT risk.

Table 4

The list of vertices in layer 1

L_1	Explanation	Source document
l_1^1	Pilot error / inappropriate flight crew actions, pilot fatigue, sensory illusion and loss of situational awareness	[58, 63]
l_1^2	Restricted visibility / reduced visual reference, disorientation / loss of visual references, pilot error during takeoff or landing, non-precision approach (NPA) procedure, and inadequate documentation	[58, 63]

Table 4 (continued)

l_1^3	Incorrect instructions to the pilot / miscommunication, misunderstanding of the situation/ loss of shared situational awareness, and phraseology used (standard versus non-standard)	[58, 63]
l_1^4	Flight in adverse environmental conditions, limited meteorological visibility with no visual ground reference / Instrument Meteorological Conditions (IMC), unfavorable take-off/landing conditions, loss of control during landing	[58, 63]
l_1^5	Aircraft equipment issues: GNSS radio frequency interference (GNSS RFI), GPWS/EGPWS malfunction / corruption / false alerts, and radio altimeters. Loss of control (LOC), inability to correct the flight path	[58, 63]

Table 5

The list of vertices in layer 2

L_2	Explanation	Causal relation with layer 1 vertices	Source document
l_2^1	Inadequate CRM system failures: concealment of errors. Failure to identify potential threats, no response (or delayed response) to terrain proximity warnings	l_1^1	[68, 69]
		l_1^2	[70, *ALAR Briefing Note 2.1 – Human Factors*]
l_2^2	Pilot errors: improper/inappropriate control inputs, inadequate flight crew actions – continued descent below minimum altitude, incorrect calculations, incorrect interaction with automation, failure to follow procedures, fatigue, disorientation, lack of situational awareness, stress	l_1^1	[70, *ALAR Briefing Note 2.1 – Human Factors*]
		l_1^2	[68, 69]
l_2^3	Absence of air traffic services or ground service error: improper runway preparation, incorrect weather information	l_1^3	[58, 68, 69]
l_2^4	Night and adverse weather conditions, ground emergencies: landslides, fires, earthquakes	l_1^3	[68, 69]
l_2^5	Runway conditions (ice, slush, snow, standing water), ice accretion: ice on wings, stabilizers, windshield (predictable factor)	l_1^2	[70, *Approach-and-landing Risk Awareness Tool*]
		l_1^5	[70, *Approach-and-landing Risk Awareness Tool*]
l_2^6	Exceeding weather minima for takeoff and landing, runway conditions (ice, slush, snow, standing water), ice accretion - ice on wings, stabilizers, and windshield (random weather factor)	l_1^2	[70, *Approach-and-landing Risk Reduction Guide*]
		l_1^4	[70, *Approach-and-landing Risk Reduction Guide*]
		l_1^5	[70, *Approach-and-landing Risk Reduction Guide*]
l_2^7	Strong wind: wind gusts, turbulence, wind shear, strong crosswind, tailwinds	l_1^1	[63; 70, *ALAR Briefing Note 8.7 – Crosswind Landing*]
		l_1^4	[70, *ALAR Briefing Note 8.7 – Crosswind Landing*]
l_2^8	Equipment malfunction / system failure: flight control system malfunction, navigation system failure, communication system failure, hydraulic system failure, and engine failure / malfunction; Terrain awareness and warning system (TAWS) / ground proximity warning system (GPWS) failure; and radio altimeter malfunction	l_1^1	[68; 69; 70, *CFIT Checklist*]
		l_1^5	[68; 69; 70, *CFIT Checklist*]

Table 6

The list of vertices in layer 3

L_3	Explanation	Causal relation with layer 2 vertices	Comment	Source document
l_3^1	Safety culture: lack of safety culture, low company safety culture level, ignoring risks, reluctance to report problems	l_2^1, l_2^5, l_2^8	–	[68; 69; 70, *ALAR Briefing Note 2.1 – Human Factors*]
l_3^2	Inadequate crew training: lack of experience, incomplete knowledge of procedures, insufficient training	l_2^1, l_2^2, l_2^5	–	[58, 63, 68–70]
l_3^3	Crew fatigue: long flights, time zone changes, sleep deprivation	l_2^2	–	[58]
l_3^4	Crew illness: viral or bacterial infections	l_2^2	–	[58]
l_3^5	Ineffective management system: insufficient coordination between crew, controllers, and ground services	l_2^3, l_2^5	–	[58, 63, 68–70]
l_3^6	Inadequate technical support: lack of timely maintenance and repair (airport)	l_2^3, l_2^4, l_2^5	–	[70]
l_3^7	Poor visibility: fog, rain, snow, thunderstorms, smoke	l_2^2, l_2^6, l_2^7	Active only with at least one layer 3 vertex	[70, *Approach-and-landing Risk Awareness Tool*]
l_3^8	Adverse terrain: mountain ranges, hills, forests, bodies of water	l_2^2, l_2^7	Active only with at least one layer 3 vertex	[63]
l_3^9	Inadequate technical support: lack of timely maintenance, repair, and upgrade (fleet)	l_2^8	–	[70]

3.2. The Integrated Rating of the CFIT Risk Based on Its Hierarchical Decomposition

First, it is necessary to determine the order of aggregating risk components at layer 2 vertices, i.e., which vertices should be aggregated to obtain the scores for layer 1 vertices. For this purpose, we construct the matrices B_3 and D_3. Their dimensions are 255×511. Next, we compute the vectors $\vec{S}(B_3)$ and $\vec{S}(D_3)$, as well as the vector $\vec{Y}_2$ of interrelation indices. A sample of the dependency indices is presented in Table 7. To reduce the table's size, the interrelation indices of layer 2 vertices with a value of 0 are omitted.

The convolution order is naturally defined for the layer 1 vertices with only two incoming arcs (l_1^3, l_1^4). For the remaining vertices (namely, l_1^1, l_1^2, and l_1^5), we apply the algorithm of subsection 2.2. Some of the resulting dichotomous hierarchical substructures are presented in Fig. 4.

Table 7

The values of the interrelation index for vertex subsets in layer 2

Vertex subsets	The index values rounded to the 4th decimal place
$l_2^1,\ l_2^2$	0.0303
$l_2^1,\ l_2^5$	0.2
$l_2^1,\ l_2^8$	0.2
$l_2^2,\ l_2^5$	0.0222
$l_2^2,\ l_2^7$	0.0322
$l_2^3,\ l_2^4$	0.3333
$l_2^3,\ l_2^5$	0.2
$l_2^4,\ l_2^5$	0.0666
$l_2^5,\ l_2^8$	0.0588
$l_2^1,\ l_2^2, l_2^5$	0.0222
$l_2^1,\ l_2^5, l_2^8$	0.0588
$l_2^3,\ l_2^4, l_2^5$	0.0666

Let us repeat the algorithm steps for constructing an integrated rating tree for the CFIT risk. We construct the matrices B_2 and D_2, both of dimensions 31×255, and then compute the vectors $\vec{S}(B_2)$, $\vec{S}(D_2)$, and $\vec{Y}_1$. Table 8 provides the interrelation indices of the vertices of layers 1 and 2 and their convolution order.

Based on the components of the vector Y_1, we construct the integrated rating tree for the aggregate risk of the selected aviation accident (CFIT). The root is the aggregate risk, and the leaves are the vertices of layer 1; their scores have been determined at the previous steps. The resulting dichotomous structure can be found in Fig. 5. According to Table 8, the pair of vertices $l_1^2,\ l_1^5$ is convoluted first: the index value for this pair is the maximum. Next, we add the vertex l_1^4 to the merged vertex v_1^{25} since the value of the interrelation index for the combination of these vertices is the maximum among all unconvoluted vertices. Finally, we convolute the remaining vertices l_1^1 and l_1^3, obtaining the aggregate vertex v_1^{13}.

Table 8

The values of the interrelation index for vertex subsets in layer 1

Vertex subsets	The index values rounded to the 4th decimal place	Convolution order
$l_1^1,\ l_1^2$	0.1794	—
l_1^1, l_1^3	0	3
l_1^1, l_1^4	0.0588	—
l_1^1, l_1^5	0.0476	—
l_1^2, l_1^4	0.0303	—
l_1^2, l_1^5	0.2258	1
l_1^4, l_1^5	0.1111	—
l_1^1, l_1^2, l_1^5	0.0256	—
l_1^2, l_1^4, l_1^5	0.0303	2

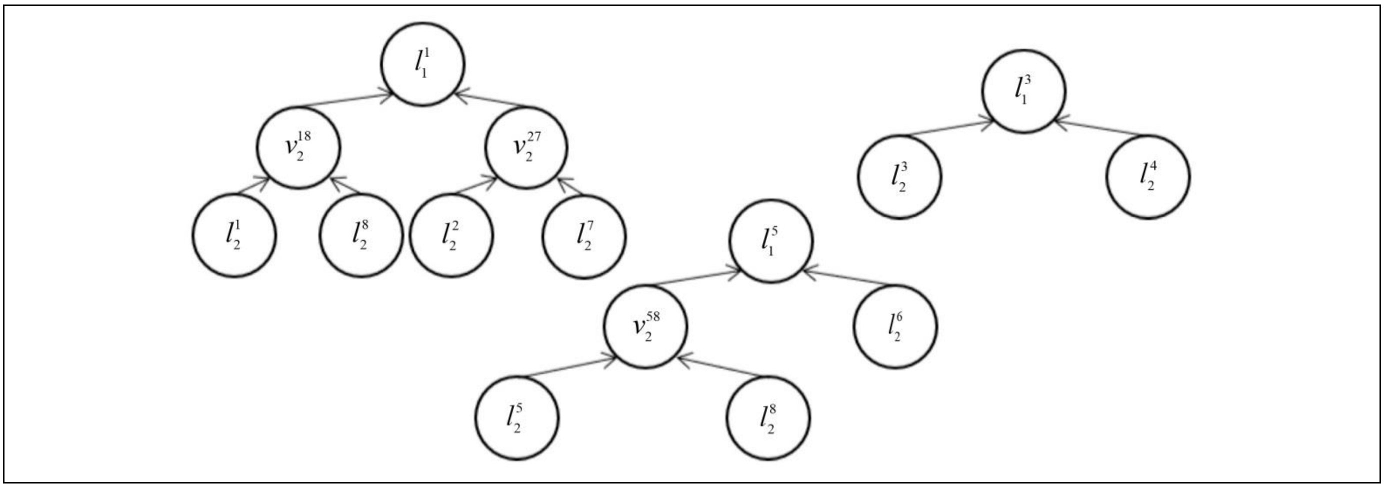

Fig. 4. Some comprehensive assessment structures of layer 1 vertices.

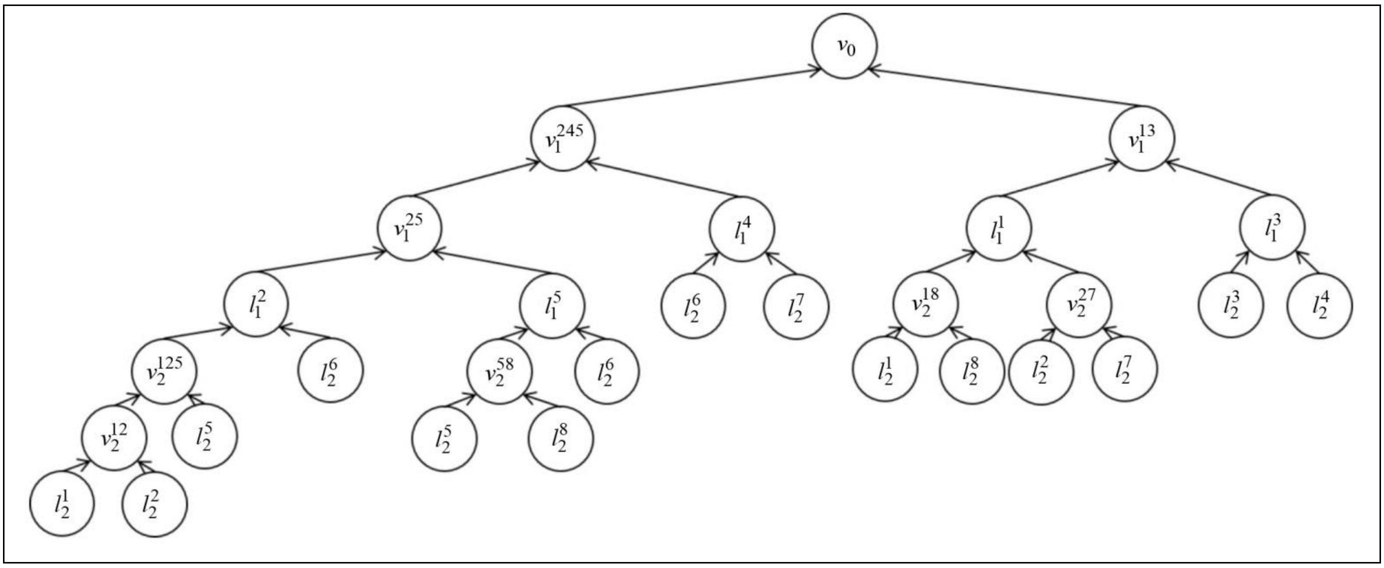

Fig. 5. The dichotomous convolution of the integrated rating of the CFIT risk.

The above example of a dichotomous convolution for the integrated rating procedure of the CFIT risk just illustrates our approach. Nevertheless, dichotomous convolutions are widely used in risk management [80, 81], and the integrated rating procedure of aviation accidents considered in this paper can be applied by flight safety experts to obtain the current risk value. Based on the risk assessment, the DM will be able to choose an appropriate control action, including refinements in industry and state standards.

No optimal structure has been proposed in this paper. We acknowledge that in the absence of a unique solution—when interrelation indices are equivalent or equal to 0—the criteria should be convoluted in pairs based on the similar nature of the cause (crew, ground services, weather conditions, or human-induced factors).

CONCLUSIONS

This paper has presented an algorithm for identifying the dichotomous convolution graph of risk components in order to determine their aggregation order. The core of this algorithm is to transform an expert-defined hierarchical decomposition of risk, reflecting the causal interrelations between its components, into a dichotomous hierarchy by adding new aggregate vertices. The aggregation order is selected based on a closeness measure of the components being convoluted, i.e., the shared connections to "causal" vertices (i.e., those located at the next decomposition level). The number of levels is generally unlimited.

The novel algorithm is an extension of the classical integrated rating mechanism. Such an extension is needed since this mechanism has no automatic generation of structures: this task is left to experts; and existing methods for generating integrated rating trees neglect the system's subject domain. The effectiveness of the algorithm has been demonstrated on an example of a complex organizational system (an airline), and the risk of *Controlled Flight Into Terrain* (CFIT)has been selected for decomposition.

Note that the above version of the algorithm treats risk components as equivalent (of equal value). In the future, we expect to consider a more general version for selecting the aggregation order of risk components in the following case: the value of the closeness index, computed under the assumed equivalence of causal components, becomes useless for unambiguous risk identification (e.g., when it is necessary to convolute three vertices with pairwise equal values of this index). The issues of identifying and validating an optimal structure, as well as those of developing stable features for the comparative analysis and selection of an appropriate structure among several ones, require separate consideration and will be addressed in further work.

Another limitation should also be emphasized: for some systems, a causal graph does not exist. The novel algorithm may be difficult to use in weakly formalizable areas of risk management, such as social, political, economic, and other systems where causal relations are not fixed in regulatory documents.

From a practical standpoint, the algorithm automatically yields a hierarchical structure for comprehensive assessment, reducing, first, the workload on an expert, and second, the variability of structures in the case of several experts.

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