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# DEVELOPMENT AND APPLICATION OF THE SCENARIO-FRACTAL ESG ASSESSMENT METHOD FOR ENTERPRISE DECISION SUSTAINABILITY

The object of research is a scenario-fractal assessment of the ecology, society, management (ESG assessment) of the sustainability of management decisions of enterprises. The problem of assessing not the general level of sustainability of the enterprise, but specific decisions was solved. Such decisions are made in conditions of military challenges, climate risks, resource instability and increasing requirements for ESG reporting. The theoretical part of the work is based on a combination of various scientific approaches. The methodological part involves the formation of a system of ESG indicators. Also used are the normalization of indicators, eclecticism of weights and a scenario ESG index. The data completeness coefficient and the fractal consistency coefficient, which show the similarity of the ESG profile of the decision at the strategic, tactical and operational levels of management, were separately taken into account. The empirical basis of the research was formed using open data of metallurgical enterprises. The decarbonization solutions of Interpipe Group, Metinvest and SSAB were analyzed. The choice of the industry was made from the standpoint of high carbon intensity of metallurgy and availability of public ESG information. The results of the method showed that the highest sustainability index is for the SSAB solution. Its advantage is related to both the environmental component and social manageability, management evidence and scenario endurance. The Interpipe solution has environmental advantages, but requires strengthening the verifiability of ESG data. The Metinvest solution is distinguished by high decarbonization ambition, but has shortcomings of a social and crisis nature. The results confirm that the sustainability of the solution must be formed through the balance of components, scenario stability and inter-level consistency.

The practical use of the obtained results is appropriate in the field of corporate ESG analysis, preparation of ESG reporting and selection of management alternatives. The method is suitable for use in conditions of uncertainty.

**Keywords:** sustainable development, ESG assessment, management decisions, scenario approach, fractal consistency, decarbonization.

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## 1. Introduction

The methodological foundation of scenario-fractal ESG assessment was formed gradually. First, scientists developed tools for working with disparate information, uncertainty, and multi-criteria. Then scenario approaches, the concepts of fractality, and corporate sustainability appeared. Over time, ESG assessment became part of financial, managerial, and institutional practice. The first period was the formation of a mathematical and analytical basis for assessment. The basis for quantitative analysis was information theory. Source [1] made it possible to interpret data as a set of numbers and carriers of information value. This is important for ESG assessment, because the indicator in the report should help distinguish management decisions by the level of sustainability. Further development is associated with set theory [2]. This approach opened up the opportunity to work with assessments that do not have hard boundaries. This is what social governance, reporting quality, or management transparency often look like. At the same time, fuzzy logic does not answer the question of whether a solution will withstand a crisis scenario. Therefore, it is useful, but only part of a broader toolkit. The hi-

erarchical approach to priorities in [3] is important for building a system of weights. A complex solution can be analyzed through the prism of criteria decomposition. In ESG assessment, such an idea is needed to divide indicators into ESG components. The limitation of this approach lies in its relative staticity. It does not explain how to change weights under the influence of scenarios. Multi-criteria evaluation of alternatives has received proper formalization in [4]. This approach is useful for comparing management decisions according to a system of certain criteria. It provides the logic of an integral index. However, in its classical form, multi-criteria methods rarely check the stability of the solution over time. This requires a combination with dynamic scenarios. Fractal geometry in [5] proposed the idea of self-similarity of structures. From the perspective of modern management, a decision is stronger when its ESG logic does not disappear between the strategic, tactical and operational levels. At the same time, fractal theory was not created for ESG, therefore it needs to be translated into the language of management vectors. The concept of post-normal science [6] explains the conditions of the functioning of enterprises due to incomplete data and the need to make operational decisions. It proves the insufficiency of linear assessment.

At this stage, most of the basic tools were created – entropy, fuzzy sets, multi-criteria, priorities and self-similarity. Despite this, they were considered in isolation from each other, the possibilities for their integration were not considered, there was no clear need to assess the sustainability of ESG-decisions of enterprises.

The second period marked a turn to corporate sustainability. Environmental and social factors gradually began to be taken into account when assessing the level of development of the enterprise, its strategy and competitive position. Important for this shift was the interpretation of natural resources as a source of advantages [7]. Environmental constraints began to be considered as a motive for technological renewal, strengthening of market position. However, ESG logic in this area has not yet become complete.

A different perspective was offered by scenario planning [8], which focused on testing the effectiveness of a decision in different market conditions, accompanied by crisis phenomena, resource shortages, and new climatic requirements. At the same time, the classical scenario approach did not yet work with ESG indicators and fractal consistency of decisions at different levels of management.

Over time, the very understanding of business effectiveness changed. The concept of the triple bottom line expanded the boundaries of enterprise assessment [9]. In addition to financial results, social and environmental effects also became a measure of success. This brought scientific thought closer to the modern ESG approach. However, the management component did not yet have the current weight.

The social block has been strengthened after researches of its connection with financial results [10]. It has become clear that even high environmental achievements can lose their sustainability when employees, safety, personnel risks or acceptability of changes are ignored.

Environmental corporate strategies have brought sustainability even closer to management [11], environmental priorities have become an object of management, which is important for evaluating decarbonization solutions. Despite this, social manageability and data verification have not yet been sufficiently revealed.

The idea of sustainable value has changed the tone of the discussion [12]. Sustainability has begun to be considered as a source of development, a vector of innovation and market opportunities.

The strategic vision of corporate responsibility has also pushed the boundaries of analysis [13]. Sustainability has become part of the competitive logic of the enterprise, and ESG solutions have become an integral part of business modeling. The change in visions has prompted the search for new approaches in management, but has not provided a way to analyze several solutions and a tool for choosing the best one.

Integrated reporting added an information dimension to this [14], in particular qualitative requirements for the disclosure of management data. The concept of shared value showed another side of ESG decisions [15]. Social and environmental outcomes may not contradict competitiveness. But this concept does not answer the applied question of how to measure the sustainability of a particular alternative.

A significant clarification was the industry specialization [16] and the issue of identifying the effectiveness of the strategy [17]. It turned out that what is critical for one industry may be secondary for another. Indicators must be weighed taking into account professional judgments and the information value of indicators. An enterprise constantly chooses between environmental goals, costs, social consequences and management capabilities. In view of this, it is necessary to see what exactly supports or weakens the sustainability of a decision.

The organizational dimension of sustainability brought the research to the issue of internal consistency [18]. The strategy should contain the right ESG guidelines that are implemented in programs, procedures and operational activities. This is where the basis for a fractal analysis of the ESG profile arises, which identifies whether the ESG logic is consistent across different levels of management. The financial dimension has emphasized the applied value of sustainability [19].

ESG decisions affect investment attractiveness and creditworthiness. A broad generalization of empirical results has established the significance of ESG for business [20]. It explains why ESG matters, but at the same time does not show how to assess the sustainability of an individual decision under conditions of uncertainty.

Thus, during this period, sustainability has become a component of strategic planning, reporting, social policy and financial expectations. That is why a method that combines the ESG profile, scenario resilience and consistency between implementation levels has subsequently arisen.

The third period is the criticism of ESG ratings and the search for ways to achieve a more transparent assessment. In [21] it is shown that the assessments of companies in different rating systems may not coincide, which is a consequence of differences in the methodologies for constructing ratings. A comparison of approaches to measuring corporate responsibility in [22] confirmed the methodological sensitivity of ESG scores. It is empirically proven that indicators, scales and weights can change the final rating. In addition, it is argued that transparency and reproducibility of calculations and their results are the principle of rating. The materiality of ESG indicators in [23] deepens the issue of indicator selection. Not every available indicator is equally important. The assessment should take into account the materiality of the indicator for a specific industry and decision. However, materiality here is not tested through scenarios. ESG integration into the investment process in [24] showed the consideration of non-financial indicators in the analysis of ESG data. However, this turned out to be insufficient. Investors need to assess both the attractiveness of assets and the sustainability of their own decision to manage them in the long term. Criticism of ratings regarding universal ESG assessments [25] has led to the fact that it has become obvious that opaque ratings cannot be trusted. ESG investment practices in [26] show that although ESG has already become part of financial analytics, there are still many open methodological issues. There is still no mechanism for assessing the sustainability of a management decision. The impact of company size on the ESG score in [27] is an important caveat. Large companies with greater analytical capabilities often have only formally better ESG scores. Such distortions must be avoided. Low-carbon multi-criteria selection in [28] is close to the environmental block of the method. The very idea of combining several goals is important here. However, it is about portfolio decisions, not enterprise management. So, methodological logic is useful, but the subject is different. The selection of indicators in the information and analytical support [29] is important for the initial stage of the methodology. Poorly selected indicators destroy the content of the index. This also applies to ESG solutions. However, the source does not work with the environmental, social and governance triad. The discrepancy of ESG ratings in [30] again shows the instability of ready-made assessments. This confirms that the enterprise needs its own calculation logic. Such a calculation should not only rank, but also explain the reasons for the result. The scenario behavior of solutions in this source is not disclosed. The problem of missing ESG data in [31] is very close to the data completeness coefficient. If the information is incomplete, the final result has lower reliability. This is especially important for open corporate sources. However, the completeness of the data does not show whether the decision is coordinated between the management levels. A detailed analysis of the discrepancy of ESG ratings in [32] explains its reasons.

Different measurements, different weights and different sets of indicators give different results. This almost directly leads to the need for a transparent methodology. However, fractal coherence is not considered there. The information system for environmental risk management in [33] adds a managerial and digital dimension. ESG decisions need information support, not just declarations. This is especially important for environmental risks. However, the social and management blocks there do not form a complete ESG model. The large-scale patterns

of environmental performance in [34] are interesting because of their work with scale. This approach partly resonates with fractal thinking. However, corporations are assessed, not management decisions. Self-similarity of management levels is not the subject of this analysis. Monitoring data and algorithmic search in [35] show how technical risks can be assessed through data. This is important as an analogy for scenario thinking. Critical conditions can be detected by changing parameters. However, ESG content is absent here. International evidence linking ESG practices and performance in [36] reinforces the practical status of ESG. It conceptually shows that sustainability is linked to company performance, but does not offer assessment methods, in particular regarding integration through the prism of scenario analysis and identification of fractal features. Managing ESG rating discrepancies in [37] moves the issue to the plane of sustainable portfolio choice, but the focus remains on the financial portfolio, not on the sustainability of the management decision. The role of standards and indices in [38] shows that ESG ratings affect the evidentiality of the analysis results and explain the vectors of capital movement. However, a method for calculating the sustainability of the decision is not proposed there either. The institutional dimension of investment activity in [39] is useful for understanding the external environment. The sustainability of the decision depends not only on the company. Regulation, support and industry conditions also matter. Therefore, the scenario block should take into account institutional assumptions. Systematic ESG assessment using machine learning in [40] reflects the digitalization of analysis, which is important for processing large data sets, but automated assessment requires a method that combines automated analysis with expert interpretation. The uncertainty of ESG investing in [41] supports scenario thinking. If ESG assessment depends on assumptions, it must be tested in different conditions. At the same time, the investment level does not replace the management level. The assessment of the decision within the enterprise is needed.

This period revealed the main problem of the modern ESG field. Assessments are widespread, but not always transparently calculated. Ratings often differ due to incomplete data and the secrecy of the methods for calculating integral indicators.

The fourth period is the modern need for transparent integration, parameterized and justified scenario and verification of real sustainability. Newer researches increasingly respond to the risk of superficial ESG. Source [42] shows that scores can be improved through strategic, rather than tactical and operational practices. Real assessment requires both the financial and economic consequences of the decision and the solution of the management problem, the degree of implementation of the management initiative, and the consistency of the consequences of the decision with environmental and social priorities. From the position of the functional-process approach, simulation modeling of management in [43] is useful in the context of formalizing management processes. Its application is well consistent with scenario-fractal ESG assessment. However, ESG is not the central topic there. Information-reflective management in [44] enhances the importance of causality and meaningful information support for analytical processes. This is the connection with the management component of the method. The relationship between the discrepancy between ESG ratings and performance in [45] shows the economic and managerial consequences of methodological uncertainty. If the assessments are unstable, the economic and managerial signals also become unstable. This confirms the need for the integral index to have a decomposition basis. The spatiotemporal clustering of environmental assessments in [46] actualizes a dynamic analysis that lies beyond the so-called one-time actions. It depends on time, environment and comparative context. This is close to the scenario component, although fractal analysis here remained outside the researcher's attention. In [47], the use of large language models in the processes of detecting ESG activity is systematically disclosed. Such models allow detecting ESG signals, but still do not

allow identifying their significance, scenario stability and managerial coherence. Large language models, big data in sustainable investing in [48] indicate the digital expansion of ESG analytics. These digital capabilities are often quantitative in nature and do not always affect the quality of diagnostic results. It is obvious that the current key requirements for analysis and diagnostic methods today are the completeness and evidence of primary and processed information. A large base without verification can create false accuracy. The protective role of ESG in conditions of uncertainty in [49] directly supports the crisis scenario. If ESG is to increase resilience, it must be tested under pressure. The baseline scenario is no longer sufficient. At the same time, the source does not analyze the self-similarity of the ESG profile of the solution. ESG sentiment and stock returns in [50] show the importance of market perception. Investors may react to ESG signals, but not take into account the content, resilience and coherence of the solution. The connection of ESG performance with financial flexibility in [51] complements modern views. Sustainability should determine the priorities of the enterprise in maneuvering resources, which is important in times of crisis. However, scenario and fractal testing are not applied there.

In the following period, sustainability began to be considered as the ability of a solution to maintain effectiveness in a changing environment [52]. In the context of scenario-fractal ESG assessment, this implies that the effectiveness of each management alternative should be achievable under different market conditions, resource constraints, information asymmetry and counterparty behavior. At the same time, such an approach does not yet form a complete ESG structure of the solution, but only strengthens the financial and analytical block of the future method.

The issue of forecast objectivity is directly related to the evidentiality of ESG assessment [53]. A forecast based on incomplete, unstable or distorted data distorts the integral ESG conclusion. Therefore, the quality of data and transparency of analytical procedures are basic requirements for the method. However, the objectivity of the forecast does not guarantee that the ESG logic is preserved between all levels of management. The use of an omnichannel approach to monitoring the assortment policy of marketplaces and customer relations expands the applied boundaries of business analytics [54]. The sustainability of the solution here has an additional manifestation in the permanence of monitoring digital channels, consumer behavior and changes in market interaction. This brings ESG analytics closer to the real conditions of the enterprise's functioning. At the same time, the ESG triad in this approach does not yet form a full-fledged method. Analytical support for the adaptation of e-commerce enterprises to market changes strengthens the scenario component of the decision-making process [55]. The adaptability of the decision-making process should be taken into account during ESG analytics in the basic, optimistic and crisis scenarios. However, ESG assessment is not the central subject here, which leaves open the issue of integrating financial adaptability with ESG criteria.

The formation of an ESG management system based on digital analytics [56] is no longer reduced to an external rating or reporting indicator. It moves into the plane of management procedures based on analytical decision-making tools. However, even systemic ESG management does not replace the method of assessing the sustainability of a separate management alternative.

Thus, the works [52–56] confirm the need for a method that combines digital analytics, in particular for predicting and ensuring the adaptability of ESG-oriented management decisions. Their common limitation is that they do not provide for the integration of ESG indicators, scenario testing of the sustainability of the decision and its fractality. This forms the basis for the development of a scenario-fractal ESG assessment of the sustainability of corporate decisions. Our review of the positions of various authors made it possible to identify the general logic of the development of ways to solve the topic under study.

After the creation of mathematical tools for working with data, approaches to scenarios, fractality, and corporate sustainability appeared. Subsequently, ESG began to be implemented in the algorithms of financial and management analysis. Later, analysts identified shortcomings in the construction of ratings, in particular, in terms of low data quality and opacity of the calculation of ESG indicators.

So, the necessary tools were formed a long time ago. But its elements were not connected by a common goal. Today, there is a need for a holistic method. It should combine the basic ESG profile of the solution, scenario endurance and fractality. Such an approach is necessary for the practice of enterprises operating in an environment of war, climate regulation, lack of resources and increasing reporting requirements. The scenario-fractal ESG assessment method meets this need. It does not reject previous developments, but collects them into an applied system. Its difference lies in the fact that the object of analysis is not the general sustainability of the enterprise, but a specific management decision. Such a decision is assessed through ESG indicators, scenarios, completeness of data and fractal consistency between levels of implementation.

So, *the object of research* is the scenario-fractal assessment of the ecology, society, management (ESG assessment) of the sustainability of management decisions of enterprises. The level of ESG development of enterprises is not always identical to the sustainability of the decisions made by enterprises. The reasons for this may be different. First, the operational situation may not be consistent with the general values and traditional management practices of the enterprise. Second, investment priorities may change under the influence of national, regional or global trends. Third, an enterprise may be forced to comply with the ESG requirements of international organizations through participation in certain projects, even in the absence of its own ESG policy or development strategy. This necessitates the transition from assessing enterprises to assessing specific decisions.

*The aim of research* is to develop a method for scenario-fractal ESG assessment of the sustainability of enterprise decisions. To achieve this goal, a number of interrelated tasks are envisaged. Among them:

- 1) to propose a structure for the method of scenario-fractal ESG assessment of the sustainability of enterprise decisions;
- 2) to apply scenario-fractal ESG assessment of the sustainability of enterprise decisions and analyze its results.

## 2. Materials and Methods

*The subject of research* is the sustainability of management decisions of enterprises in the context of ESG priorities. It is about the ability of decisions to maintain environmental, social and management effectiveness in an unstable economic environment. Under such conditions, management decisions should be evaluated for effectiveness in different scenarios of development of events.

*The methodological basis of research* is the method of scenario-fractal ESG assessment of the sustainability of enterprise decisions. Its logic is based on combining a system of ESG indicators, as well as processes of generating scenarios for the implementation of decisions and analyzing the self-similarity of the decision at the strategic, tactical and operational levels of management.

*The main hypothesis of research* is that the sustainability of a management decision cannot be assessed by only one ESG indicator. It is formed through a combination of the basic ESG profile, scenario stability and fractal coherence between management levels. If the solution remains effective in different scenarios, and the ESG logic is repeated at different levels of management, then the solution has signs of sustainability and internal consistency.

*Description of variables:* The research uses several groups of indicators. The environmental component includes indicators that characterize the level of decarbonization and technological readiness of the enterprise. The social component covers the manageability of the transition

and the social vulnerability of the solution. The management component reflects the quality of ESG reporting and the verifiability of ESG data. This division makes it possible to evaluate the solution by environmental result, social acceptability, and managerial demonstrability.

The proposed method provides for the consideration of the vectors of influence of indicators, namely, stimulants and disincentives. The former includes indicators which value improves the sustainability of the solution – the level of decarbonization, technological readiness, social manageability, and the quality of reporting. The latter – the social vulnerability of the solution. Its growth worsens the final assessment, which is why it is possible to apply reverse normalization for it.

*Data sources:* For demonstration testing, data from metallurgical enterprises were used. The decisions of Interpipe Group, Metinvest and SSAB on decarbonization of production were considered. The choice of this industry is explained by its high carbon intensity and the availability of open ESG information. The information base of the research is open data of enterprises, corporate reports, ESG reports and public announcements of companies. Open sources have different completeness, therefore the assessment results are interpreted as analytical.

Formation of the primary indicator base assumed that for each decision an observation card was created with the name of the enterprise, the content of the decision, source, year and type of data. Next, the base included indicators that directly described the assessed decarbonization decision. After that, data from corporate reports, ESG reports and public information of companies were compared. In the absence of quantitative values, the indicator was converted into a scale score of 0–1.

The logic of scale coding: 0 – no evidence, 0.25 – fragmentary mention, 0.50 – basic description, 0.75 – detailed confirmation, 1.00 – quantitative or documented confirmation. For de-incentives, the value after coding was interpreted as the level of risk, and the reverse direction was used during normalization. An expert survey was used to determine the importance of indicators. Criteria for inciting experts: professional experience in performing ESG analysis, management; independence of judgment. It was proposed to evaluate the indicators on a scale from 1 to 10. After that, average values were calculated. All significant deviations of values from the average were checked for their reasoning, rather than mechanical removal from the sample.

The scenario coefficients were determined by gradually adjusting the basic ESG components. A value of 1.00 was taken as the base scenario. For the crisis scenario, the coefficients were reduced in accordance with the expected sensitivity of the decision to risks. For the decarbonization scenario, the environmental component could be strengthened if there was a suitable technological background or climatic relevance. The final coefficients were established after checking the content of the sources, the logic of the scenario and the limits of the 0–1 scale.

*The data processing algorithm* involves several successive stages. Forming a matrix of ESG indicators for selected management decisions. Bringing indicators to a common scale of measurement from 0 to 1. Calculation of the coefficient of information security, which shows the completeness of available data. Determination of indicator weights. Calculation of the basic ESG components of the management decision. Formation of several conditions (scenarios) for the implementation of the decision – basic, crisis and decarbonization. For each scenario, the weights of ESG components and the coefficients of change of the corresponding components are set. Assessment of the self-similarity of the ESG profile of the decision at the strategic, tactical and operational levels of management.

The final index of sustainability of the decision is formed as a product of three elements – the coefficient of completeness of ESG data; fractal coherence coefficient; weighted scenario ESG index.

A basic sustainability scale is used to interpret the results. A solution with a low value of the sustainability index is considered critical or unstable. A solution with an average value belongs to the acceptable level. A high sustainability index value indicates a solution's ability to maintain ESG performance under most scenarios.

*Limitation:* Results depend on the completeness, reliability and comparability of open ESG data. Part of the indicators can be presented through scale coding, and not as direct numerical values. Therefore, the final sustainability index should be interpreted as an analytical basis for comparing decisions. It should not be equated with the absolute ESG rating of enterprises.

### 3. Results and Discussion

#### 3.1. The structure of the method of scenario-fractal ESG-assessment of the sustainability of enterprise decisions

In conditions of uncertainty, when development trajectories are difficult to predict, the ability to make decisions that will ensure their acceptable effectiveness under various scenarios of development is a relevant managerial competence. In the context of ESG priorities, acceptable performance is the sustainability of management decisions. That is, the sustainability of a solution means its ability to maintain environmental, social, and managerial effectiveness under changing conditions. The method of scenario-fractal ESG assessment is designed to determine the sustainability of the company's management decisions. This method has three components:

- formation of a system of ESG indicators, namely: environmental, social and management indicators;

- generation of scenarios of conditions in which the management decision will be implemented;
- analysis of self-similarity (fractality) of ESG indicators at different management levels (strategic, tactical, operational).

In Fig. 1, the stages of the scenario-fractal ESG assessment of the sustainability of the company's decisions are specified within these components:

1. Formation of the ESG indicator system:
  - 1.1. Construction of the indicator matrix:

$$X = [x_{ij}], \quad i = 1, \dots, n, \quad j = 1, \dots, m, \tag{1}$$

where  $x_{ij}$  – the value of the  $j$ -th ESG indicator for the  $i$ -th management decision;  $n$  – the number of management decisions;  $m$  – the total number of ESG indicators.

ESG indicators should be presented as a combination of three sets

$$J = J_E \cup J_S \cup J_G, \tag{2}$$

where  $J$  – the total set of ESG indicators;  $J_E$  – the set of environmental indicators;  $J_S$  – the set of social indicators;  $J_G$  – the set of management indicators.

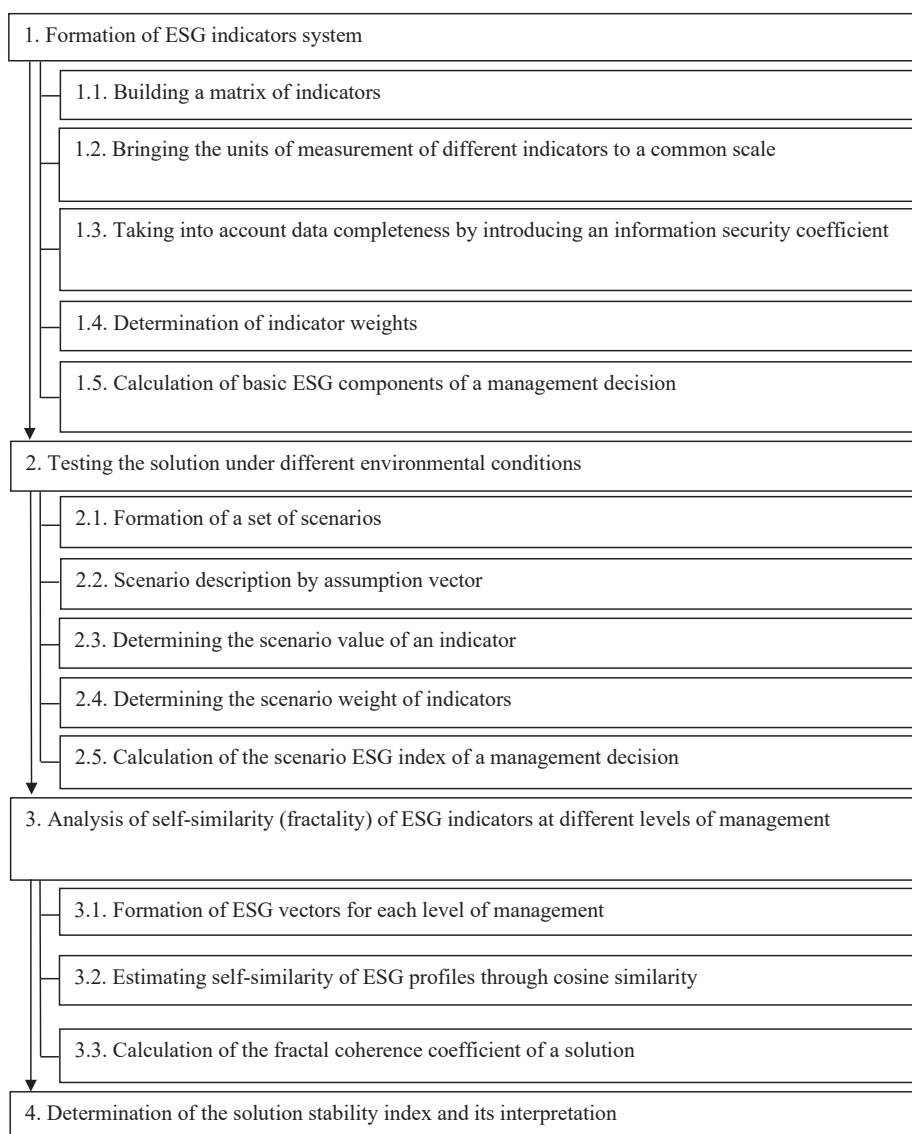


Fig. 1. Stages of scenario-fractal ESG assessment of sustainability of enterprise decisions

1.2. Conversion of the unit of measurement of different indicators to a common scale for stimulants and de-stimulants, respectively:

$$z_{ij} = \frac{x_{ij} - \min x_j}{\max x_j - \min x_j}, \quad z_{ij} = \frac{\max x_j - x_{ij}}{\max x_j - \min x_j}, \quad (3)$$

where  $z_{ij}$  – the normalized value of the  $j$ -th indicator for the  $i$ -th decision;  $x_{ij}$  – the actual value of the indicator;  $\min x_j$  – minimum value of the  $j$ -th indicator;  $\max x_j$  – maximum value of the  $j$ -th indicator.

A value close to 1 – the best position, a value close to 0 – a weak result.

1.3. Taking into account the completeness of data based on the calculation of the information security coefficient

$$C_i = \frac{a_i}{A}, \quad (4)$$

where  $C_i$  – completeness coefficient of ESG data for the  $i$ -th decision;  $a_i$  – number of available ESG indicators;  $A$  – total number of indicators in the methodology.

The  $C_i$  coefficient shows the reliability of the information base.

1.4. Determination of indicator weights. To achieve a high level of objectivity in determining weights, it is advisable to combine expert assessment and information value of data.

Equal weights can be used for preliminary testing

$$w_j^R = \frac{1}{m_b}, \quad (5)$$

where  $w_j^R$  – equal weight of the  $j$ -th indicator;  $m_b$  – number of indicators in the corresponding ESG component.

The expert assessment of the importance of an indicator is determined as follows

$$\bar{b}_j = \frac{1}{h} \sum_{a=1}^h b_{aj}, \quad (6)$$

where  $\bar{b}_j$  – the average expert assessment of the importance of the indicator;  $b_{aj}$  – the assessment of the  $j$ -th indicator by the  $a$ -th expert;  $h$  – the number of experts.

The normalized expert weight has the form

$$w_j^E = \frac{\bar{b}_j}{\sum_{j=1}^{m_b} \bar{b}_j}, \quad (7)$$

where  $w_j^E$  – the expert weight of the  $j$ -th indicator;  $\bar{b}_j$  – the average expert assessment of its importance;  $m_b$  – the number of indicators in the corresponding ESG component.

The objective weight is determined through entropy logic. It takes into account how much the indicator distinguishes the evaluated decisions. First, the fraction of the normalized value is calculated

$$p_{ij} = \frac{z_{ij}}{\sum_{i=1}^n z_{ij}}, \quad (8)$$

where  $p_{ij}$  – the fraction of the normalized value of the  $j$ -th indicator for the  $i$ -th decision;  $z_{ij}$  – the normalized value of the corresponding indicator;  $n$  – the number of management decisions.

The entropy of the indicator is determined as follows

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^n p_{ij} \ln p_{ij}, \quad (9)$$

where  $e_j$  – the entropy of the  $j$ -th indicator;  $p_{ij}$  – the fraction of the normalized value;  $n$  – the number of evaluated decisions.

If  $p_{ij} = 0$ , the following condition is accepted

$$p_{ij} \ln p_{ij} = 0. \quad (10)$$

The information utility of the indicator is determined by the formula

$$d_j = 1 - e_j, \quad (11)$$

where  $d_j$  – the information utility of the  $j$ -th indicator;  $e_j$  – the entropy of this indicator.

The objective weight of the indicator is calculated as follows

$$w_j^O = \frac{d_j}{\sum_{j=1}^{m_b} d_j}, \quad (12)$$

where  $w_j^O$  – objective weight of the  $j$ -th indicator;  $d_j$  – information utility of the indicator;  $m_b$  – number of indicators in the corresponding ESG component.

The combined weight of the indicator has the following form

$$w_j^C = \lambda w_j^E + (1 - \lambda) w_j^O, \quad (13)$$

where  $w_j^C$  – combined weight of the  $j$ -th indicator;  $w_j^E$  – expert weight of the indicator;  $w_j^O$  – objective weight of the indicator;  $\lambda$  – influence coefficient of the expert component.

The coefficient  $\lambda$  is set within the following limits

$$0 \leq \lambda \leq 1. \quad (14)$$

With a limited sample, it is advisable to increase the value of  $\lambda$ . If there is enough data, the objective component may play a greater role.

1.5. Calculation of basic ESG components of a management decision

$$E_i = \sum_{j=1}^{m_E} w_{Ej}^C z_{Eij}, \quad (15)$$

where  $E_i$  – environmental component of sustainability of the  $i$ -th decision;  $w_{Ej}^C$  – combined weight of the  $j$ -th environmental indicator;  $Z_{Eij}$  – normalized value of this indicator;  $m_E$  – number of environmental indicators.

$$S_i = \sum_{j=1}^{m_S} w_{Sj}^C z_{Sij}, \quad (16)$$

where  $S_i$  – social component of sustainability of the  $i$ -th decision;  $w_{Sj}^C$  – combined weight of the  $j$ -th social indicator;  $Z_{Sij}$  – normalized value of this indicator;  $m_S$  – number of social indicators.

$$G_i = \sum_{j=1}^{m_G} w_{Gj}^C z_{Gij}, \quad (17)$$

where  $G_i$  – management component of sustainability of the  $i$ -th decision;  $w_{Gj}^C$  – combined weight of the  $j$ -th management indicator;  $Z_{Gij}$  – normalized value of this indicator;  $m_G$  – number of management indicators.

2. Verification of the decision under different environmental conditions.

2.1. Formation of a set of scenarios

$$R = \{r_1, r_2, \dots, r_s, \dots, r_p\}, \quad (18)$$

where  $R$  – set of scenarios;  $r_s$  – separate scenario of the development of the external environment;  $p$  – total number of scenarios.

2.2. Description of scenarios by an assumption vector

$$r_s = (\delta_{1s}, \delta_{2s}, \dots, \delta_{js}, \dots, \delta_{ms}), \tag{19}$$

where  $r_s$  –  $s$ -th scenario;  $\delta_{js}$  – coefficient of change of the  $j$ -th ESG indicator;  $m$  – number of ESG indicators.

2.3. Determining the scenario value of an indicator

$$x_{ijs} = x_{ij} \cdot \delta_{js}, \tag{20}$$

where  $x_{ijs}$  – the value of the  $j$ -th indicator for the  $i$ -th decision in the  $s$ -th scenario;  $x_{ij}$  – the base value of this indicator;  $\delta_{js}$  – the scenario coefficient of change.

2.4. Determining the scenario weight of indicators

$$\tilde{w}_{js} = \frac{w_j^C \theta_{js}}{\sum_{j=1}^{m_b} w_j^C \theta_{js}}, \tag{21}$$

where  $\tilde{w}_{js}$  – the normalized scenario weight of the  $j$ -th indicator;  $w_j^C$  – the combined weight of the indicator;  $\theta_{js}$  – the scenario significance coefficient of the indicator;  $m_b$  – the number of indicators in the corresponding ESG component.

Conditions for the correspondence of scenario weights of ESG components

$$\alpha_s + \beta_s + \gamma_s = 1, \tag{22}$$

where  $\alpha_s, \beta_s, \gamma_s$  – the weights of the corresponding components in the  $s$ -th scenario.

2.5. Calculating the scenario ESG index of a management decision

$$I_{is} = \alpha_s E_{is} + \beta_s S_{is} + \gamma_s G_{is}, \tag{23}$$

where  $I_{is}$  – the ESG index of the  $i$ -th decision in the  $s$ -th scenario;  $E_{is}$  – the environmental assessment of the decision;  $S_{is}$  – the social assessment of the decision;  $G_{is}$  – management assessment of the decision;  $\alpha_s, \beta_s, \gamma_s$  – scenario weights of ESG components.

3. Analysis of self-similarity (fractality) of ESG indicators at different levels of management.

3.1. Formation of ESG vectors for each level of management

$$V_{il} = (E_{il}, S_{il}, G_{il}), \tag{24}$$

where  $V_{il}$  – the ESG vector of the  $i$ -th decision at the  $l$ -th level of management;  $E_{il}$  – the environmental component at this level;  $S_{il}$  – the social component at this level;  $G_{il}$  – the management component at this level.

3.2. Self-similarity of ESG profiles

$$\cos(V_{il}, V_{ir}) = \frac{E_{il}E_{ir} + S_{il}S_{ir} + G_{il}G_{ir}}{\sqrt{E_{il}^2 + S_{il}^2 + G_{il}^2} \cdot \sqrt{E_{ir}^2 + S_{ir}^2 + G_{ir}^2}}, \tag{25}$$

where  $\cos(V_{il}, V_{ir})$  – the similarity of ESG vectors at the  $l$ -th and  $r$ -th levels;  $E_{il}, S_{il}, G_{il}$  – the ESG components at the  $l$ -th level;  $E_{ir}, S_{ir}, G_{ir}$  – the ESG components at the  $E_{ir}$ -th level.

3.3. Measurement of fractal coherence of the decision

$$F_i = \frac{2}{q(q-1)} \sum_{l=1}^{q-1} \sum_{r=l+1}^q \cos(V_{il}, V_{ir}), \tag{26}$$

where  $F_i$  – the fractal coherence coefficient of the  $i$ -th decision;  $q$  – the number of management levels;  $V_{ir}$  – ESG-vector of the decision at the  $r$ -th level;  $\cos(V_{il}, V_{ir})$  – cosine similarity between ESG-vectors;  $V_{il0}$  – ESG-vector of the decision at the  $l$ -th level.

The coefficient  $F_i$ , which approaches indicates that the management levels have similar ESG-profiles. The lower the value, the more pronounced the gap between the declared goals and the actual implementation.

4. Determination of the index of sustainability of the decision

$$SSI_i^* = C_i \cdot F_i \cdot \sum_{s=1}^p \rho_s I_{is}, \tag{27}$$

where  $SSI_i^*$  – adjusted index of sustainability of the  $i$ -th management decision;  $C_i$  – coefficient of completeness of ESG-data;  $F_i$  – coefficient of fractal coherence;  $\rho_s$  – weight of the  $s$ -th scenario;  $I_{is}$  – scenario ESG-index of the decision;  $p$  – number of scenarios.

The weights of the scenarios must meet the condition

$$\sum_{s=1}^p \rho_s = 1, \tag{28}$$

where  $\rho_s$  – weight of the  $s$ -th scenario;  $p$  – number of scenarios.

The acceptable level of effectiveness is set through the threshold value

$$SSI_i^* \geq SSI_{\min},$$

where  $SSI_i^*$  – adjusted sustainability index of the management decision;  $SSI_{\min}$  – minimum permissible threshold value of the sustainability index.

Threshold values should be formed by combining normative, statistical and expert logic

$$T_h = \mu_h T_h^N + \nu_h T_h^S + \omega_h T_h^E, \tag{29}$$

where  $T_h$  – threshold value for the  $h$ -th sustainability level;  $T_h^N$  – normative threshold;  $T_h^E$  – expert threshold;  $T_h^S$  – statistical threshold;  $\mu_h, \nu_h, \omega_h$  – weights of approaches to forming the threshold.

The weights of the approaches must meet the condition

$$\mu_h + \nu_h + \omega_h = 1, \tag{30}$$

where  $\mu_h$  – weight of the normative component;  $\nu_h$  – weight of the statistical component;  $\omega_h$  – weight of the expert component.

For the initial interpretation, the basic scale can be used (Table 1). Its boundaries should be specified taking into account the industry, sample and data quality.

**Table 1**

Basic scale for interpreting the sustainability index of enterprise decisions

Value	Levels	Interpretation
$0.00 \leq SSI_i^* < 0.25$	Critical	High risk of loss of ESG performance
$0.25 \leq SSI_i^* < 0.50$	Unstable	Decision requires significant adjustment
$0.50 \leq SSI_i^* < 0.75$	Acceptable	Decision maintains basic sustainability under some scenarios
$0.75 \leq SSI_i^* < 1.00$	High	Decision demonstrates sustainability under most scenarios

**3.2. Application of scenario-fractal ESG assessment of sustainability of enterprise decisions and analysis of its results**

The scenario-fractal ESG assessment method was applied to compare the sustainability of management decisions in the metallurgical industry, which data on ESG indicators are publicly available. Let's consider specific management decisions of companies that are approximately the same in terms of activity. The first decision concerns the decarbonization trajectory of Interpipe Group [57]. The second decision is related to the transition of Metinvest to low-carbon steel production [58, 59]. The third decision reflects SSAB's program for fossil-free steel production [60, 61].

Table 2 presents the management decisions selected for the demonstration assessment. Interpipe’s decision has a strong factual basis. The 61% reduction in specific emissions already exceeds the 55% target associated with the European Green Deal. This result forms a strong environmental basis for the solution [57]. At the same time, this does not mean automatic superiority in all ESG components. The Metinvest solution has the highest long-term ambition.

The claimed emission reduction of more than 90% is the largest of the three solutions. However, the time horizon until 2050 creates a significant implementation risk. Therefore, this solution requires particularly careful scenario testing. The SSAB solution has the highest technological certainty. The transition to fossil-free mini-mills has a specific benchmark until around 2030. This strengthens the connection between the strategic goal, tactical actions and operational implementation.

The next step is to form a system of ESG indicators (Table 3). It covers environmental, social and governance components. Each component contains two indicators, which ensures comparability of the assessment structure. The system of indicators is not limited to environmental impact. This is important because a decarbonization solution can be strong environmentally, but weak socially or governance. The environmental component contains two different dimensions.  $E_1$  shows the scale of emission reduction.  $E_2$  shows how much the company has a technological basis for implementing the solution. It is the combination of these two indicators that reduces the risk of evaluating only declarations. The social component assesses the impact of the solution

on people and the stability of the transition.  $S_1$  is a stimulator, because higher manageability of the transition increases sustainability.  $S_2$  is a disincentive, because greater social vulnerability worsens the result. The management component is needed to check the credibility of the solution.  $G_1$  assesses the quality of ESG reporting.  $G_2$  shows the verifiability of ESG data. Without these indicators, a strong environmental statement may remain insufficiently evidential.

After the indicators were formed, their initial values were determined (Table 4). Some of the values are based on open quantitative data. Some are given through scale coding, since open sources do not always contain comparable numerical indicators. The values in Table 4 are of different nature. For Interpipe, the indicator  $E_1 = 61$  means that the reduction in specific emissions has already been achieved. This position confirms the current result, not the future intention. Metinvest has  $E_1 = 90$ , which is the highest value among the three solutions. At the same time, this indicator reflects the strategic goal until 2050. It is combined with a lower value  $E_2 = 0.55$ , which reflects the complexity of the current implementation. SSAB has a lower value  $E_1 = 48$ , but the highest value  $E_2 = 0.90$ , which indicates that the solution has a strong technological basis.

The transition to mini-mills and the use of fossil-free sponge iron support this assessment. Social assessments also differ. Interpipe has  $S_1 = 0.70$  and  $S_2 = 0.30$ , indicating a moderately managed transition. Metinvest has the highest social vulnerability  $S_2 = 0.70$ , which is related to the military and operational context. SSAB has the best social profile, as  $S_1 = 0.80$  and  $S_2 = 0.25$ .

**Table 2**

Management solutions selected for demonstration evaluation

Solution designation	Enterprises	Management decision content	Open evidence base
$i_1$	Interpipe Group	Accelerating decarbonization of pipe and rail production	61% reduction in specific CO <sub>2</sub> emissions for seamless pipes
$i_2$	Metinvest	Transition to low-carbon steel production	Target to reduce emissions by more than 90% by 2050
$i_3$	SSAB	Transition to fossil-free steel	Transformation of blast furnace system into fossil-free mini-mills by around 2030

**Note:** based on [57–61]

**Table 3**

System of indicators for evaluating solutions

Components	Indicators	Indicator types	Directions of influence	The logic of measurement
E	$E_1$ – level of decarbonization readiness	quantitative	stimulant	Percentage of emission reduction
E	$E_2$ – technological readiness	scale 0–1	stimulant	Availability of technological base, investments or energy support
S	$S_1$ – social manageability of the transition	scale 0–1	stimulant	Consideration of employees, safety, employment and adaptation of personnel
S	$S_2$ – social vulnerability of the decision	scale 0–1	destimulant	Risk of personnel, safety or social losses
G	$G_1$ – quality of ESG reporting	scale 0–1	stimulant	Level of standards, transparency and disclosure framework
G	$G_2$ – verifiability of ESG data	scale 0–1	stimulant	Availability of internal or external verification

**Table 4**

Initial values of indicators for the three solutions

Solution	$E_1$ , %	$E_2$	$S_1$	$S_2$	$G_1$	$G_2$	Coding explanation
$i_1$ , Interpipe	61	0.85	0.70	0.30	0.55	0.30	High actual progress but weaker external verifiability
$i_2$ , Metinvest	90	0.55	0.55	0.70	0.75	0.50	Very high ambition but significant military and operational vulnerability
$i_3$ , SSAB	48	0.90	0.80	0.25	0.90	0.80	High technological readiness and strong reporting infrastructure

Next, the indicators are normalized. This is needed to bring the different indicators to a scale from 0 to 1. For the stimulants, direct normalization (3) was used. For the  $S_2$  destimulant, inverse normalization (4) was used. Table 5 shows the normalized values of the ESG indicators.

A value of 1.000 indicates the best position in the sample, and 0.000 indicates the weakest position. Metinvest receives  $E_1 = 1.000$  because its stated level of commitment to decarbonization is the highest. Interpipe has  $E_1 = 0.310$  because 61% is between 48% and 90%. SSAB receives  $E_1 = 0.000$  because it has the lowest value for this indicator. The situation is different for technological readiness. SSAB receives  $E_2 = 1.000$ , Interpipe – 0.857, and Metinvest – 0.000. This shows that long-term ambition does not always mean the highest current readiness. In the social component, SSAB has the maximum values for both indicators. Interpipe also has a strong social position, because  $S_1 = 0.600$  and  $S_1 = 0.889$ . Metinvest receives zero values, which reflects the highest social vulnerability among the three solutions. After normalization, it is necessary to determine the weights of the indicators. For this, an expert research was performed. Its purpose was to establish the relative importance of the indicators for the metallurgical industry. Experts were required to have experience, professional specialization, and independence of judgment. To determine the weights, it is not mass, but relevant competence that is important. This is especially important for metallurgy, where ESG solutions have technological, social, and investment implications. A minimum experience of five years makes it possible to weed out random respondents. Industry awareness is required to understand production constraints. Functional specialization ensures the representation of all ESG components. The sample covered different macroregions of Ukraine. Kyiv, Lviv, Kyiv and Dnipropetrovsk regions are represented by the largest number of experts, with 13 experts, or over 50%. This is explained by the concentration of manage-

ment, consulting, and analytical centers. The survey was conducted in the form of a structured questionnaire. Experts rated the importance of each indicator on a scale from 1 to 10. Scores of 9–10 indicate a critically important role for the indicator. Scores of 7–8 indicate high importance. Scores of 5–6 indicate an average role for the indicator. In this example, the average scores range from 5.80 to 8.70.

Table 6 provides a justification for the representativeness of the expert sample.

The sample is representative for the targeted expert assessment.

Functional balance is ensured by the participation of specialists in ecology, social security, management and reporting. Regional diversity covers 10 territorial groups. This reduces the risk of regional bias in assessments.

Next, the average expert assessments (7) and the normalized expert weight (8) are calculated. Table 7 presents the results of the expert assessment.

The highest average expert score is  $E_1$ . It is 8.70 points. This means that experts consider decarbonization ambition to be a key environmental indicator.

After normalization, the weight of  $E_1$  is 0.600. The  $E_2$  indicator has 5.80 points and a weight of 0.400. The difference between them is 0.200 weight points. This shows the priority of the emission reduction goal over technological readiness.

In the social component,  $S_1$  has 7.70 points, and  $S_2$  has 6.30 points. The corresponding weights are 0.550 and 0.450. Therefore, the social manageability of the transition is slightly more important than social vulnerability. In the governance component,  $G_1$  and  $G_2$  have the same scores – 7.50 points. Therefore, their weights are the same and equal to 0.500. This means that the quality of reporting and the verifiability of ESG data are equivalent.

Table 5

Normalized values of the ESG indicators

Solution	$E_1$	$E_2$	$S_1$	$S_2$	$G_1$	$G_2$
$i_1$ , Interpipe	0.310	0.857	0.600	0.889	0.000	0.000
$i_2$ , Metinvest	1.000	0.000	0.000	0.000	0.571	0.400
$I_3$ , SSAB	0.000	1.000	1.000	1.000	1.000	1.000

Note: calculated by the authors based on data from [57–61]

Table 6

Justification for the representativeness of the expert sample

Signs of representativeness	As provided in the training approbation
Professional relevance	Experts related to ESG, industry or management
Functional balance	Environmental, social and management areas are represented
Regional diversity	Experts from different regions of Ukraine are included
Practical orientation	Some of the experts have experience in industry and consulting
Scientific and analytical component	Analytics and management specialists are included

Table 7

Results of the expert assessment

Components	Indicators	Average expert ratings $\bar{b}_j$	Sum of ratings in the component	Expert weights $w_j^E$
E	$E_1$	8.70	14.50	0.600
E	$E_2$	5.80	14.50	0.400
S	$S_1$	7.70	14.00	0.550
S	$S_2$	6.30	14.00	0.450
G	$G_1$	7.50	15.00	0.500
G	$G_2$	7.50	15.00	0.500

The distribution of expert assessments of the significance of ESG indicators is shown in Fig. 2.

The boxplot in Fig. 2 demonstrates the distribution of expert assessments of the importance of individual indicators. The highest median level is for indicator  $E_1$ , which is consistent with its average score of 8.70 points. The lowest position of the box is characteristic of  $E_2$ , which average score is 5.80 points. Management indicators  $G_1$  and  $G_2$  have close distributions, which confirms their equal average expert weight.

Entropy weights (9) and (10) are calculated separately, taking into account condition (11), and the information utility of the indicator (12) and its objective weight (13) are also determined

Table 8 shows entropy calculations.

Table 8 shows the information power of each indicator. In the environmental component,  $E_1$  has  $D_j = 0.502$ . For  $E_2$ , this value is 0.372.

Because of this, the objective weight of  $E_1$  is 0.574. The gap between the objective weights of  $E_1$  and  $E_2$  is 0.148. Therefore, the level of decarbonization readiness distinguishes decisions better than technological readiness.

This confirms the expert logic. In the social component,  $S_1$  has  $D_j = 0.398$ , and  $S_2 = 0.371$ . The difference is only 0.027. Therefore, the objective weights are very close: 0.518 and 0.482. In the management component,  $G_2$  has a greater information utility than  $G_1$ . The  $D_j$  value is 0.455 versus 0.403. Therefore, the verifiability of ESG data receives a higher objective weight – 0.530.

After that, combined weights (14) were formed. In this case,  $\lambda = 0.5$  was taken. This means an equal role of the expert and entropy components.

Table 9 presents the combined weights of ESG indicators.

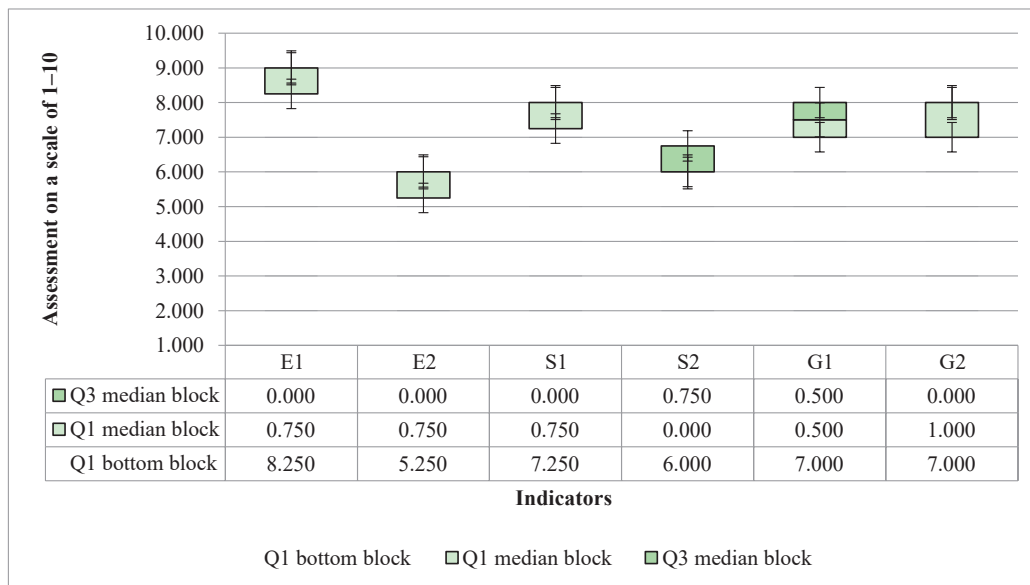


Fig. 2. Boxplot of expert assessments of the importance of ESG indicators (constructed on the basis of individual expert assessments, which accurately reproduces the average values of Table 7 ( $E_1 = 8.70$ ;  $E_2 = 5.80$ ;  $S_1 = 7.70$ ;  $S_2 = 6.30$ ;  $G_1 = 7.50$ ;  $G_2 = 7.50$ ); the original individual assessments are not given in the manuscript, therefore, if actual questionnaire data are available, this figure should be clarified)

Table 8

Entropy calculations

Components	Indicators	$\sum z_{ij}$	$e_j$	$D_j = 1 - e_j$	Objective weights $w_j^o$
E	$E_1$	1.310	0.498	0.502	0.574
E	$E_2$	1.857	0.628	0.372	0.426
S	$S_1$	1.600	0.602	0.398	0.518
S	$S_2$	1.889	0.629	0.371	0.482
G	$G_1$	1.571	0.597	0.403	0.470
G	$G_2$	1.400	0.545	0.455	0.530

Table 9

Combined weights of ESG indicators

Components	Indicators	Expert weights $w_j^E$	Objective weights $w_j^o$	$\lambda$	Combined weights $w_j^C$
E	$E_1$	0.600	0.574	0.5	0.587
E	$E_2$	0.400	0.426	0.5	0.413
S	$S_1$	0.550	0.518	0.5	0.534
S	$S_2$	0.450	0.482	0.5	0.466
G	$G_1$	0.500	0.470	0.5	0.485
G	$G_2$	0.500	0.530	0.5	0.515

As can be seen from Table 9, the final weights are not arbitrary. They combine professional judgment and the informational usefulness of the actual data. It is precisely such weights that correspond to the logic of the method. For  $E_1$ , the combined weight is 0.587. For  $E_2$ , it is 0.413. The difference of 0.174 shows that the environmental component depends more on the scale of the decarbonization ambition. For the social component,  $S_1 = 0.534$ , and  $S_2 = 0.466$ . The advantage of the manageability of the transition is 0.068. For the management component,  $G_2 = 0.515$ , which is 0.030 more than  $G_1$ . This strengthens the value of the verifiability of ESG data.

After determining the weights, the basic ESG components (16)–(18) were calculated, Table 10.

Table 10

Basic ESG components of management decisions

Solution	$E_i$	$S_i$	$G_i$	Comments
$i_1$ , Interpipe	0.536	0.735	0.000	Strong social and environmental profile, but weak governance
$i_2$ , Metinvest	0.587	0.000	0.483	High decarbonization commitment, but social vulnerability
$i_3$ , SSAB	0.413	1.000	1.000	Strongest social and governance profile

Table 10 shows the transition from individual indicators to the three ESG components. Interpipe has  $E_i = 0.536$ . This is formed from a lower  $E_1 = 0.310$  and a high  $E_2 = 0.857$ . Technological readiness partially compensates for the lower normalized ambition. Metinvest has the highest environmental component  $E_i = 0.587$ . This is explained by the maximum value of  $E_1 = 1.000$ . At the same time,  $E_2 = 0.000$ , so the environmental advantage is not absolute. SSAB has  $E_i = 0.413$ , but receives maximum values for the social and governance components.  $S_i = 1.000$  and  $G_i = 1.000$ . This means that its solution is the most balanced in terms of social and governance conditions.

Fig. 3 shows the comparative baseline ESG solutions.

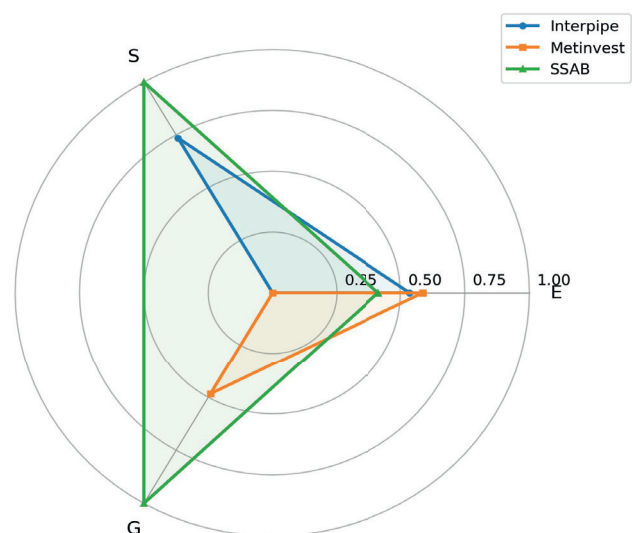


Fig. 3. Radar plot of basic ESG solutions (based on Table 10;  $E$ ,  $S$  and  $G$  are the basic ESG components of management solutions)

Fig. 3 shows that the basic ESG solutions are asymmetric. Interpipe has relatively strong environmental and social components, but has zero management component. Metinvest has the highest environmental component, but its social component is zero. SSAB demonstrates the most balanced profile due to the combination of strong social and management components.

The next stage is scenario assessment. It is needed to check whether the solution remains effective under different conditions. Table 11 shows the scenario assumptions.

Table 11

Scenario assumptions

Scenario	Scenario content	Component weights $\alpha_s; \beta_s; \gamma_s$	Validity $\rho_s$
$r_1$	Basic conditions for implementing the solution	0.333; 0.333; 0.334	0.40
$r_2$	Crisis conditions, increased military, personnel and financial risks	0.250; 0.350; 0.400	0.30
$r_3$	Decarbonization pressure, increased requirements for emissions and transparency	0.500; 0.250; 0.250	0.30

The baseline scenario has almost equal weights for the ESG components. This provides a neutral basis for comparison. In the crisis scenario, the social and governance components together have a weight of 0.750. Thus, under adverse conditions, the sustainability of the solution mainly depends on manageability and social sustainability. In the decarbonization scenario, the environmental component has a weight of 0.500. This is twice the weight of each other component. This structure reflects the strengthening of climate regulation and market requirements for steel.

The scenario ESG components are defined through the coefficients of change (21). Table 12 presents the scenario coefficients of change for the ESG components.

Table 12

Scenario coefficients of change for the ESG components

Solution	Scenario	$\delta_E$	$\delta_S$	$\delta_G$	Justification
$i_1$	$r_1$	1.00	1.00	1.00	The current trajectory is saved
$i_1$	$r_2$	0.95	0.90	0.95	Crisis conditions reduce the pace of implementation
$i_1$	$r_3$	1.08	1.00	1.00	Climatic pressure reinforces the importance of the progress made
$i_2$	$r_1$	1.00	1.00	1.00	The long-term strategy is maintained
$i_2$	$r_2$	0.80	0.75	0.90	Military risks have the strongest impact on implementation
$i_2$	$r_3$	1.10	1.00	1.00	High ambition manifests itself better under climatic pressure
$i_3$	$r_1$	1.00	1.00	1.00	The current trajectory is saved
$i_3$	$r_2$	0.96	0.95	0.98	The crisis impact is lower due to a stronger institutional base
$i_3$	$r_3$	1.12	1.00	1.00	The decarbonization scenario reinforces the solution's strengths

Table 12 shows that the scenarios change not only the component weights, but also the ESG components themselves. This is consistent with the logic of the method. The largest crisis reduction is given for Metinvest. For Metinvest in the crisis scenario  $\delta_E = 0.80$ ,  $\delta_S = 0.75$ ,  $\delta_G = 0.90$ . This is the strongest reduction among the three solutions. It reflects a higher sensitivity to military and operational risks. For SSAB, the crisis coefficients are higher. They are 0.96, 0.95, 0.98. This means a lower sensitivity to the crisis scenario. In the decarbonization scenario, SSAB has  $\delta_E = 1.12$ , which is the highest environmental gain.

The scenario ESG index is determined by formula (24), Table 13.

Table 13

Results of the scenario ESG assessment

Solution	$I_{i_1}$ , baseline	$I_{i_2}$ , crisis	$I_{i_3}$ , decarbonization	$\sum \rho_s I_{is}$
$i_1$ , Interpipe	0.423	0.355	0.474	0.418
$i_2$ , Metinvest	0.357	0.280	0.444	0.361
$i_3$ , SSAB	0.804	0.833	0.781	0.806

Table 13 shows the scenario sustainability of solutions. SSAB has the highest result in all scenarios. The baseline sustainability index is 0.804. In the crisis scenario, it increases to 0.833 due to the high role of the social and governance component. Interpipe has a baseline sustainability index of 0.423. In the crisis scenario, it decreases to 0.355. The drop is 0.068 points. In the decarbonization scenario, the sustainability index increases to 0.474, i. e. by 0.051 compared to the baseline level. Metinvest has a baseline sustainability index of 0.357. In the crisis scenario, it decreases to 0.280. The drop is 0.077 points. In the decarbonization scenario, the sustainability index increases to 0.444, which confirms the strength of the long-term environmental ambition. SSAB's weighted scenario sustainability index is 0.806. This is almost twice as much as Interpipe, where the value is 0.418. SSAB's advantage over Metinvest is 0.445 points.

Fig. 4 shows a graphical interpretation of the scenario sensitivity of ESG indices.

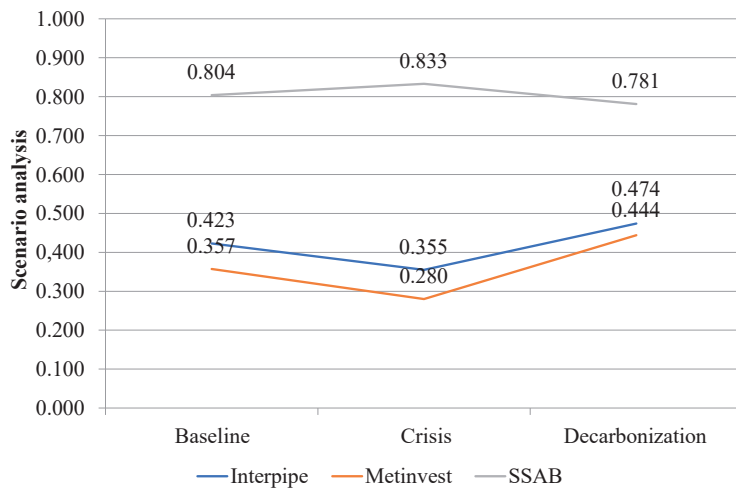


Fig. 4. Sensitivity diagram of scenario ESG indicators (constructed according to the data in Tables 11–13; summarized by the authors based on open data of enterprises and the authors' calculations according to sources [57–61])

As can be seen from Fig. 4, the SSAB solution demonstrates the highest scenario ESG indicators in all three scenarios. Its values are 0.804 in the baseline, 0.833 in the crisis and 0.781 in the decarbonization scenario. For Interpipe and Metinvest, a significantly lower level of indicators is observed. Both solutions are more sensitive to the crisis scenario.

The deviations of the scenario ESG indices from the baseline are shown in Fig. 5.

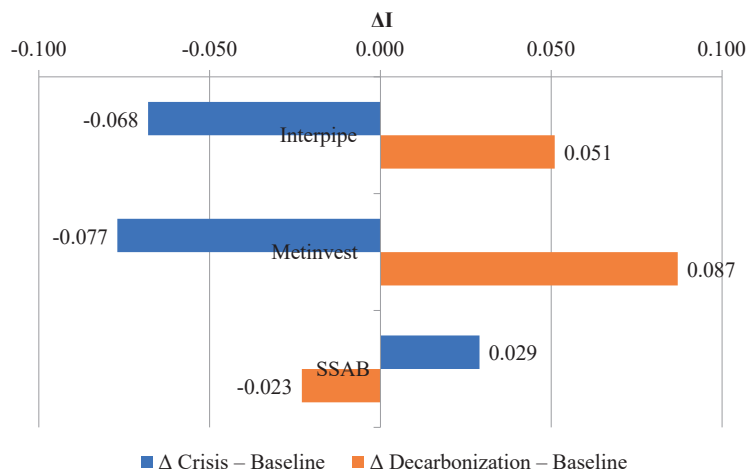


Fig. 5. Sensitivity diagram of deviations from the baseline scenario (constructed according to the data of Table 13; the deviation is defined by the authors as the difference between the crisis or decarbonization scenario and the baseline scenario)

The diagram above reflects the direction and magnitude of the change in the scenario ESG indicator relative to the baseline scenario. The largest decrease in the crisis scenario is for Metinvest, where the change is  $-0.077$ . For Interpipe, the decrease is  $-0.068$ . In the decarbonization scenario, the largest increase is for Metinvest, which confirms the strength of its decarbonization component.

Next, it is possible to perform the fractal part of the method. It shows the self-similarity of the ESG profile of the decision at the strategic, tactical and operational levels (25).

Table 14 shows the ESG vectors of management decisions. The strategic level reflects the declared ESG logic of the decision. The tactical level shows programs, tools and organizational actions. The operational level is built on the basic ESG components from Table 14.

Table 14

ESG vectors of management decisions

Decision	Strategic level	Tactical level	Operational level
$i_1$ , Interpipe	0.80; 0.65; 0.45	0.75; 0.70; 0.40	0.536; 0.735; 0.000
$i_2$ , Metinvest	0.90; 0.60; 0.70	0.65; 0.45; 0.60	0.587; 0.000; 0.483
$i_3$ , SSAB	0.95; 0.85; 0.90	0.90; 0.80; 0.90	0.413; 1.000; 1.000

For Interpipe, the strategic vector is (0.80; 0.65; 0.45). The operational vector is (0.536; 0.735; 0.000). The largest gap occurs in the management component, which decreases from 0.45 to 0.000. For Metinvest, the strategic vector is (0.90; 0.60; 0.70). The operational vector is (0.587; 0.000; 0.483). The largest gap concerns the social component, which decreases to 0.000. For SSAB, the strategic and tactical vectors are very close. The strategic vector is (0.95; 0.85; 0.90). The tactical vector is (0.90; 0.80; 0.90). This indicates a consistency between goals and instruments.

The cosine similarity is determined by formula (26), and the fractal coherence coefficient by (27).

Table 15 shows the calculation of fractal coherence.

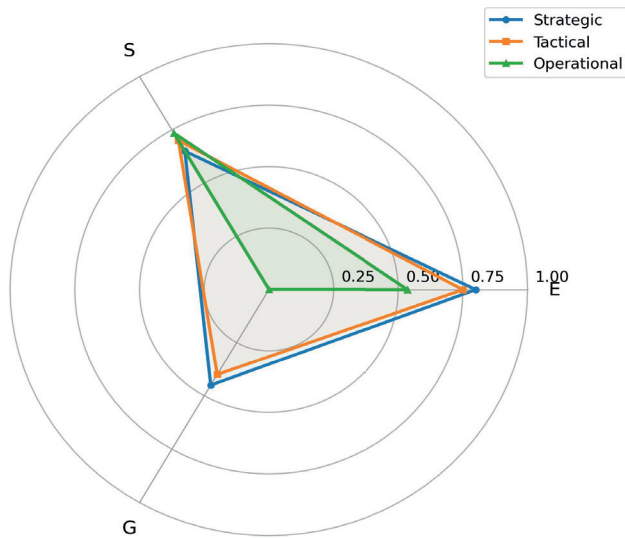
Table 15

Calculation of fractal coherence

Decision	Strategic-tactical	Strategic-operational	Tactical-operational	$F_i$
$i_1$ , Interpipe	0.998	0.877	0.901	0.925
$i_2$ , Metinvest	0.996	0.913	0.937	0.949
$i_3$ , SSAB	1.000	0.909	0.919	0.943

Table 15 shows how similar the ESG profiles are at different levels. For Interpipe, the strategic-tactical similarity is 0.998. However, the strategic-operational similarity drops to 0.877. The reason is the zero operational management component. Metinvest has the highest  $F_i = 0.949$ . The strategic-tactical similarity is 0.996. The tactical-operational similarity is 0.937. Despite the weak social component, the shape of the ESG profile remains quite similar. SSAB has  $F_i = 0.943$ . The strategic-tactical similarity is 1.000. This means almost complete correspondence between strategic vision and tactical actions. The operational environmental component lowers the average value. The difference between the highest  $F_i$  of Metinvest and the lowest  $F_i$  of Interpipe is 0.024. This is a small gap. Therefore, the fractal component does not change the rating radically, but rather refines the scenario results.

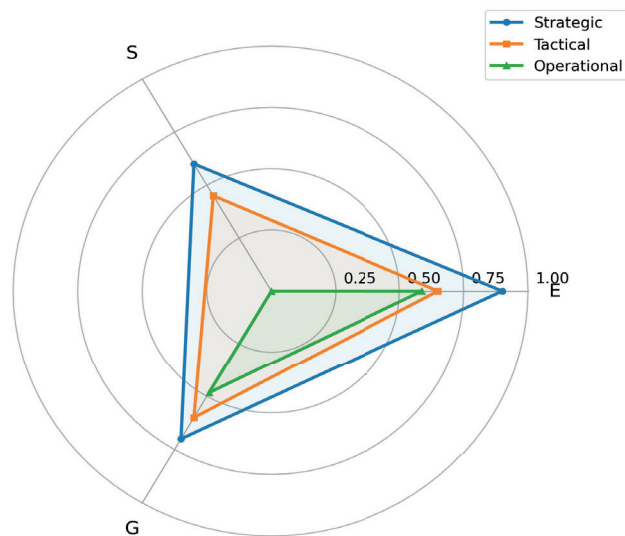
Fig. 6 shows the self-similarity of Interpipe's ESG solutions at different levels of management.



**Fig. 6.** Radar plot of Interpipe ESG solutions by management levels (constructed according to the data in Tables 14–15; management levels reflect the strategic, tactical and operational profiles of the solution; the fractal coherence coefficient is  $F_i = 0.925$ )

As can be seen from Fig. 6, for Interpipe the strategic and tactical levels are close to each other. At the same time, at the operational level, a noticeable gap appears in the G component, which decreases to 0.000. It is this gap that explains the need to strengthen the managerial provability of the solution.

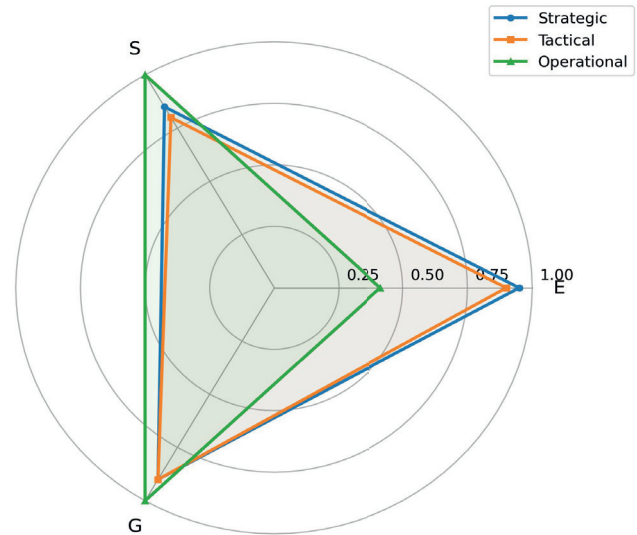
The self-similarity of Metinvest ESG solutions at different management levels is shown in Fig. 7.



**Fig. 7.** Radar plot of ESG-Metinvest solution by management levels (constructed according to the data of Table 14–15; management levels reflect the strategic, tactical and operational profiles of the solution; the fractal coherence coefficient is  $F_i = 0.949$ )

As shown in Fig. 7, the Metinvest solution retains a fairly close configuration of the strategic, tactical and operational profiles. At the same time, the failure of the social component at the operational level is clearly visible. This explains the instability of the solution due to the conditions of its practical implementation.

The self-similarity of the ESG-profiles of the SSAB solution at different management levels is shown in Fig. 8.



**Fig. 8.** Radar plot of SSAB ESG solutions by management levels (constructed according to the data of Tables 14–15; management levels reflect the strategic, tactical and operational profiles of the solution; the fractal coherence coefficient is  $F_i = 0.943$ )

Fig. 8 confirms the high level of coherence of SSAB's ESG logic at different management levels. The strategic and tactical profiles almost coincide. The operational profile has a lower environmental component, but retains strong social and management components.

Table 16 shows the assessment of data completeness, which is performed according to formula (5).

**Table 16**

Data completeness assessment				
Solution	Indicators $A$ provided	Indicators $a_i$ available	$C_i$	Comments
$i_1$ , Interpipe	6	6	1.000	All six indicators are filled with direct or coded open data
$i_2$ , Metinvest	6	6	1.000	All six indicators are filled with direct or coded open data
$i_3$ , SSAB	6	6	1.000	All six indicators are filled with direct or coded open data

Formally, all six indicators are available for all solutions. Therefore,  $C_i = 1.000$  for each solution. This means the same completeness of the data. At the same time, the equality of  $C_i$  does not mean the same quality of information. For example,  $E_1$  has a quantitative percentage value. Instead,  $G_2$  is estimated through scale coding. Therefore, the results should be interpreted as a training analytical approbation.

The final index of the stability of the solution (28) is given in Table 17.

**Table 17**

Summary calculation					
Solution	$C_i$	$F_i$	Weighted scenario sustainability indices	$SSI_i^*$	Sustainability levels
$i_1$ , Interpipe	1.000	0.925	0.418	0.387	Unsustainable
$i_2$ , Metinvest	1.000	0.949	0.361	0.343	Unsustainable
$i_3$ , SSAB	1.000	0.943	0.806	0.760	High

The conducted researches showed that the highest sustainability is achieved by the SSAB solution. Its weighted scenario sustainability index is 0.806. After multiplying by  $F_i = 0.943$ , let's obtain  $SSI'_i = 0.760$ . Interpipe has a weighted scenario sustainability index of 0.418. After taking into account  $F_i = 0.925$ , the final sustainability index is 0.387. Therefore, fractal consistency supports the result, but does not bring the solution to an acceptable level. Metinvest has a weighted scenario sustainability index of 0.361. After multiplying by  $F_i = 0.949$ , let's obtain 0.343. High fractal consistency does not compensate for the weaker scenario performance. The main reason is the zero social component in the basic profile. The difference between SSAB and Interpipe is 0.373 points. The difference between SSAB and Metinvest is 0.417 points. This confirms the significant advantage of SSAB in terms of integral sustainability of the solution.

Table 18 provides the management interpretation of the results.

Table 18

Management Interpretation of the Results

Solutions	Strengths	Weaknesses	Management conclusions
$i_1$ , Interpipe	High actual progress on decarbonization	Insufficient verification of ESG data	It is advisable to strengthen independent verification and formalize ESG control
$i_2$ , Metinvest	Significant strategic ambition on decarbonization	High social and operational vulnerability	It is necessary to combine green modernization with occupational safety and personnel stability
$i_3$ , SSAB	Coherence of strategy, tactics and operational profile	Dependence on large-scale investments and technological implementation	The solution has a high level of sustainability, but requires control of implementation deadlines

Thus, the proposed method gives both a numerical result and makes it possible to identify the weaknesses of solutions. For Interpipe, the main problem is managerial provability. For Metinvest, it is social and operational vulnerability. For SSAB, it is dependence on large-scale technological implementation. Interpipe does not have a critical environmental problem. On the contrary, the solution has a strong factual decarbonization basis. However,  $G_i = 0.000$  significantly reduces the final sustainability index. Therefore, strengthening the verifiability of ESG data is a priority. Metinvest has a strong strategic ambition. However,  $SSI'_i = 0.343$  shows an unstable level. This means that the strategic goal requires strengthening the implementation base. Occupational safety, personnel stability and reducing social vulnerability are especially important. SSAB has the best integral position. The value  $SSI'_i = 0.760$  exceeds the high-level threshold by 0.010. The margin is small, so the solution requires control of investments, timing and technological implementation.

The example uses six indicators, two normalization methods, expert weights, entropy weights and combined weights. Three scenarios and coefficients of change of ESG components are also given. This ensures the full implementation of the scenario block.

The fractal part is also implemented quantitatively. Three ESG vectors are constructed for each solution. Then, pairwise cosine similarity and the  $F_i$  coefficient are calculated. Therefore, fractality here has not a declarative, but a mathematical reflection.

Thus, scenario-fractal ESG assessment allows comparing the sustainability of similar management solutions. The first dimension of the assessment covers the basic ESG profile. The second dimension shows scenario sustainability. The third dimension reflects the self-similarity of ESG logic at different levels of management.

In the example given, the most sustainable is the SSAB solution.

Its sustainability index is 0.760. The Interpipe solution has significant environmental potential, but requires strengthening of management evidence. Metinvest's solution has high strategic ambition, but remains sensitive to crisis conditions.

### 3.3. Discussion of the research results

Sustainability means the ability of a solution to maintain its effectiveness under changing conditions. The sustainability of a management solution should be assessed based on the sustainability indices of the basic ESG profile, taking into account scenario sustainability and fractal coherence. The highest final sustainability index was obtained by the SSAB solution, which, better than the solutions of other enterprises, maintains ESG performance in the basic, crisis and decarbonization scenarios. SSAB's high result is not due only to the environmental component, but also to the social and managerial ones. They ensured the high scenario sustainability of the solution. The Interpipe solution turned out to have environmental potential, but requires stronger ESG confirmation. The weak point of the Metinvest solution was identified not in the decarbonization ambition, but in the conditions of its implementation. The fractal component did not radically change the results of the solution analysis. It showed the nature of the gaps between the levels of management. In addition, fractality does not duplicate the ESG index. It shows the inter-level consistency of the management decision. The results obtained are analytical, not rating in nature. They should not be identified with the official ESG rating of enterprises.

The method assesses the sustainability of specific management decisions. The first limitation is related to open data. The research used corporate reports, ESG reports and public announcements of companies. Such sources have different completeness, structure and level of detail. The values of the indicators are presented through scale coding. At the same time, completeness does not equal quality. A direct percentage value has a different evidentiary value than a scale assessment. The second limitation concerns the comparability of companies. For correctness, one industry was chosen – metallurgy. However, even within the same industry, enterprises differ in technologies, assets and operating conditions, including those caused by war. The third limitation is related to scenario coefficients that reflect analytical assumptions regarding changes in ESG components. These coefficients show the strongest crisis sensitivity among alternative solutions. However, it is advisable to refine them on a broader empirical basis. The fourth limitation concerns the expert block. The research used a targeted expert sample. It is representative of the methodological task, but is not a mass sociological survey. The fifth limitation is related to the fractal part. ESG vectors partly depend on the interpretation of open data. Cosine similarity provides a mathematical estimate of self-similarity. However, the quality of this estimate depends on the correctness of the formation of vectors. The results are also sensitive to weights and threshold values. Changing the weights affects the final sustainability indices. In turn, the base scale requires clarification of the boundaries for specific industries, which is necessary to reduce the risk of mechanical interpretation of the results. Therefore, the method is useful for comparative analysis of management decisions under conditions of data quality, scenario assumptions and correctness of weights.

The proposed method differs from traditional ESG assessment methods in that it is not a simple combination of environmental, social and management indicators that characterize the enterprise from the position of ESG priorities or activities. In this research, the unit of analysis is the management decision itself. An enterprise may have strong ESG reporting, but individual decisions may be unstable. The opposite situation is also possible. In the proposed method, the matrix part structures the indicators by components:  $E, S, G$ . The method then provides for scenario and fractal testing. Compared to classical scenario analysis, this method assumes that scenarios adjust ESG indicators and component weights. In addition, in most ESG assessment methods,

management levels are not compared through the fractality of the profile. In this method, management levels are presented as ESG vectors, the fractality of which is determined through the cosine measure. This allows to identify discrepancies between the stated ESG goals and the actual decisions to achieve them. Compared to methods where weights are set only by experts, this method is more balanced. It combines expert and entropy weights. At the same time, the method does not deny traditional ESG indicators, but uses them as a basis. Despite this, it provides a transparent way to summarize indicators, verify data and interpret results. Thus, the method transfers the analysis from the level of the overall rating of the company to the level of sustainability of the decision. This allows to more accurately identify strengths, weaknesses and conditions for maintaining performance.

The practical significance of the proposed method allows assessing the instability of a specific management decision. This is important for enterprises that implement management decisions in conditions of uncertainty. The practical application of the results is possible in corporate ESG analysis, strategic planning, preparation of ESG reporting, assessment of decarbonization projects and selection of modernization priorities.

The method is advisable to apply under several conditions. First, the compared solutions should belong to the same industry or to areas of activity that are close in terms of implementation. Second, enterprises should have available open or internal data on environmental, social and management indicators. Third, the assessment should take into account the scenarios of the solution implementation that reflect the basic, crisis and regulatory enhanced conditions. Fourth, it is advisable to check the consistency of the ESG logic of the solution at the strategic, tactical and operational levels of management.

The results obtained can be used by enterprise managers to identify weaknesses in management decisions. ESG analysts can use the method to quantitatively compare alternatives and verify the evidence base of ESG data. Investors can use the results to pre-assess the sustainability of decarbonization initiatives. Consulting organizations can use the method when preparing recommendations for increasing the scenario sustainability of solutions. As part of the testing, this is confirmed by the fact that SSAB's solution received a final sustainability index of 0.760, while Interpipe's – 0.387, and Metinvest's – 0.343. Therefore, the method not only ranks the alternatives, but also explains the reasons for the differences between them.

The application of the method has certain limitations. The results depend on the completeness, reliability and comparability of ESG data. This is especially important when using open corporate reporting. Some indicators may be missing or presented using different methodologies.

The resulting sustainability index should be interpreted as an analytical basis for comparing solutions. It should not be identified with an absolute ESG rating. The most correct is to apply the method to enterprises in the same industry, as well as enterprises of approximately the same scale. This reduces the risk of distortion of results due to a different structure of ESG indicators. Prospects for further research are associated with expanding the empirical base and testing the method on enterprises in other industries. It is advisable to deepen the system of indicators, in particular by including financial, innovation, energy and security parameters. The procedure for determining scenario coefficients requires separate development, since they significantly affect the final sustainability indices. Further research can also be aimed at reducing the risk of mechanical interpretation of the results obtained. A promising direction is the automation of scenario-fractal ESG assessment. The success of its development depends on how much digital analytics will take into account the industry specifics of enterprises. The key issue is also the permanence of data updating and the formation of interactive ESG profiles. Automated assessment should be combined with expert review, as some ESG indicators rely on qualitative analysis.

Further combination of quantitative calculations, scenario analysis and expert judgment can increase the reliability of the assessment of the sustainability of management decisions.

#### 4. Conclusions

1. It is substantiated that the eclecticism of three dimensions – basic ESG profile, scenario sustainability and fractal coherence – generates a new method of scenario-fractal ESG assessment of management decisions of enterprises. ESG profile, which includes environmental, social and management indicators, is relatively traditional. However, if the values of the indicators are normalized, weighted and checked by scenarios and for signs of fractality, this makes it possible to assess the current effectiveness of the decision. It also allows to take into account the market behavior of the business entity under changing conditions.

Based on the results of specifying the essence of the scenario-fractal ESG assessment method, its content, purpose and logic of application were clarified. The scenario-fractal ESG assessment method can be considered as a tool for in-depth diagnostics of the sustainability of management decisions. This method should be used not for the general characteristics of the enterprise, but for assessing the sustainability of a specific management decision. The proposed method combines quantitative calculation, scenario thinking and analysis of the internal consistency of the decision. The object of assessment is not the general ESG position of the enterprise, but a separate management decision. The method combines a number of ESG indicators, normalization vectors, expert-entropy weighting, various implementation scenarios and levels of management fractality. Unlike existing ones, the proposed method takes into account the coefficients of data completeness and fractal consistency, which makes it possible to take into account the provability of information, scenario stability and self-similarity of the ESG decision.

The method involves the transition from individual ESG indicators to an adjusted decision sustainability index. This sustainability index combines a weighted scenario ESG index, a coefficient of data completeness and fractal consistency. Such integration makes it possible to determine the final level of sustainability, as well as explain the sources of its strengthening or weakening.

2. The application of the developed method to assess the decisions of such enterprises as: Interpipe, Metinvest and SSAB showed that the method allows both to rank the decisions and to interpret the reasons for their sustainability or unsustainability. Sustainability is formed when the environmental goal is supported by social governance, managerial evidence and consistency between the levels of implementation. Therefore, high environmental ambition in itself does not guarantee a strong result. Thus, Interpipe, Metinvest and SSAB showed a different nature of their sustainability. The balance between ESG components, scenario endurance and inter-level consistency of implementation is crucial for sustainability.

Quantitative calculations confirmed the superiority of SSAB's decision. Its weighted scenario ESG index was 0.806, while for Interpipe this indicator was 0.418, and for Metinvest – 0.361. Taking into account fractal coherence showed that the sustainability index of SSAB's solution was 0.760, which corresponds to a high level. For Interpipe, the value was 0.387, and for Metinvest, it was 0.343, which corresponds to an unsustainable level.

In the baseline scenario, SSAB's sustainability index was 0.804, in the crisis scenario – 0.833, and in the decarbonization scenario – 0.781. This indicates the ability of the solution to maintain ESG performance even with changes in the weights of each of the ESG components.

The results also showed the different nature of the weaknesses of the solutions. For Interpipe, the key constraint was managerial evidence. For Metinvest, the main limiting factor was the social component. For SSAB, the social and managerial components were the highest, equal to 1.000, which explains its overall advantage.

The fractal part did not change the scenario results. The fractal coherence coefficient was 0.925 for Interpipe, 0.949 for Metinvest and 0.943 for SSAB. This shows that all three solutions have relatively high cross-level similarity of ESG profiles, however, the final consistency depends not only on the shape of the profile but also on the level of underlying ESG components and scenario resilience.

### Conflict of interest

The authors declare that they have no conflict of interest in connection with the current research, including financial, personal, authorial or any other that could influence the research and the results presented in this paper.

### Financing

The research was conducted without financial support.

### Data availability

All data are available in the main text of the manuscript.

### Use of artificial intelligence

The authors confirm that no artificial intelligence technologies were used in the creation of the current paper.

### Authors' contributions

**Oleh Kniaz:** Conceptualization, Methodology, Verification, Project administration; **Petro Pererva:** Investigation, Resources, Data curation, Supervision; **Ihor Franiv:** Writing – review and editing; **Roman Rusyn-Hrynyk:** Software, Visualization; **Kateryna Pelekh:** Formal analysis, Writing – original draft.

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