UDC 004.942:519.865:658.16
DOI: 10.15587/2706-5448.2025.330650

Artem Sinkovskyi,
Yurii Tryus

DEVELOPMENT OF A MODEL OF COMPREHENSIVE ASSESSMENT OF ENTERPRISE BANKRUPTCY RISK LEVEL

The object of this study is the process of assessing the risk level of enterprise bankruptcy based on a comprehensive analysis of both quantitative and qualitative characteristics of its business processes. The problem addressed in this work concerns the improvement of bankruptcy risk prediction models. Existing approaches suffer from several significant drawbacks. In particular, the BR model lacks sufficient flexibility. It requires strict preliminary ranking of influencing factors and relies on formalized weighting systems. This limits the individualization of the analysis and reduces the accuracy of the assessment.

The essence of the obtained results lies in the development of a model of comprehensive assessment of enterprise bankruptcy risk level (MCAEBRL). This model implements a comprehensive analysis of the enterprise's business processes using both quantitative and qualitative characteristics. Ranking of factors is not mandatory. Instead, the model uses actual normalized weights determined by experts. It supports flexible rating scales for various indicator types, enables fuzzification of data to handle linguistic evaluations of indicators, and allows a group of experts to be involved to enhance the objectivity of the results.

The importance of the obtained results is explained by the features of the MCAEBRL construction. A process-based and integrated approach was used to analyze the enterprise's activities. A multi-level hierarchy of business processes was employed, as well as quantitative and qualitative indicators for their characterization. Assessments were conducted using broad rating scales. The model uses fuzzy set theory to handle both precise and imprecise data.

The proposed model can be practically applied to assess the financial stability of enterprises across various industries. It is especially useful in unstable economic environments. The model is suitable for working with data of different nature and accuracy levels. It can also be used in cases where expert knowledge needs to be taken into account, thus improving the objectivity of bankruptcy risk assessment.

Keywords: *business processes, enterprise, bankruptcy risk, model, assessment, expert, fuzzy sets.*

Received: 28.02.2025
Received in revised form: 27.04.2025
Accepted: 19.05.2025
Published: 28.05.2025

How to cite
Sinkovskyi, A., Tryus, Y. (2025). Development of a model of comprehensive assessment of enterprise bankruptcy risk level. Technology Audit and Production Reserves, 3 (2 (83)), 81–87. https://doi.org/10.15587/2706-5448.2025.330650

1. Introduction

In the context of dynamic economic development and constant changes in the market environment, there is an increasing need to develop effective tools for the early diagnosis of financial problems in enterprises. In particular, assessing the level of bankruptcy risk is a critically important task for ensuring the stability and security of both individual businesses and the national economy as a whole [1]. Timely identification of threats and the prevention of crisis phenomena help to preserve resources, avoid socio-economic consequences, and ensure the sustainable functioning of business structures.

Traditional approaches to bankruptcy risk assessment are primarily based on the analysis of financial ratios and accounting data [2]. However, practice shows that such methods are often insufficiently effective given the complexity of modern business processes. They often fail to take into account informal factors that can significantly impact a company's financial stability: management quality, innovation potential, the condition of business processes, among others [3]. This creates a need for comprehensive models capable of processing both quantitative and qualitative information.

One of the promising directions is the application of fuzzy set theory, which makes it possible to account for uncertainty, ambiguity, and subjectivity in decision-making processes [4]. The use of fuzzy models enables the integration of heterogeneous data, thereby improving the accuracy and reliability of bankruptcy risk assessments.

An important aspect of modern bankruptcy risk analysis is the introduction of a process-based approach to examining enterprise activity [5]. Business processes form the foundation of an organization's operations, and their efficiency or dysfunction directly affects financial stability. Therefore, assessing the condition of key business processes is a necessary component of comprehensive bankruptcy risk diagnostics.

The scientific aim of this research is to develop and substantiate a new model for assessing enterprise bankruptcy risk, building on earlier methodology [6]. The proposed MCAEBRL model, based on a process-oriented business approach, integrates both quantitative and qualitative performance indicators using fuzzy set theory. The study achieved significant results: the model improves the accuracy of risk assessment by filtering out unqualified expert input, assessing the consistency of expert judgments, and handling uncertainty in business data. MCAEBRL is adaptable to various business environments, and a web-based implementation is already underway.

From the standpoint of scientific novelty, the research proposes a new approach to risk analysis in business processes. It introduces a systematization of business processes based on their impact on the overall risk level. A tree-like hierarchy of risk factors is constructed to organize these risks structurally. For aggregation within fuzzy logic,

ISSN-L 2664-9969; E-ISSN 2706-5448

the Ordered Weighted Averaging (OWA) operator is applied [7]. Adaptive evaluation scales are also introduced, enabling adjustment to the specific features of each enterprise.

From a practical standpoint, the developed methodology allows enterprises to regularly monitor the condition of their business processes and promptly identify areas requiring attention or corrective actions [8]. The proposed approach contributes to improving the accuracy of bankruptcy risk forecasting, optimizing resource allocation, and developing effective anti-crisis strategies.

As a result of the practical implementation of the developed model, enterprises obtain a systematic analysis tool for their stability, based not only on historical data but also on predictive assessments of key process development [9]. This ensures competitive advantages in a volatile economic environment and enables adaptive management decisions in response to external and internal factors.

Thus, the integration of fuzzy logic methods with a process-based approach to bankruptcy risk assessment forms the basis for the development of a modern, flexible, and adaptive risk management system that meets the challenges of today's business environment [10].

2. Materials and Methods

The object of this research is the process of assessing the risk level of enterprise bankruptcy based on a comprehensive analysis of both quantitative and qualitative characteristics of its business processes.

The problem of bankruptcy forecasting began to receive significant attention in leading capitalist countries, particularly in the United States, immediately after the end of World War II. A reduction in military contracts was one of the factors that contributed to a rise in the number of bankruptcies [11].

In modern research, a variety of mathematical models and methods are actively used to assess bankruptcy risk. These include methods of multiplicative discriminant analysis (MDA) of the risk of enterprise bankruptcy [9] and logit, probit models.

Among the prominent Ukrainian scholars, who have studied bankruptcy probability forecasting, [12] is noteworthy for developing a discriminant model for the integral assessment of an enterprise's financial condition.

Building on this foundation, and considering the need for a more holistic evaluation framework, the business process approach to analyzing an enterprise's activities has gained traction as an effective approach for determining the level of bankruptcy risk, especially in the context of uncertainty. Within this framework, it is advisable to apply an economic and mathematical model specifically tailored for such assessments. Namely, the Bankruptcy Risk Model (BRM) (see, for example, [3]). This model is formulated as follows

$$BRM = < G, L, \Phi >, \quad (1)$$

where G – a tree-like hierarchy of factors of enterprise bankruptcy, in particular business processes and their indicators, L – a set of qualitative assessments of each factor level in the hierarchy, and Φ – a system of relations of advantages of some factors over others for one level of the hierarchy of factors.

A tree-like hierarchy G can be described using a directed acyclic graph, where there are no horizontal edges within one ranking level containing a single root vertex

$$G = < F, V >, \quad (2)$$

where $F = \{F_i\}$ – a set of vertices corresponding to factors, with F_0 – the root vertex of the graph corresponding to the risk factor of bankruptcy of the enterprise as a whole, $V = \{V_{ij}\}$ – a set of edges that connect peaks neighboring levels hierarchy. In a tree-like graph G edges are arranged so that the beginning of the edge corresponds to the vertex F_i of the lower level of the hierarchy (rank), and the end of the edge is the vertex F_j of the rank that is one lower. Fig. 1 shows a diagram of a three-level tree-like hierarchy G of the form (2), where the vertex F_0 corresponds to the bankruptcy risk factor of the enterprise as a whole (zero level of the hierarchy), vertices $F_i (i = \overline{1,n})$ correspond to bankruptcy risk factors at the level of business processes (the first level of the hierarchy), and vertices $F_{\{i,j\}}$ correspond to the j-th indicator that characterizes i-th business process ($j = \overline{1,m_j}, i = \overline{1,n}$) (second level of hierarchy), m_i – the number of indicators characterizing the i-th business process.

Therefore, the set of vertices F of the hierarchy G from Fig. 1 can be written as follows

$$F = \left\{ \begin{matrix} \{F_0\}, \{F_1, F_2, ..., F_n\}, \{F_{1.1}, F_{1.2}, ..., F_{1.m_1}\}, \{F_{2.1}, F_{2.2}, ..., F_{2.m_2}\}, ..., \\ \{F_{n.1}, F_{n.2}, ..., F_{n.m_n}\} \end{matrix} \right\}. \quad (3)$$

The set of L qualitative assessments of each factor level in the hierarchy G corresponds to the structure of the set of vertices F of the G hierarchy and contains qualitative assessments, some of which are given by the decision maker or an expert. In particular, these are assessments that correspond to quantitative and qualitative indicators of business processes that characterize the activities of the enterprise and directly affect the risk of its bankruptcy and correspond to the lower level of the hierarchy. The other part is assessments of factors of higher levels, usually calculated on the basis of lower-level assessments according to certain rules, and on their basis a qualitative assessment of the state of the entire enterprise is determined.

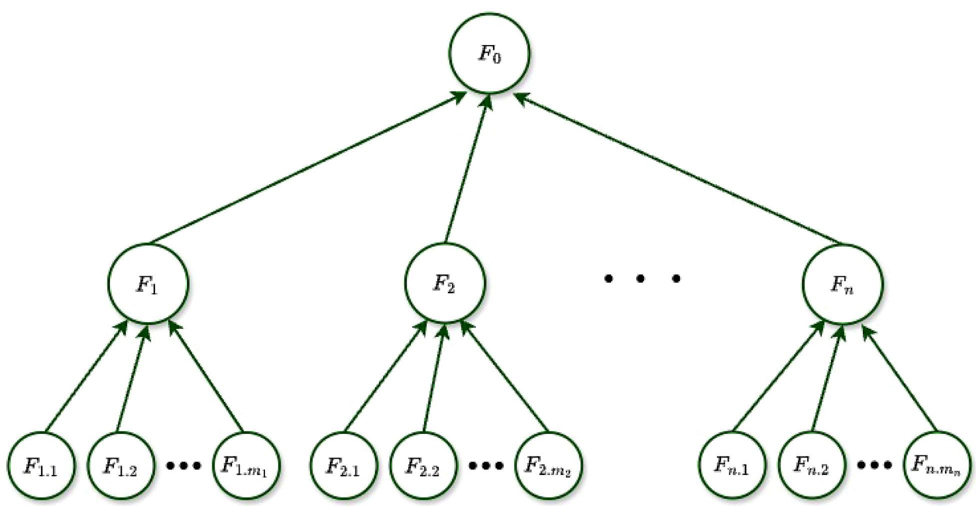

Fig. 1. Diagram three-level tree-like hierarchies G

For example, a set of vertices F of the form (3) of a three-level tree-like hierarchies G has the following form

$$L=\left\{\begin{matrix}\{L_0\},\{L_1,L_2,...,L_n\},\{L_{1.1},L_{1.2},...,L_{1.m_1}\},\{L_{2.1},L_{2.2},...,L_{2.m_2}\},..., \\ \{L_{n.1},L_{n.2},...,L_{n.m_n}\}\end{matrix}\right\}, \quad (4)$$

where L_0 – the assessment that characterizes the state of the entire enterprise and corresponds to the top of the hierarchy F_0, similarly the assessment L_i characterizes the state of the i-th business process enterprise and is responsible top $F_i(i=\overline{1,n})$, and the estimate $L_{i.j}$ characterizes the state of the j-th indicator i-th business process $(j=\overline{1,m_j},i=\overline{1,n})$ and corresponds to the vertex $F_{i.j}\,(j=\overline{1,m_j},i=\overline{1,n})$, m_i – the number of indicators characterizing the i-th business process. At the same time estimates from sets $\{L_{1.1},L_{1.2},...,L_{1.m_1}\},\{L_{2.1},L_{2.2},...,L_{2.m_2}\},...,\{L_{n.1},L_{n.2},...,L_{n.m_n}\}$ are given by the OPS or experts, and estimates from sets $\{L_0\},\{L_1,L_2,...,L_n\}$ are determined according to certain rules in particular using operations on fuzzy numbers (see, for example, [3]).

Often a set of qualitative scores for each factor in the hierarchy G uses the following linguistic rating scale

$$A_5=\{A_{5.1},A_{5.2},A_{5.3},A_{5.4},A_{5.5}\}= \\ =\left\{\begin{matrix}\text{Very low (VL), Low (L), Medium (M),} \\ \text{High (H), Very high (VH)}\end{matrix}\right\}. \quad (5)$$

A system of relations Φ is a system of advantages of some factors over others for one level of the hierarchy of factors

$$\Phi=\{F_i(\phi)F_j\,|\,\phi\in(\succ,\approx)\}, \quad (6)$$

where $\succ$ represents the advantage of one factor over another, $\approx$ – relationship equivalence of factors, F_i,F_j – factors that respond indices i, j.

When business processes and their quantitative and qualitative indicators are ranked by importance by a decision-maker or expert, the Fishburn weight system [13] can be used to determine the weights of the elements in the sets F of the form (3). This system simplifies the procedure for weight assessment by using recurrent relationships.

A BRM hierarchy may have more levels, in particular when the indicator F_{ij} of i-th business process can be characterized by additional indicators: F_{ijk}, $k=\overline{1,m_{ij}}$. In this case to determine the status of the indicator F_{ij} in the form of relationship functions $\mu_{i.j}(x)$ an aggregation procedure similar to the procedure described in step 5 must be performed. It is clear that in this case the hierarchy G, qualitative assessment system L, system of advantages Φ have to reflect this feature. Fig. 2 represents version schemes four-level tree-like hierarchies G.

The BR-model serves as a foundational framework for assessing bankruptcy risk under uncertainty. Two notable methods that utilize this model are the fuzzy set-based risk assessment method and the matrix-based risk assessment method.

The fuzzy set-based risk assessment method [3] employs fuzzy logic to handle the inherent uncertainty in financial indicators. By assigning degrees of membership to various financial states, it allows for a more nuanced evaluation of a company's financial health. This method has been successfully applied to Ukrainian banks, where it demonstrated improved accuracy over traditional statistical models such as ARMA, logit, and probit. Key financial indicators used in this approach include assets, capital, cash (liquid assets), household deposits, and liabilities.

The matrix-based risk assessment method [3, 14] involves constructing a matrix that combines financial indicators with their associated risk levels. Each cell in the matrix represents a specific combination of financial ratios, enabling a comprehensive evaluation of bankruptcy risk. While it is easier to implement, it tends to be less accurate than the fuzzy set-based method.

3. Results and Discussion

The BR model is not particularly flexible. Therefore, let's propose a more general and complex model for assessing the risk of enterprise bankruptcy. This model does not require prior ranking of factors (business processes) or the indicators that characterize them. As a result, it rejects the use of the Fishburn weight system. Instead, it uses real-valued normalized weights. These weights are determined directly by an expert rather than through formal methods. In addition, the comprehensive model assumes using not only the standard (five-level) 01-classifier to determine linguistic grade factors and indicators but also more wide-scale assessment by choice of user. The comprehensive model also provides a procedure for involving a group of experts, which will ensure greater objectivity and accuracy in determining the level of bankruptcy risk of an enterprise.

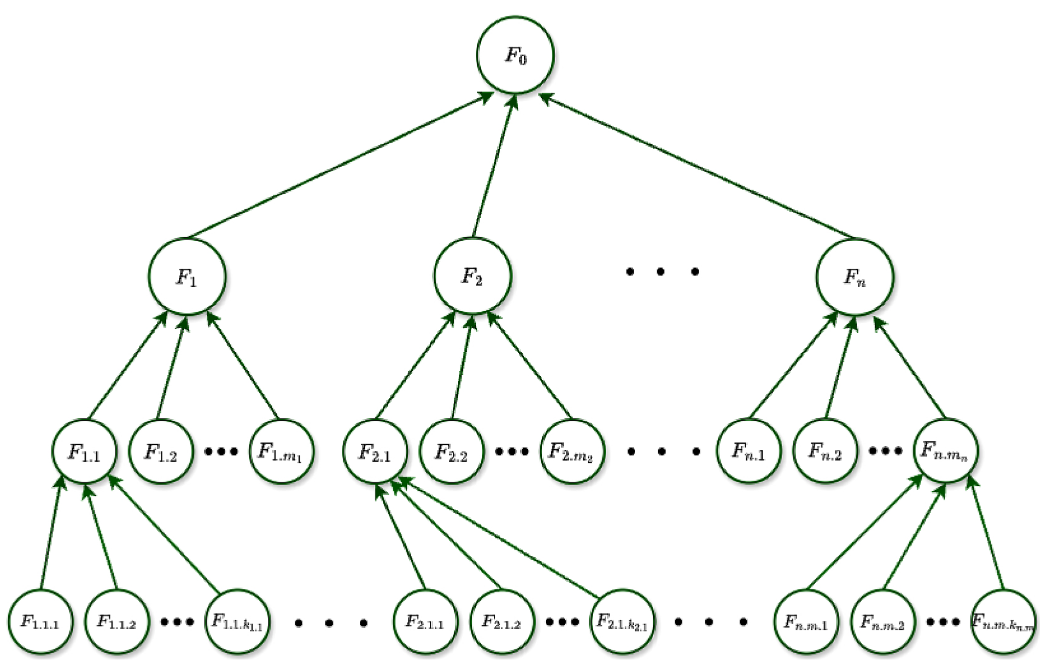

Fig. 2. Scheme of a four-level tree-like hierarchy G

Model of comprehensive assessment of enterprise bankruptcy risk level, further named MCAEBRL, is of the following form

$$MCAEBRL = < H, A, V, W, E, M, R >, \quad (7)$$

where H – a set of business processes and corresponding quantitative (statistical, economic, financial) and qualitative indicators that characterize the activities of the enterprise and affect the level of bankruptcy risk; A – a system of scales for assessing the state of business process in enterprises based on their quantitative and qualitative indicators, as well as scales for evaluating the impact (weight) of business processes on the level of bankruptcy risk; V – the set of numerical and qualitative indicators that characterize business processes enterprises are obtained on the basis of enterprises activities for a certain reporting period; W – the set of values of the weights of business processes and their indicators included in the set H; E – the set of estimates of quantitative and qualitative indicators that characterize the level of the state of each business process from the set H and are set by experts using selected scales from system A depending the values of these indicators from the set V; M – the set of methods for assessing (predicting) the level of bankruptcy risk of an enterprise based on the values of numerical and qualitative indicators characterizing its business processes; R – results of assessing the level of enterprise bankruptcy risk and recommendations for preventing and eliminating this risk both at the level of the entire enterprise and at the level of key business processes.

Let's consider detailed components of the model (7).

In the future, without limiting generality, let's refer to it as MCAEBRL, where H describes a three-level structure (hierarchy)

$$H = \left\{ F_0, F, < F^N, F^Q > \right\}, \quad (8)$$

where F_0 contains the name of the enterprise which state is being analyzed and its details (0th level hierarchy – level enterprises); $F = \{F_i\}$ – the set of basic types of business processes that characterize the activities of an enterprise $i = \overline{1,n}$, n – the number of business processes (in the 1st-level hierarchy – level business processes); $F^N = \{F_{ij}^N\}$ – the set of quantitative indicators characterizing i-th type of business processes F_i $i = \overline{1,n}$, $j = \overline{1,m_i^N}$, where m_i^N – the number of relevant quantitative indicators for F_i (2nd-level of hierarchy – indicator level); $F^Q = \{F_{ij}^Q\}$ – the set of qualitative indicators characterizing i-th type of business process F_i $i = \overline{1,n}$ $j = \overline{1,m_i^Q}$, where m_i^Q – the number of qualitative indicators for F_i (2nd-level of hierarchy – indicator level).

Graphic presentation structures H of the form (8) is shown in Fig. 3.

The set of scales A is used to assess the importance of business process impacts on the level of bankruptcy risk. It also helps evaluate the state of business processes in enterprises. The evaluation is based on their values, including quantitative and qualitative indicators. Additionally, the set includes rules for converting these values into a specific format. For example, this format can be a fuzzy format

$$A = \{A^W, A^N, A^Q, A^F\}, \quad (9)$$

where $A^W = \{A_k^W\}$ – the set of scales for assessing the weight of business processes from the set F, quantitative indicators from the set F^N and qualitative indicators from the set F^Q, which are characterized according to the structure H of type (8), by the level of their impact on the risk of bankruptcy or by the level of their importance for the activities of the enterprise; $A^N = \{A_k^N\}$ – the set of scales for assessing the level of the state of the enterprise's business processes based on the values of their quantitative indicators, $k = 1, r^N$, r^N – the number of different scales used to assess quantitative indicators; $A^Q = \{A_k^Q\}$ – the set of scales for assessing the level of the state of the enterprise's business processes based on the values of their qualitative indicators, $k = 1, r^Q$, r^Q the number of different scales used to assess qualitative indicators; $A^F = \{A_k^F\}$ – the set of rules for converting the values of quantitative and qualitative indicators into a certain format, for example, into a linguistic (fuzzy) format, in particular into trapezoidal fuzzy numbers, $k = \overline{1, r^F}$, r^F – the number of different fuzzification rules.

To estimate element weights of sets F, F^N, F^Q of H an interval scale can be used

$$A_1^W = (0;1],$$

by means of which experts determine the validity of the elements when applying, for example, the normalization method; or ordinal scale

$$A_2^W = \{1, 2, 3, ..., N\},$$

by means of which experts determine the validity of the elements (ranked) when applying, for example, the ranking method, or the method of paired comparisons.

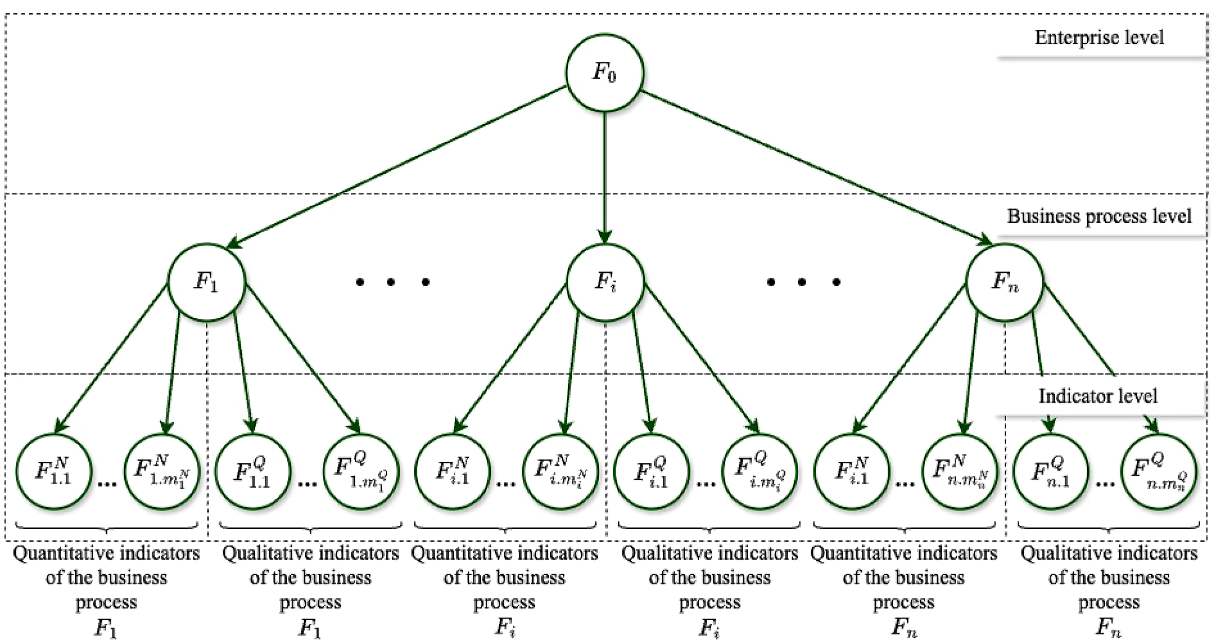

Fig. 3. Scheme of a three-level hierarchy of enterprise structure

To evaluate the level of status of quantitative (numerical) indicators can use such scales from the set A^N:

– interval scale

$$A_1^N = 1^N = [0;1],$$

– or three-point scale

$$A_2^N = B_3^N = \{1;2;3\},$$

– or five-point scale

$$A_3^N = B_5^N = \{1;2;3;4;5\},$$

– or nine-point scale

$$A_4^N = B_9^N = \{1;2;3;4;5;6;7;8;9\}.$$

If necessary, n-point scale for assessing the state of quantitative (numerical) indicators that characterize business processes in enterprises may be used

$$A_m^N = B_n^N = \{1;2;3;...n-1;n\},$$

where n is some fixed natural number.

To evaluate qualitative indicators traditional scales from the set A^Q can be used, for example:

$A_1^Q = L_3^Q = \{L_1$ – low level (H), L_2 – medium level (C),
L_3 – high level (B)$\}$,

or

$A_2^Q = L_5^Q = \{L_1$ – very low level (LN), L_2 – low level (H),
L_3 – medium level (C), L_4 – high level (B),
L_5 – very high level (DV)$\}$,

or, for more accurate assessments of qualitative indicators, extended scale

$A_3^Q = L_9^Q = \{L_1$ – very low level (LN), L_2 – low level (H),
L_3 – level above low (VN), L_4 – level lower medium (NS),
L_5 – medium level (C), L_6 – level above average (BC),
L_7 – level lower high (HB), L_8 – high level (B),
L_9 – very high level (DV)$\}$.

It should be noted that, if necessary, it is possible to translate estimates of quantitative and qualitative indicators from the point scale to the qualitative scale and vice versa, depending on the methods used to assess the level of bankruptcy risk, while it is possible to assume that there will be a mutually unambiguous correspondence between the B^N and L^Q scales, for example

$$B_3^N \leftrightarrow L_3^Q,\ B_5^N \leftrightarrow L_5^Q,\ B_9^N \leftrightarrow L_9^Q. \quad (10)$$

V is a set of incoming data, i. e., values of relevant quantitative and qualitative indicators that characterize business processes in enterprises, and has the following structure

$$V = V^N, V^Q, \quad (11)$$

where $V^N = \{V_{ij}^N\}$ – the set of values of corresponding quantitative indicators $\{F_{ij}^N\}$, $i=\overline{1,n}$, $j=\overline{1,m_i^N}$; $V^Q = \{V_{ij}^Q\}$ – the set of values of corresponding qualitative indicators $\{F_{ij}^Q\}$, $i=\overline{1,n}$, $j=\overline{1,m_i^Q}$.

The values of numerical indicators of the set V^N are set by the user (entered or downloaded from the database of another information system) based on the reporting documentation of the enterprise for a certain period. The values of numerical indicators are set in the appropriate units of measurement, for example, monetary units, measures of weight, %, pieces, etc. At the same time, if for some reason the value is unknown for some indicator, then the value 0 corresponds to it. The values of qualitative indicators of the set V^Q are determined by an invited expert or a group of invited experts and also based on the reporting documentation of the enterprise for a certain period and/or based on the results of an audit, a survey of enterprise employees, an analysis of the activities of management personnel, etc., while using the selected evaluation scale from the set A^Q.

The set of weights W, which is included in model (1), can be represented as follows

$$W = \{W_0, W_1, W_2\}, \quad (12)$$

where $W_0 = \{w_0^N, w_0^Q\}$ – weights for the 0-level structure H, $w_0^N \in (0;1]$ – weight (importance) of quantitative characteristics of business processes in relation to the enterprise as a whole; $w_0^Q \in (0;1]$ – the weight (importance) of qualitative characteristics of business processes in relation to the enterprise as a whole, $w_0^N + w_0^Q = 1$; $W_1 = <W_1^N, W_1^Q>$ – the weight of business processes in relation to the enterprise as a whole; $W_1^N = \{w_i^N\}$ – the set of weights of each business process F_i in relation to the enterprise as a whole, taking into account only quantitative indicators, $w_i^N \in (0;1]$, $i=\overline{1,n}$, $\sum_{i=1}^{n} w_i^N = 1$; $W_1^Q = \{w_i^N\}$ – the set of weights of each business process F_i in relation to the enterprise as a whole, taking into account only qualitative indicators, $w_i^Q \in (0;1]$, $i=\overline{1,n}$, $\sum_{i=1}^{n} w_i^Q = 1$; $W_2 = <W_2^N, W_2^Q>$ – weights of indicators in relation to business processes, in particular; $W_2^N = \{w_{ij}^N\}$ – the set of weights of each quantitative indicator F_{ij}^N in relation to the business process F_i of the enterprise, $w_{ij}^N \in (0;1]$, $i=\overline{1,n}$, $j=\overline{1,m_i^N}$, $\sum_{j=1}^{m_i^N} w_{ij}^N = 1$; $W_2^Q = \{w_{ij}^Q\}$ – the set of weights of each qualitative indicator F_{ij}^Q in relation to the business process F_i of the enterprise, $w_{ij}^Q \in (0;1]$, $i=\overline{1,n}$, $j=\overline{1,m_i^Q}$, $\sum_{j=1}^{m_i^Q} w_{ij}^Q = 1$.

The importance of business processes and their quantitative and qualitative indicators are determined, as a rule, by experts (using appropriate scales and systems from the set A^W) based on their role and importance for the company's operations and impact on the processes that cause bankruptcy.

The set E contains: *assessments quantitative and qualitative indicators* that characterize the state level of each business process from the set H and are set by experts using selected scales from the system A depending on the values of these indicators from the set V, and has the following structure

$$E = <E_2^N, E_2^Q>, \quad (13)$$

where $E_2^N = \{E_{ij}^N\}$ – the set of estimates of the 2nd level of the structure H – the level of the state of quantitative indicators F_{ij}^N, $i=\overline{1,n}$, $j=\overline{1,m_i^N}$, which are set by experts based on input data from the set V^N, a chosen multiple – choice rating scale A^N (note that based on chosen one ballroom scale determination procedure grades, for the level of quantitative status indicators can automate if customer will provide information about intervals permissible values indicators F_{ij}^N: $[V_{ij}^{\min}, V_{ij}^{\max}]$, $i=\overline{1,n}$, $j=\overline{1,n_i^N}$ which will greatly simplify the work of experts. In addition, if necessary, the point estimates can be converted into a scale of qualitative

ISSN-L 2664-9969; E-ISSN 2706-5448

assessments using one of the ratios (10)); $E_2^Q=\{E_{ij}^Q\}$ – the set of assessments of the 2nd level of the structure H – the level of the state of qualitative indicators F_{ij}^Q, $i=\overline{1,n_i^N}$, $j=1,m_i^Q$, which are set by experts based on input data from the set V^Q, using the selected assessment scale from the set A^Q (note that under certain conditions, qualitative assessments $E_{ij}^Q=V_{ij}^Q$, or they are converted into corresponding point scores using one of the relations (10)).

The set of methods M assessment (forecasting) of the level risk of bankruptcies enterprises is based on values quantitative and qualitative indicators that characterize its business processes, it is possible to present like this

$$M=<M^N,M^Q,M^C>, \quad (14)$$

where M^N – methods for analyzing quantitative indicators that characterize the business processes of an enterprise, for example, methods of multiplicative discriminant analysis of the risk of enterprise bankruptcy (MDA) based on the models of E. Altman, R. Lees, D. Chesser, R. Taffler, G. Tishaw, J. Fulmer, etc., as well as methods based on neural networks; M^Q – methods of analyzing qualitative indicators that characterize business processes, for example, group examination methods (questionnaire methods [15, 16], the brainstorming method storming [17], Delphi method [18]); M^C – methods of comprehensive analysis of the risk of enterprise bankruptcy, for example, the method of predicting enterprise bankruptcy using fuzzy logic, the matrix method of predicting enterprise bankruptcy and fuzzy neural networks (see, for example, [14]).

The results R of the assessment of the level of enterprise bankruptcy risk and recommendations for their prevention and elimination can be formally presented as follows

$$R=<RLB,RPE>, \quad (15)$$

where $RLB=\{RL_0,RL_1^N,RL_1^Q\}$ – results of assessing the level of bankruptcy risk, with: $RL_0=\{S_0,RB_0,DS_0\}$ contains information about the state of the enterprise S_0 in general, appropriate level of risk bankruptcies RB_0 and the degree of similarity DS_0 of the obtained result (Degree of Similarity); $RL_1^N=S_1^N,DS_1^N$ contains information about the state of $S_1^N=S_{1,i}^N$ each business process of the enterprise F_i, $i=1,n$ by quantitative indicators and their degree of similarity $DS_1^N=\{DS_{1,i}^N\}$; $RL_1^Q=S_1^Q,DS_1^Q$ contains information about the status of $S_1^Q=S_{1,i}^Q$ each business process of the enterprise F_i, $i=1,n$ by qualitative indicators and their degree of similarity $DS_1^Q=\{DS_{1,i}^Q\}$; $RPE=<RP,RE>$ – the set of measures of prevention and elimination of risks of bankruptcy, while: RP – the set of measures to prevent bankruptcy risks; RE – the set of measures to eliminate bankruptcy risks.

Relevant sets of measures to prevent bankruptcy risks are developed in accordance with industry standards [19], with generative artificial intelligence offering additional support in their formulation. In this context, the enterprise's state S_0, it's bankruptcy risk level RB_0, and the similarity degree DS_0 between the fuzzy evaluation and the nearest baseline linguistic assessment are determined using a selected metrics. The procedure is based on the aggregated fuzzy estimate and adheres to the correspondence rule between predefined fuzzy state evaluations and bankruptcy risk levels (Tables 1–3), as defined by the chosen linguistic scale A^Q. The resulting value DS_Σ quantifies the proximity of the fuzzy assessment to its linguistic prototype.

MCAEBRL can be utilized by financial analysts, investors, and business managers to assess bankruptcy risk with greater accuracy, enabling the early detection of potential financial issues and the implementation of preventive actions. Furthermore, the model can be valuable for credit institutions when evaluating the creditworthiness of enterprises.

A comparative analysis between BRM and MCAEBRL models is presented in Table 4.

Table 1

Correlation between the enterprise's financial condition and its bankruptcy risk level according to the scale L_3^Q

L_3^Q Level	Enterprise condition S_0	Bankruptcy risk level RB_0
L_1	Low (L)	High (H)
L_2	Average (A)	Average (A)
L_3	High (H)	Low (L)

Table 2

Correlation between the enterprise's financial condition and its bankruptcy risk level according to the scale L_5^Q

L_5^Q Level	Enterprise condition S_0	Bankruptcy risk level RB_0
L_1	Very low (VL)	Very high (VH)
L_2	Low (L)	High (H)
L_3	Average (A)	Average (A)
L_4	High (H)	Low (L)
L_5	Very high (VH)	Very low (VL)

Table 3

Correlation between the enterprise's financial condition and its bankruptcy risk level according to the Scale L_9^Q

L_9^Q Level	Enterprise condition S_0	Bankruptcy risk level RB_0
L_1	Very low (VL)	Very high (VH)
L_2	Low (L)	High (H)
L_3	Above low (AL)	Below high (BH)
L_4	Below average (BA)	Above average (AA)
L_5	Average (A)	Average (A)
L_6	Above average (AA)	Below average (BA)
L_7	Below high (BH)	Above low (AL)
L_8	High (H)	Low (L)
L_9	Very high (VH)	Very low (VL)

Table 4

Qualitative comparison between BRM and MCAEBRL

Aspect	BRM	MCAEBRL
Structure	Three-level tree (enterprise → business processes → indicators) with linguistic assessments L at each node and Fishburn system Φ to derive weights	Complex model with multi-level hierarchy but no Fishburn. Uses real, normalized weights set by experts; supports a wide variety of scales and fuzzification rules
Weighting	Fishburn weight system: derives ordinal weights via recurrent rank relations	Explicit weights W set directly by an expert or expert panel on an interval [0,1] or ordinal scale
Scales	Fixed linguistic scale (e. g., five-point fuzzy) with fixed aggregation rules (fuzzy or matrix)	Any numeric scales (3-, 5-, 9-point or continuous [0,1]) and linguistic scales, plus fuzzification rule sets
Industry Adaptability	Limited: fixed scales and procedures need tweaking to fit industry specifics but offer less configurability	Highly adaptable: hierarchy H, scales A, and methods M can be tailored to any sector, but demands extra research and calibration

The proposed model for comprehensive assessment of enterprise bankruptcy risk has been partially implemented in a web-oriented information-analytical system currently being developed [20].

Note that, although MCAEBRL boasts a clearly formalized structure and spans a wide array of quantitative and qualitative indicators, its theoretical universality is constrained by the need to involve experts directly in setting the normalized weights and choosing assessment scales. In practice, this means results can vary across industries depending on experts' skills and preferences, which undermines reproducibility unless there is a strict protocol for expert selection and engagement.

In the future, it is planned to conduct further research to refine and expand the proposed model, exploring its adaptability to various industries and improving the accuracy of the bankruptcy risk assessment. Additionally, the development of more advanced algorithms and the integration of real-time data sources will be considered to enhance the model's predictive capabilities.

The conditions of martial law in Ukraine did not affect the conduction of the research.

4. Conclusions

In the course of the research, a novel model (MCAEBRL) was developed to predict bankruptcy risk using fuzzy logic techniques. Unlike existing models, this one is built on a process-oriented business approach, in which the enterprise is considered a complex system (a business model) and involves the analysis of both quantitative and qualitative performance indicators using fuzzy set theory.

Unlike the standard BR model, MCAEBRL offers significant improvements. The use of fuzzy logic provides flexibility in evaluation, allowing for the inclusion of ambiguous and uncertain data, which are typical in business processes. Excluding unqualified experts from the evaluation process after assessing their competence enhances the accuracy and objectivity of the evaluation. The application of the developed formulas to determine the consistency of expert assessments highlights the importance of considering all possible variables when analyzing bankruptcy risk. Furthermore, the assessment of expert competence enables a clearer understanding of what needs to be improved to enhance the enterprise's performance.

MCAEBRL can be adapted to other exotic business processes, thus expanding its potential areas of application. It is proposed for research in areas that are continuously affected by an unstable economic environment and require reliable and rapid bankruptcy risk assessment methods.

The constructed mathematical framework is a significant contribution to the study of bankruptcy risk determination processes, offering a new approach and tools for its economic analysis. At the same time, it is only a part of further research that requires a more detailed understanding of the interaction between various factors.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship, or otherwise, that could affect the research and its results presented in this paper.

Financing

The research was performed without financial support.

Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors have used artificial intelligence technologies within acceptable limits to provide their own verified data, which is described in the research methodology section.

References

1. Havrylenko, V. O. (2018). *Metodolohiia ta orhanizatsiia oblikovo-analitychnoho zabezpechennia antykryzovoho upravlinnia pidpryiemstvom.* [Doctoral dissertation].
2. Mizumoto, M., Tanaka, K. (1976). Fuzzy-Fuzzy Automata. *Kybernetes, 5 (2),* 107–112. https://doi.org/10.1108/eb005415
3. Zaychenko, Y. P. (2008). *Fuzzy models and methods in intellectual systems.* Kyiv: Publishing House Slovo, 354.
4. Wygralak, M. (1983). Fuzzy inclusion and fuzzy equality of two fuzzy subsets, fuzzy operations for fuzzy subsets. *Fuzzy Sets and Systems, 10 (1-3),* 157–168. https://doi.org/10.1016/s0165-0114(83)80112-2
5. Davenport, T. H. (1994). Managing in the New World of Process. *Public Productivity & Management Review, 18 (2),* 133. https://doi.org/10.2307/3380643
6. Caeldries, F., Hammer, M., Champy, J. (1994). Reengineering the Corporation: A Manifesto for Business Revolution. *The Academy of Management Review, 19 (3),* 595. https://doi.org/10.2307/258943
7. *ISO 9001:2015. Quality management systems – Requirements* (2015). ISO. Available at: https://www.iso.org/standard/62085.html Last accessed: 30.04.2025
8. Karasmanis, T. (2014). *Why Model Business Processes? Business Analysis.* The Global Standard. IIBA. Available at: https://www.iiba.org/professional-development/knowledge-centre/articles/why-model-business-processes Last accessed: 30.04.2025
9. Eisenbeis, R. A. (1977). Pitfalls in the application of discriminant analysis in business, finance, and economics. *The Journal of Finance, 32 (3),* 875–900. https://doi.org/10.1111/j.1540-6261.1977.tb01995.x
10. Premachandra, I. M., Bhabra, G. S., Sueyoshi, T. (2009). DEA as a tool for bankruptcy assessment: A comparative study with logistic regression technique. *European Journal of Operational Research, 193 (2),* 412–424. https://doi.org/10.1016/j.ejor.2007.11.036
11. Pysarevskyi, I. M., Steshenko, O. D. (2008). *Upravlinnia ryzykamy.* Kharkiv: KhNAMG, 124. Available at: https://core.ac.uk/download/pdf/11320342.pdf Last accessed: 05.05.2025
12. Tereshchenko, O. O. (2003). Dyskryminantna model intehralnoi otsinky finansovoho stanu pidpryiemstva. *Ekonomika Ukrainy, 8,* 35–41.
13. Fishburn, P. C., Kochenberger, G. A. (1985). Aggregating assignment constraints. *Naval Research Logistics Quarterly, 32 (4),* 653–663. https://doi.org/10.1002/nav.3800320412
14. Zgurovsky, M. Z., Zaychenko, Y. P. (2017). The Fundamentals of Computational Intelligence: System Approach. *Studies in Computational Intelligence.* Springer International Publishing, 375. https://doi.org/10.1007/978-3-319-35162-9
15. Yager, R. R. (1988). On ordered weighted averaging aggregation operators in multicriteria decisionmaking. *IEEE Transactions on Systems, Man, and Cybernetics, 18 (1),* 183–190. https://doi.org/10.1109/21.87068
16. Slavkovic, A. (2002). *Evaluating Polygraph Data.* Carnegie Mellon University. Available at: https://www.stat.cmu.edu/tr/tr766/tr766.pdf Last accessed: 26.04.2025
17. Mergel, T. V. (2015). Application of "Brainstorming" Interactive Method in Educational Process. *Medical Education, 4,* 44–47. Available at: https://core.ac.uk/download/pdf/276622155.pdf Last accessed: 07.05.2025
18. Dalkey, N., Helmer, O. (1963). An Experimental Application of the DELPHI Method to the Use of Experts. *Management Science, 9 (3),* 458–467. https://doi.org/10.1287/mnsc.9.3.458
19. *ISO/IEC. ISO/IEC 27001 for Small Businesses – Practical Advice* (2010). ISO.
20. Sinkovskyi, A., Tryus, Y. (2024). Web-Oriented Information and Analytical System for Assessing the Risk of Bankruptcy. *Information Technology for Education, Science, and Technics.* Cham: Springer, 406–425. https://doi.org/10.1007/978-3-031-71801-4_30

✉***Artem Sinkovskyi,*** *Assistant, Department of Computer Science and System Analysis, Cherkasy State Technological University, Cherkasy, Ukraine, ORCID: https://orcid.org/0009-0009-8877-7351, e-mail: a.sinkovskyi@chdtu.edu.ua*

Yurii Tryus, *Doctor of Pedagogical Sciences, PhD, Professor, Department of Computer Science and System Analysis, Cherkasy State Technological University, Cherkasy, Ukraine, ORCID: https://orcid.org/0000-0002-0739-2065*

✉*Corresponding author*