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COMPOSITE ASSESSMENT OF THE ECONOMIC PERFORMANCE OF CIRCULAR TRANSFORMATION PERFORMANCE IN INDUSTRIAL ENTERPRISES IN THE ECONOMY – ENVIRONMENT – SOCIETY DIMENSION

The object of research is the economic effectiveness of the processes of circular transformation of industrial enterprises. The problem lies in the absence of an integrated enterprise-level approach that would make it possible to identify of inter-block imbalances, ensure analytical consistency of indicators, and strengthen the basis for managerial decision-making.

The paper provides a comprehensive assessment of circular transformation performance in industrial enterprises in the economy – environment – society dimension.

A composite CEI-360 index is proposed, combining a harmonized system of indicators, fixed min-max normalization, block weighting, and aggregation with limited inter-block compensability. In addition, a structural-balance coefficient is introduced to distinguish the overall level of effectiveness from the consistency of change across the economic, environmental, and social dimensions.

The empirical basis is panel data for five Ukrainian industrial enterprises from different industries for 2015–2025 using scenario modeling for 2026–2030. The results showed growth in 2015–2021, a systemic decline in 2022 (–15.7%) and a further differentiated recovery in 2023–2025 exceeding the 2021 level. The scenario analysis confirmed the stable advantage of the circular-cluster development trajectory over the inertial one (up to +0.108 CEI-360 points in 2030).

The originality of the research lies in the development of an integrated tool for assessing circular transformation performance with explicit consideration of structural consistency across dimensions. The practical significance of the findings lies in using the framework for strategic diagnostics, benchmarking, monitoring of dynamics, and substantiating managerial decisions on the priorities of circular enterprise development.

Keywords: *circular transformation, economic performance, economic development, innovation potential, enterprise competitiveness, digitalization.*

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1. Introduction

In modern industry, the transition to a circular economy is considered a condition for the long-term sustainability of enterprises, which involves the transformation of production, investment and resource processes. It is not only the implementation of individual solutions that is important, but also their actual performance within the business system. At the same time, in management practice, such changes are mostly assessed by fragmented indicators, which makes it difficult to identify the systemic balance of the transformation.

The scientific literature has developed a conceptual understanding of the circular economy as a regenerative system aimed at reducing resource use, waste generation and losses by closing material and energy flows [1]. At the same time, research indicates its conceptual heterogeneity: in some works, circularity is interpreted mainly through reduce-reuse-recycle practices with limited coverage of the systemic nature of transformation [2], while in other approaches it is considered as an "essentially contested concept" [3]. Further research confirms the preservation of conceptual plurality and the need for its consolidation [4]. At the enterprise level, measuring circular transformation performance remains methodologically unregulated. In particular, in the field of evaluation, taxonomy of indicators [5] and their classification by object and scale of measurement [6] have been proposed. Despite this, assessment approaches remain fragmented: they differ in the level of analysis, the structure of indicators and the logic of aggregation, which results in the lack of a well-established integrated approach to assessing circular transformation performance as a holistic organizational and economic process.

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Micro-level approaches are characterized by methodological incompatibility. Research shows that most indicators focus on recycling, waste management and remanufacturing, while reuse and resource efficiency are underrepresented [7]. The heterogeneity of the structure and analytical logic of indicators is also confirmed [8].

Review researches emphasize that the lack of standardization creates a fragmented landscape for assessing circular and environmental performance [9]. Additionally, the multi-level nature of approaches (enterprises, supply chains, ecosystems) and their orientation towards the triple bottom line concept and the life cycle approach [10] are recorded. The interpretative flexibility of the concept is also emphasized, which complicates the formation of a single research and applied framework [11].

As a result, circular transformation performance assessments remain poorly comparable over time and across enterprises, which limits their managerial value. This necessitates an integrated tool that can compare economic (*Econ*), environmental (*Env*) and social (*Soc*) dimensions and take into account uneven and lagged effects of transformation.

The methodological principles of constructing composite indicators indicate that the aggregation rule determines the content and interpretation of the final result, and is not a purely technical solution [12]. In traditional additive models, high values of individual indicators can compensate for low values of others, forming the effect of inter-block compensability. In the context of circular transformation, this means the possibility of overestimating the integrated assessment due to the overlap of environmental or social shortcomings with economic results, which justifies the need to limit inter-block compensability.

The social dimension of the circular economy remains methodologically underdeveloped. Researches emphasize the potential of circular practices for achieving sustainable development goals [13] and at the same time record the conceptual ambiguity of the category itself [14]. The lack of agreed approaches to measuring social effects [15] and their insufficient empirical verification [16] are noted. At the same time, structured systems of social indicators have been proposed, which confirms the expediency of separating the social block of assessment [17]. Additionally, the weak operationalization of the connection between circular practices and sustainability at the enterprise level is indicated [18]. In general, the social dimension should be considered as a full-fledged component of assessing the performance of circular transformation. In many approaches, the social component is represented by generalized indicators of sustainable development, which only indirectly reflect circular changes, as a result of which it is often integrated into composite assessments without proper coordination with economic and environmental dimensions. For industrial enterprises, this creates methodological constraints, as transformations in production, resource use, employment and skills directly affect the ability to deliver circular outcomes.

An additional challenge is the gap between retrospective assessment and scenario analysis. Researches highlight the need for integrated assessment frameworks that combine project and organizational level indicators [19], while other researches also note the lack of standardized reporting approaches and the gap between the circular economy literature and sustainability reporting research [20].

As a result, there is a need for a tool that allows the comparison of actual and projected trajectories within a single analytical space.

For Ukrainian industrial enterprises, this problem is especially acute, because circular transformation is taking place under conditions of high uncertainty, investment constraints, disruptions in production and logistics links, export instability, and uneven enterprise recovery. Under such conditions, the assessment instrument must be suitable not only for retrospective diagnostics, but also for comparing alternative transformation scenarios within a single index space. This is why the approach proposed in this paper is tested on panel data for Ukrainian industrial enterprises for 2015–2025 and is used to assess both the actual dynamics of circular transformation performance and the prospective trajectories of its development over the 2026–2030 horizon.

Thus, despite the substantial development of research in the field of circular economy assessment, a methodologically coherent approach at the industrial-enterprise level is still lacking. In particular, existing approaches do not simultaneously ensure an integrated assessment of circular transformation performance within the economy – environment – society dimension. They also fail to provide control of inter-block compensability and to enable the identification of structural imbalances. Furthermore, intertemporal comparability between retrospective and scenario-based assessments remains insufficiently addressed.

The object of research is the economic effectiveness of the processes of circular transformation of industrial enterprises.

The aim of research is to develop and substantiate a composite assessment of the economic performance framework for circular transformation performance of industrial enterprises based on the CEI-360 (Circular Economy Index 360) in the economy – environment – society dimension. The approach forms a single architecture of normalization, weighting and aggregation of indicators, provides for limited inter-block compensability and formalizes the structural balance between the economic, environmental and social performance blocks. It is aimed at ensuring intertemporal comparability, identifying structural imbalances and supporting robust managerial interpretation under conditions of heterogeneous reporting.

In the applied dimension, the proposed tool provides annual diagnostics, cross-enterprise comparison, analysis of transformation trajectories and determination of priorities for circular investments, increasing resource efficiency and organizational changes at the enterprise level.

To achieve this aim, the research addresses the following objectives:

1. To form a data panel of Ukrainian industrial enterprises for 2015–2025 and assess the data quality profile for calculating CEI-360.
2. To analyze the dynamics of circular transformation performance based on the CEI-360 index and determine the main stages of development.
3. To decompose CEI-360 into economic, environmental and social blocks and assess their balance.
4. To assess the impact of structural balance on the composite result through the decomposition of the index.
5. To compare the scenarios for the development of circular transformation performance for 2026–2030 and check the robustness of the results.

2. Materials and Methods

2.1. Methodology for calculating the composite index CEI-360

This research applies a composite assessment framework to evaluate circular transformation performance of industrial enterprises in the economy – environment – society dimension. Methodologically, the research consists of two interconnected stages: retrospective assessment for 2015–2025 and forward-looking scenario assessment for 2026–2030 implemented as a what-if analysis. The empirical basis of the research was formed using publicly available corporate disclosures and issuer-level data sources. These include annual reports, audited financial statements, management reports, investor relations materials, and financial reporting archives. The data were collected from the official websites of PJSC "ArcelorMittal Kryvyi Rih" [21], PJSC "Interpipe Nizhnedneprovsky Tube Rolling Plant" [22], PrJSC "Centravis Production Ukraine" [23], JSC "Ukrainian Energy Machines" [24], and JSC "Motor Sich" [25]. In addition, issuer disclosures and annual reports from the public database SMIDA [26] were used, along with open financial reporting datasets published on portal by the State Statistics Service of Ukraine [27].

The computational procedures for data structuring, indicator transformation, normalization, aggregation, and scenario recalculation were implemented using a reproducible spreadsheet-based workflow, with all parameters fixed ex ante.

To ensure reproducibility, the indicator specification, lag classes, normalization bounds, weighting rules, and scenario operators were fixed ex ante and applied uniformly across all enterprises and periods within the research design. This section presents the research design and computational procedures only; empirical results and their interpretation are discussed in the next section. The overall workflow for constructing and computing the CEI-360 composite index and the accompanying data quality profile is summarized in Fig. 1.

The CEI-360 composite index integrates heterogeneous indicators into a unified index scale while preserving the interpretability of the three performance blocks–economic (*Econ*), environmental (*Env*), and social (*Soc*). The framework is designed to ensure limited inter-block compensability and to provide a separate measure of structural balance across the performance blocks. The empirical basis is further characterized through a standalone data quality profile, which supports the interpretation of index values and is not included in the computational core of CEI-360.

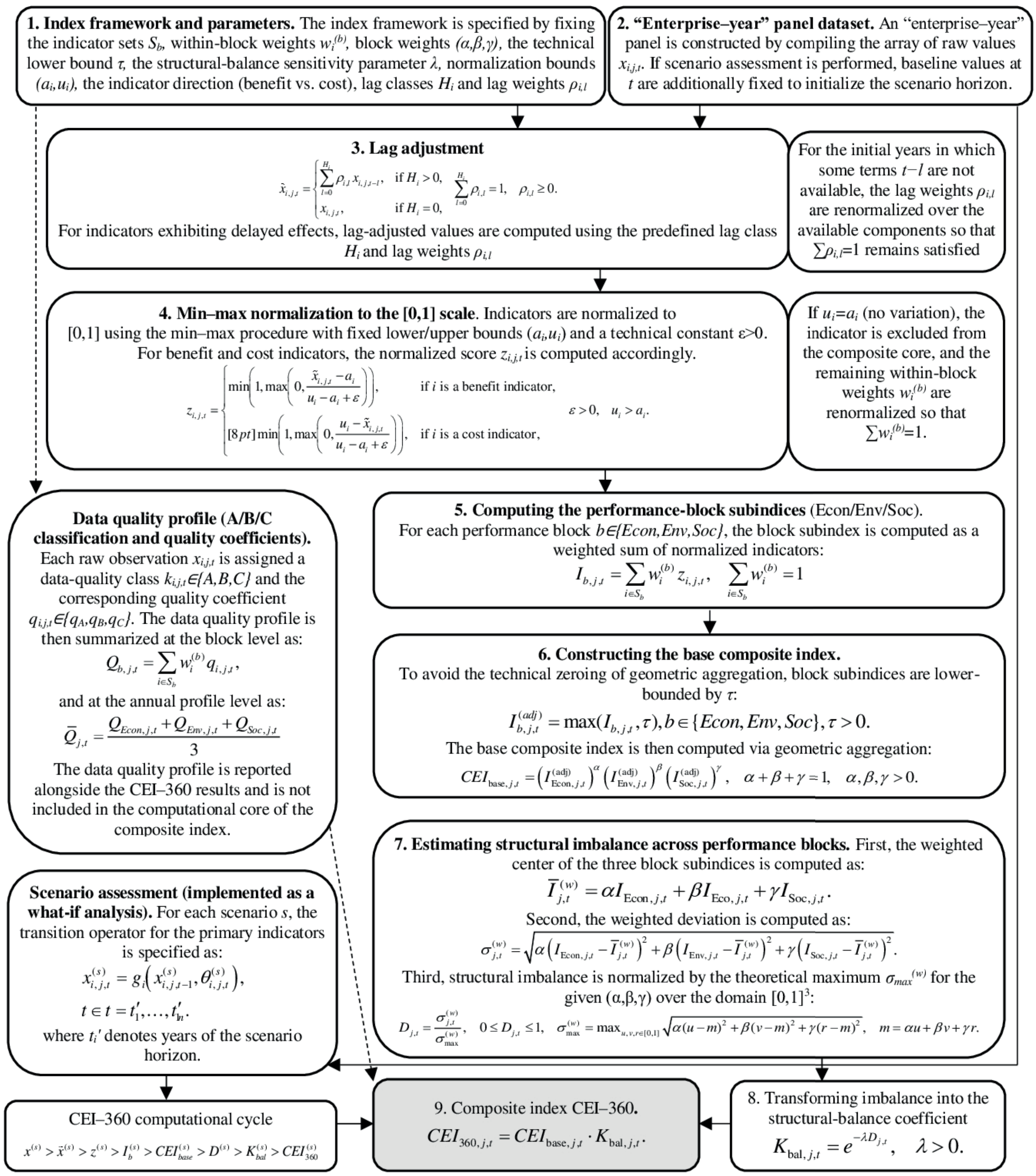

Fig. 1. Computational workflow for constructing and calculating the composite index CEI-360 and the data quality profile

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2.2. Indicator construction

The research is based on an enterprise-year panel, where $j = 1, ..., J$ denotes an enterprise and t denotes the year. The enterprise-year observation is the basic unit of analysis. The retrospective period is used to assess actual circular transformation dynamics, whereas the forward-looking horizon is used for scenario assessment in the form of a what-if analysis.

To enable comparability across enterprises of different scale, raw data are transformed – where methodologically required–into intensity or ratio forms. Scaling follows predefined rules and may be implemented by normalization per unit of output, revenue, material input, or employment, or by expressing indicators as shares or percentages.

Prior to computation, a fixed indicator specification is established within the three performance blocks. For each indicator, the specification defines its substantive meaning, unit of measurement, direction (benefit-type (stimulant) and cost-type (destimulant) indicators), scaling rule, data source, reconstruction rule, lag class, and normalization bounds.

Indicators included in the composite core of CEI-360 are selected based on circular relevance, intertemporal comparability, and the feasibility of reproducibility at the firm level. Accordingly, the core includes only indicators that directly reflect outcomes of circular change rather than general operational characteristics lacking a clear link to circular transformation.

Primary indicators are denoted by $x_{i,j,t}$, where i indexes the indicators within the relevant performance block. For a subset of indicators – most notably investment-related and workforce/skills-related measures – the effects of managerial decisions materialize with time delays. To account for delayed effects, a lag adjustment is applied. For indicators with delayed effects, a smoothed (lag-adjusted) value is used as defined in:

$$\tilde{x}_{i,j,t} = \sum_{l=0}^{H_i} \rho_{i,l} x_{i,j,t-l},$$
$$\sum_{l=0}^{H_i} \rho_{i,l} = 1, \rho_{i,l} \geq 0, \quad (1)$$

where H_i – the fixed lag depth for indicator i, and $\rho_{i,l}$ – lag weights. For indicators without a pronounced lag structure, the unadjusted value is used

$$\tilde{x}_{i,j,t} = x_{i,j,t}. \quad (2)$$

The lag structure is defined extant by indicator type and reflects a typical temporal sequence of managerial implementation in industrial settings, without claiming causal identification of lag parameters. In the baseline configuration, $H_i = 2$ is assigned to circular-investment indicators, $H_i = 1$, to workforce/skills indicators, and $H_i = 0$ to operational indicators of resource and environmental efficiency. Lag weights ρ_i,l are specified using a monotone-decay template – for example, (0.50, 0.30, 0.20) for $H_i = 2$ and (0.70, 0.30) for $H_i = 1$. This specification reflects "moderate decay" of delayed effects; a decay parameter is not estimated and is not treated as a calibrated model parameter.

For boundary years of the observation period, lag aggregation is computed using available values only: in (1), only the components $xi,j,t–l$ that fall within the available panel are included, and the corresponding weights $\rho i,l$ are renormalized over the available components so that the condition $\Sigma \rho i,l = 1$ remains satisfied. This ensures computational reproducibility without artificially extending time series and without altering the model logic for the initial years of the panel.

Indicators of organizational readiness for change (e. g., cooperation, coordination, and managerial architecture) are excluded from the computational core of the performance-block subindices, because they represent enabling conditions and mechanisms rather than transformation outcomes. Such variables are used only as an interpretive module and as a basis for scenario parameterization.

2.3. Indicator normalization

Indicator normalization is based on using a min-max scheme that distinguishes benefit (stimulant) and cost (destimulant) indicators. To avoid conflicts with the notation used for lag structure, the normalization bounds for indicator i are denoted as ai (lower bound) and ui (upper bound), with $ui > ai$.

For a cross-industry industrial sample, a hybrid rule is applied when setting normalization bounds. Indicators that are directly comparable across industries, such as shares and standardized intensity measures, use common bounds (ai,ui) are used. By contrast, indicators with pronounced technological specificity are first normalized using industry-specific benchmark bounds and then mapped onto the common [0,1] scale. This reduces the risk of misleading cross-enterprise comparisons when different technological regimes imply structurally different "normal" ranges. The normalized score is obtained according to

$$z_{i,j,t} = \begin{cases} \min\left(1, \max\left(0, \dfrac{\tilde{x}_{i,j,t} - a_i}{u_i - a_i + \varepsilon}\right)\right), & \text{if } i \text{ is a benefit indicator;} \\ \min\left(1, \max\left(0, \dfrac{u_i - \tilde{x}_{i,j,t}}{u_i - a_i + \varepsilon}\right)\right), & \text{if } i \text{ is a cost indicator,} \end{cases} \quad (3)$$

where $\varepsilon > 0$ is a technical constant introduced to avoid division by zero.

If, within the baseline panel, a given indicator satisfies $u_i = a_i$ (no variation), the indicator has no discriminatory power and is excluded from composite aggregation. In this case, the weights of the remaining indicators within the corresponding performance block are proportionally renormalized to preserve the condition $\Sigma_{wi}^{(b)} = 1$ (4) in (4), thereby maintaining both intertemporal and cross-enterprise comparability of the subindex.

After normalization, each of the three performance-block subindices is computed. For each performance block $b \in \{Econ, Env, Soc\}$, the subindex is defined as in:

$$I_{b,j,t} = \sum_{i \in S_b} w_i^{(b)} z_{i,j,t},$$
$$\sum_{i \in S_b} w_i^{(b)} = 1, \quad (4)$$

where S_b denotes the set of indicators belonging to block b and $w_i^{(b)}$ denotes the weight of indicator i within block b.

In the baseline configuration, equal weights are assigned within each block. Alternative weighting schemes are tested in the robustness analysis. This choice reduces the risk of arbitrary shifts in results under heterogeneous corporate reporting and keeps the interpretation transparent.

2.4. Data quality profile

Because corporate reporting is heterogeneous, the CEI-360 framework includes a separate data quality profile that describes the empirical basis of the primary indicators $x_{i,j,t}$. This profile is reported alongside CEI-360, but it is not treated as a component of circular transformation performance. Instead, it reflects how well the underlying values are empirically defined, traceable, and reproducible.

Each observation is assigned to one of three classes: A (direct value), B (controlled reconstruction), and C (proxy estimate). Each class has a corresponding quality coefficient used only for reporting and interpretation. The data quality profile does not enter the computational core of CEI-360, so performance is not mixed with data quality.

For data-quality classes $k \in \{A, B, C\}$, the corresponding quality coefficients are defined in:

$$q_{i,j,t} = \begin{cases} q_A, & \text{if } x_{i,j,t} \text{ is classified as A;} \\ q_B, & \text{if } x_{i,j,t} \text{ is classified as B;} \\ q_C, & \text{if } x_{i,j,t} \text{ is classified as C,} \end{cases}$$
$$q_A = 1.00, q_B = 0.85, q_C = 0.70. \quad (5)$$

The parameters q_A, q_B, q_C form a data-quality scale from direct values to proxy estimates. They are interpreted as an ordinal measure of how well the primary indicators are empirically defined. This scale is not a penalty mechanism and does not change indicator values or performance-block subindices.

For each performance block $b \in \{Econ, Env, Soc\}$, the block-level data-quality coefficient is computed as a weighted average of indicator-level coefficients using the same within-block weights $w_i^{(b)}$ as in the subindex calculation:

$$Q_{b,j,t} = \sum_{i \in S_b} w_i^{(b)} q_{i,j,t},$$
$$\sum_{i \in S_b} w_i^{(b)} = 1. \quad (6)$$

The integrated data-quality coefficient of the annual profile is computed as the mean of the block-level coefficients

$$\bar{Q}_{j,t} = \frac{Q_{Econ,j,t} + Q_{Env,j,t} + Q_{Soc,j,t}}{3}. \quad (7)$$

Accordingly, $Q_{b,j,t}$ and $\bar{Q}_{j,t}$ are interpreted as indicators of the empirical quality of the annual profile, including the definability, traceability, and reproducibility of the underlying values, rather than as components of transformation performance.

2.5. Aggregating performance-block subindices into the composite index of circular transformation performance

At the final aggregation stage, the performance-block subindices $I_{b,j,t}$ (namely $I_{Econ,j,t}$, $I_{Env,j,t}$ and $I_{Soc,j,t}$) are integrated into a single composite measure of circular transformation performance at the enterprise level. The core component of this measure is the base composite index $CEI_{base,j,t}$, which captures the overall progress in the "economy – environment – society" dimension under limited inter-block compensability.

At the top aggregation level, block weight α, β and γ are introduced (baseline configuration: $\alpha = 0.40$; $\beta = 0.35$; $\gamma = 0.25$), reflecting the relative importance of the economic, environmental, and social performance blocks, respectively:

$$\alpha + \beta + \gamma = 1,$$
$$\alpha, \beta, \gamma > 0. \quad (8)$$

The weights are interpreted as top-level managerial priorities and determine each block's contribution to the composite result. Their sum equals one, ensuring scale invariance of the index. To prevent technical zero values in geometric aggregation, a lower bound τ is introduced (baseline $\tau = 0.01$)

$$I_{b,j,t}^{(adj)} = \max(I_{b,j,t}, \tau),\ b \in \{Econ, Env, Soc\}. \quad (9)$$

The sensitivity of results to τ is examined in the robustness analysis using alternative values $\tau \in \{0.001; 0.01; 0.05\}$. Importantly, τ is applied only to compute CEI_{base} in (10) and is not used in the computation of $\sigma^{(w)}$, D or K_{bal} in (12)–(14), so that the assessment of structural imbalance reflects the actual performance-block values without technical substitutions.

The base composite index is defined as

$$CEI_{base,j,t} = \left(I_{Econ,j,t}^{(adj)}\right)^{\alpha} \left(I_{Env,j,t}^{(adj)}\right)^{\beta} \left(I_{Soc,j,t}^{(adj)}\right)^{\gamma}. \quad (10)$$

Even with geometric aggregation, it is analytically useful to identify structural imbalance across the performance blocks separately; for this purpose, the model introduces the structural-balance coefficient $K_{bal,j,t}$, which is based on the normalized weighted deviation of the performance-block subindices.

Inter-block imbalance is assessed through the weighted deviation of subindices from their weighted center

$$\bar{I}_{j,t}^{(w)} = \alpha I_{Econ,j,t} + \beta I_{Env,j,t} + \gamma I_{Soc,j,t}. \quad (11)$$

The weighted dispersion of the three performance-block subindices is interpreted as a measure of structural imbalance across the *Econ, Env*, and *Soc* dimensions. To ensure comparability, this dispersion is normalized by its theoretical maximum for the given block weights α, β, and γ over the domain $[0,1]^3$. The resulting normalized imbalance index is defined as follows:

$$\sigma_{j,t}^{(w)} = \sqrt{\alpha\left(I_{Econ,j,t} - \bar{I}_{j,t}^{(w)}\right)^2 + \beta\left(I_{Env,j,t} - \bar{I}_{j,t}^{(w)}\right)^2 + \gamma\left(I_{Soc,j,t} - \bar{I}_{j,t}^{(w)}\right)^2},$$
$$D_{j,t} = \frac{\sigma_{j,t}^{(w)}}{\sigma_{\max}^{(w)}}, \quad (12)$$

where $\sigma_{max}^{(w)}$ denotes the maximum attainable weighted dispersion under the constraint that block subindices lie within [0,1].

For the baseline weights $\alpha = 0.40$, $\beta = 0.35$, and $\gamma = 0.25$, the maximum in (13) is attained at a corner point of $[0,1]^3$ (in particular, for the configuration $(u,v,r) = (0,1,1)$):

$$\sigma_{\max}^{(w)} = \max_{u,v,r \in [0,1]} \sqrt{\alpha(u-m)^2 + \beta(v-m)^2 + \gamma(r-m)^2},$$
$$m = \alpha u + \beta v + \gamma r.$$
$$\sigma_{\max}^{(w)} = \sqrt{0.4 \cdot 0.6} = 0.4899. \quad (13)$$

To transform imbalance into a measure of structural balance, an exponential mapping is applied

$$K_{bal,j,t} = e^{-\lambda D_{j,t}}. \quad (14)$$

The parameter λ is calibrated using an anchoring rule $\lambda = -ln(K^*)/D^*$, where D^* is a reference imbalance level and K^* is the desired multiplicative reduction of the index at that imbalance level. In the baseline configuration, $D^* = 0.5$ and $K^* = 0.85$, which yields $\lambda = 0.325$. This calibration ensures a moderate and interpretable correction.

The final composite index, CEI-360 (Circular Economy Index 360), is defined as follows

$$CEI_{360,j,t} = CEI_{base,j,t} \cdot K_{bal,j,t}. \quad (15)$$

Within this construction, CEI_{base} reflects the overall progress under limited inter-block compensability, whereas K_{bal} provides a separate measure of structural balance by reflecting the degree of structural imbalance across the three dimensions.

The scenario module is implemented as scenario assessment in the form of a what-if analysis and parameterized through changes in the primary indicators using the transition operator in (16), while retaining the normalization bounds, lag-adjustment rules, and weight system defined in the baseline configuration:

$$x_{i,j,t}^{(s)} = g_i\left(x_{i,j,t-1}^{(s)}, \theta_{i,j,t}^{(s)}\right),$$
$$t \in t = t_1', \ldots, t_h'. \quad (16)$$

For non-negative intensity indicators, a multiplicative update is used: $x_t = x_{t-1}(1 + \delta_t)$.

For shares or levels bounded in (0,1), a logistic update with boundary regularization is applied. For indicators that may take negative values, an additive update is used: $x_t = x_{t-1} + \Delta_t$. For each scenario, the full computational cycle is repeated (lag adjustment, normalization, performance-block subindices, CEI_{base}, K_{bal} and CEI_{360}) under unchanged normalization rules and lag structure.

3. Results and Discussion

3.1. Formation of the panel sample and assessment of data quality

The empirical sample is structured as an enterprise – year panel of five case enterprises to test the operational viability of the CEI-360 composite index in the heterogeneous industrial environment of Ukraine over 2015–2025. Table 1 reports the research objects (industrial enterprises), their industry profiles, and the structure of data coverage by data-quality classes (*A*, *B*, *C*). The integrated coefficient of the annual data quality profile, $\bar{Q}_{j,t}$, is additionally reported alongside the block-level coefficients $Q_{b,j,t}$.

Table 1

Sample of enterprises and the data quality profile (2015–2025)

Code	Company	Industry profile	Role in the sample	*A*, %	*B*, %	*C*, %	$\bar{Q}_{j,t}$
MECH-01	PJSC ArcelorMittal Kryvyi Rih	Metallurgy (integrated steelworks)	Material-intensive baseline production	56.0	24.0	20.0	0.904
MECH-02	PJSC Interpipe NTRP *(Interpipe Nizhnedneprovsky Tube Rolling Plant)*	Pipe manufacturing	Export-oriented steel processing	61.0	22.0	17.0	0.916
MECH-03	PrJSC Centravis Production Ukraine	Seamless stainless-steel tubes	Technologically mature production	67.0	18.0	15.0	0.928
MECH-04	JSC Ukrainian Energy Machines	Power engineering/ machine building	Complex machine building, long modernization cycle	50.0	28.0	22.0	0.892
MECH-05	JSC Motor Sich	Aircraft engine manufacturing	High-tech machine building under elevated environmental risk	44.0	33.0	23.0	0.882

Note: the technical coding MECH-01-MECH-05 is used to unify tables and graphical visualizations

Table 2 summarizes the data quality profile by performance blocks, whereas Table 3 reports the block-level data-quality coefficients for 2025. These tables serve not only as descriptive information but also as an explicit context of empirical definability within which the CEI-360 values should be interpreted.

Table 2

Data quality by model performance blocks (aggregated over the 2015–2025 panel)

Performance block	*A*, %	*B*, %	*C*, %	$\bar{Q}_b$
Economic (*Econ*)	62	23	15	0.921
Environmental (*Env*)	57	24	19	0.907
Social (*Soc*)	48	28	24	0.886

Table 3

Block-level data-quality coefficients in 2025

Code	Q_{Econ}	Q_{Env}	Q_{Soc}	$\bar{Q}_{j,2025}$
MECH-01	0.934	0.916	0.888	0.913
MECH-02	0.941	0.925	0.901	0.922
MECH-03	0.951	0.936	0.914	0.934
MECH-04	0.921	0.901	0.872	0.898
MECH-05	0.907	0.886	0.851	0.881

Note: $\bar{Q}_{j,2025}$ is reported as an aggregated reference characteristic of the annual data quality profile

3.2. Dynamics of the composite CEI-360 index in 2015–2025

The panel results of the composite index CEI-360 for 2015–2025 are visualized as a mean trajectory with a min–max corridor (Fig. 2). The primary pattern revealed by Fig. 2 is a common three-stage trajectory across the sample: steady improvement in 2015–2021, a systemic contraction in 2022, and differentiated recovery in 2023–2025.

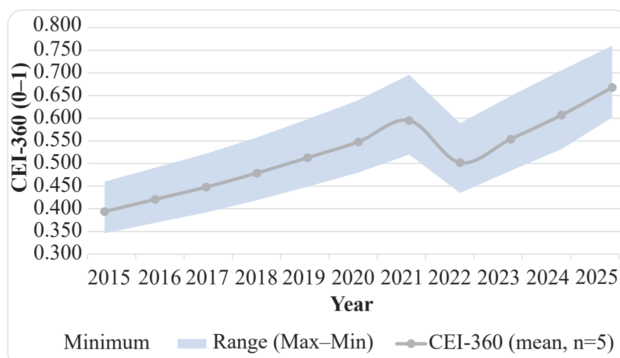

Fig. 2. Retrospective dynamics of CEI-360: sample mean with min-max range, 2015–2025

The unweighted mean value of the composite index CEI-360 equals 0.5952 in 2021 and 0.5018 in 2022, implying a decline of 0.0934 index points (15.7% relative to the 2021 level). In 2025, the mean value increases to 0.6678, which is 0.0726 points above the 2021 level (112.2% of the pre-crisis 2021 mean). The min-max corridor in Fig. 2 indicates persistent cross-enterprise differentiation: in 2025, the gap between the maximum and minimum values equals 0.158 points (MECH-03: 0.760; MECH-05: 0.602).

3.3. Decomposition of CEI-360 and assessment of inter-block balance

To identify the performance dimensions driving the decline and subsequent recovery – and to verify whether the composite signal conceals cross-dimensional imbalance – the analysis decomposes CEI-360 into its three dimension-specific subindices and evaluates the structural-balance component via *D* and K_{bal}.

The decomposition is implemented in two stages. First, the mean block subindices I_{Econ}, I_{Env} *and* I_{Soc} are compared for the key years 2021, 2022, and 2025, together with the mean imbalance $\bar{D}$ and the mean structural-balance coefficient $\bar{K}_{bal}$ (Table 4).

Table 4

Mean performance-block values and structural balance in key years (unweighted mean across the sample)

Year	I_{Econ}	I_{Env}	I_{Soc}	$\bar{D}$	$\bar{K}_{bal}$	$\bar{CEI}_{360}$	ΔCEI (vs. reference year)
2021	0.648	0.617	0.602	0.135	0.957	0.595	–
2022	0.553	0.587	0.515	0.234	0.927	0.502	−0.093 (2022–2021)
2025	0.720	0.660	0.654	0.065	0.979	0.668	+0.166 (2025–2022)

Table 4 shows that the 2022 decline is inter-block in nature, yet the response of the performance blocks is asymmetric. The mean I_{Econ} decreases from 0.648 to 0.553 (–0.095), and I_{Soc} decreases from 0.602 to 0.515 (–0.087), whereas the decrease in I_{Env} is less pronounced, from 0.617 to 0.587 (–0.030). Within this sample, the environmental performance block exhibits a relatively more inertial response compared to the economic and social blocks. During 2023–2025, the recovery of mean levels is accompanied by partial alignment of the outcome structure: $\bar{D}$ decreases from 0.234 in 2022 to 0.065 in 2025, consistent with the stabilization of $\bar{K}_{bal}$.

Second, the structure of the 2025 results is detailed at the enterprise level by decomposing the composite outcome into CEI_{base} and K_{bal}, computed according to formulas (12)–(15) under the baseline parameter configuration (Table 5).

Table 5

Structural decomposition of CEI-360 in 2025

Code	I_{Econ}	I_{Env}	I_{Soc}	$\sigma^{(w)}$	D
MECH-01	0.7200	0.6400	0.6300	0.0414	0.0845
MECH-02	0.7500	0.7100	0.6900	0.0249	0.0508
MECH-03	0.7900	0.7700	0.7400	0.0196	0.0400
MECH-04	0.6600	0.6000	0.6200	0.0264	0.0540
MECH-05	0.6800	0.5800	0.5900	0.0471	0.0961

Continuation of Table 5

Code	K_{bal}	CEI_{base}	CEI_{360}	$\Delta_{bal}=(CEI_{base}-CEI_{360})$	$\Delta_{bal,\%}$
MECH-01	0.9729	0.6682	0.6501	0.0181	2.71%
MECH-02	0.9836	0.7206	0.7088	0.0118	1.64%
MECH-03	0.9871	0.7702	0.7603	0.0100	1.30%
MECH-04	0.9826	0.6284	0.6175	0.0109	1.73%
MECH-05	0.9692	0.6207	0.6017	0.0191	3.08%

3.4. Enterprise-level decomposition of the index and the role of structural correction

The decomposition in Table 5 indicates that high values of CEI-360 are not driven by the dominance of a single subindex. In 2025, the highest value is observed for MECH-03 (0.7603), which corresponds to high scores in all three subindices ($I_{Econ} = 0.79$; $I_{Env} = 0.77$; $I_{Soc} = 0.74$) and the lowest imbalance ($D = 0.04$); consequently, the structural correction is minimal ($\Delta_{bal,\%} = 1.30\%$). By contrast, MECH-05 exhibits a lower overall level (0.6017) together with higher structural imbalance across the performance blocks ($D = 0.0961$), which reduces K_{bal} to 0.9692 and increases the correction ($\Delta_{bal,\%} = 3.08\%$). On average in 2025, $\bar{K}_{bal} = 0.9791$ (range: 0.9692–0.9871), implying that the balance correction reduces CEI_{base} by roughly 2%. Thus, K_{bal} operates as a "soft" diagnostic signal of cross-dimensional balance, adding interpretive transparency without overturning the overall dynamic pattern.

3.5. Scenario modelling and robustness analysis of CEI-360 (2026–2030)

Applying the model to the 2026–2030 horizon extends retrospective diagnostics into scenario assessment within a what-if analytical setting and allows CEI-360 to be evaluated under alternative configurations of managerial decisions and external conditions. Fig. 3 presents the operational parameterization of scenarios (managerial logic, dominant impact channels, and typical annual ranges of parameter changes θ), which is essential for reproducibility because the relative dominance of scenarios in this framework is conditional on the adopted parameterization.

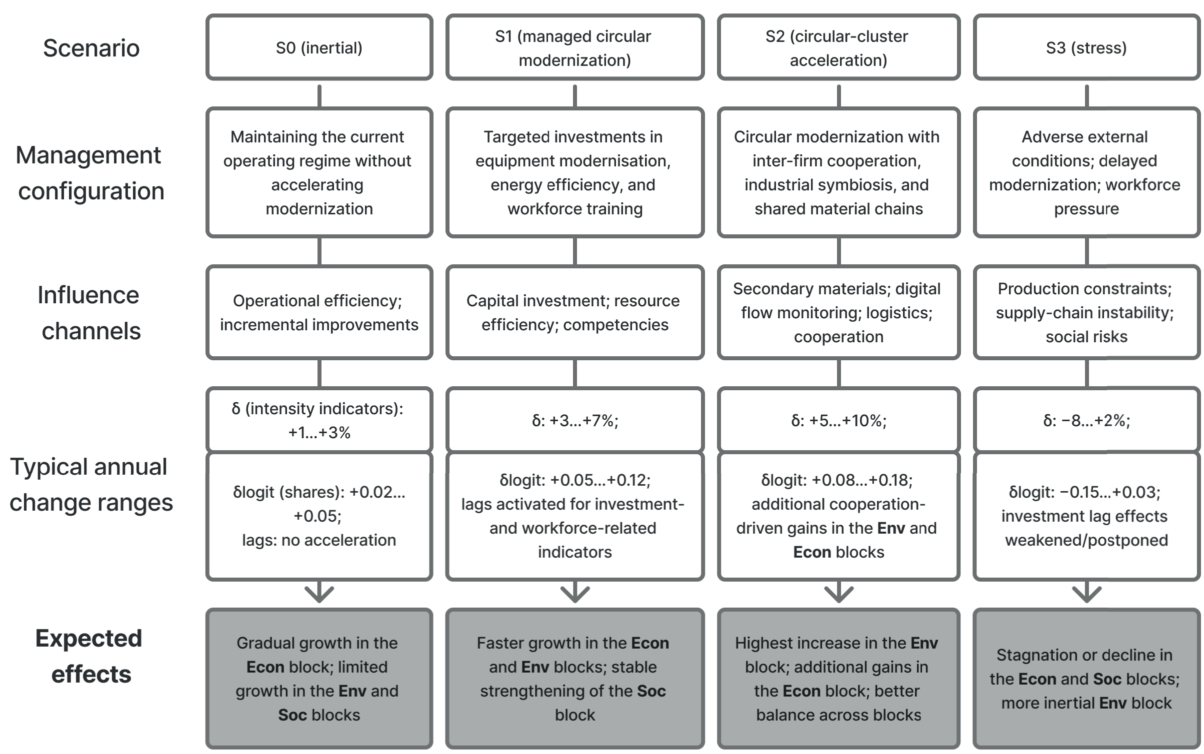

Fig. 3. Operational parameterization of scenarios

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Table 6 reports the mean scenario trajectories of CEI-360 for 2026–2030 (simple unweighted mean across the sample, $n = 5$).

Table 6

Mean scenario trajectories of CEI-360 for the sample (n = 5), 2026–2030

Year	*S0*	*S1*	*S2*	*S3*	*Δ(S2–S0)*	*Δ(S2–S3)*
2026	0.681	0.693	0.702	0.662	0.021	0.040
2027	0.695	0.719	0.737	0.657	0.042	0.080
2028	0.708	0.746	0.775	0.652	0.067	0.123
2029	0.721	0.774	0.812	0.646	0.091	0.166
2030	0.736	0.800	0.844	0.641	0.108	0.203

Under the baseline assumptions, the highest values are achieved by *S2* (circular–cluster acceleration), whereas *S3* (stress scenario) consistently yields the lowest index values. The gap between *S2* and *S0* increases from 0.021 in 2026 to 0.108 in 2030, indicating an accumulated effect of the combined modernization-and-cooperation trajectory under the assumed scenario logic. At the same time, the ordering "*S2* > *S1* > *S0* > *S3*" should not be interpreted as a universal conclusion beyond the adopted parameterization; within this model, it indicates that, given the assumed ranges of changes in primary indicators and the specified impact channels, *S2* generates the most favorable overall CEI-360 result together with the highest degree of inter-block balance.

The practical value of the scenario module lies not in "predicting a winner" but in comparing trajectories within a unified index space and assessing sensitivity to alternative decision configurations. Table 7 details the 2030 outcomes by enterprise. Across all five cases, *S2* is the best-performing configuration; however, the magnitude of *Δ(S2–S0)* differs. The largest gains are observed for MECH-02 (+ 0.121) and MECH-01 (+ 0.116), while the gain is smaller for MECH-03 (+ 0.096), which is consistent with a higher baseline in 2025.

Table 7

Scenario outcomes of CEI-360 in 2030 by enterprise

Code	*S0*	*S1*	*S2*	*S3*	*Δ (S2–S0)*	*Δ (S2–S3)*	Best scenario
MECH-01	0.717	0.783	0.833	0.625	0.116	0.208	S2
MECH-02	0.783	0.855	0.904	0.679	0.121	0.225	S2
MECH-03	0.839	0.905	0.935	0.725	0.096	0.210	S2
MECH-04	0.681	0.742	0.788	0.596	0.107	0.192	S2
MECH-05	0.660	0.718	0.762	0.580	0.102	0.182	S2

Thus, the model does not imply an identical scenario effect; it captures heterogeneity in marginal gains conditional on the initial state and transformation structure.

Because the interpretability of the proposed framework depends on parameter stability, this subsection reports the main robustness checks for both the computational core of CEI-360 and the standalone data quality profile. For the CEI-360 core, 24 parameter configurations are tested. The results confirm the stability of the main conclusions: in all configurations, the scenario ordering by mean CEI-360 is preserved (*S2* > *S1* > *S0* > *S3*). The enterprise ranking in 2025 remains unchanged in 21 out of 24 configurations; in the remaining three cases, only a local swap between adjacent positions (MECH-01/MECH-02) is observed, without changes in the leader (MECH-03) and the lowest-ranked case (MECH-05). Rank agreement (Spearman's ρ) between the baseline and alternative configurations for the 2025 ranking lies in the range 0.90–1.00 (median 1.00). Varying λ within 0.25–0.40 changes the mean CEI-360 in 2025 by no more than ±0.009 points relative to the baseline configuration and does not affect the interpretation of the overall dynamics. The primary takeaway from the robustness analysis is that the main empirical conclusions remain stable with respect to plausible alternative parameter settings.

Separately, the sensitivity of the data quality profile to an alternative scale of quality coefficients q is examined (baseline: A = 1.00, B = 0.85, C = 0.70; conservative: A = 1.00, B = 0.80, C = 0.60). This test does not change CEI-360 values, but it affects the interpretive profile $Q_{b,j,t}$ and $\bar{Q}_{j,t}$. As expected, cases with a higher share of proxy components are more sensitive to the change in the q-scale, confirming the role of the data quality profile as an indicator of empirical definability rather than a component of performance. This confirms that the data quality profile functions as an interpretive companion to CEI-360 rather than as a hidden source of variation in the performance index itself.

3.6. Discussion

The results obtained confirm the conclusions of previous researches on the fragmentation of approaches to assessing the circular economy at the enterprise level, but at the same time expand them. Unlike approaches in which indicators are mainly classified [5, 6], the CEI-360 index provides their integrated assessment within a single analytical system.

The identified differentiated dynamics of the economic, environmental and social blocks are consistent with the research results that record the uneven development of the components of circularity [7, 8]. At the same time, the results obtained show that such heterogeneity has applied significance, since it reflects the different speed of adaptation of enterprises to circular changes.

The results also confirm the concept of the multiplicity of the circular economy [2, 4]. The composite index partially smoothes the differences between the components, while its decomposition and the use of the structural balance coefficient (Kbal) allow them to be identified. This is consistent with approaches to constructing composite indicators, which emphasize the decisive role of the aggregation procedure [12].

The proposed approach involves limiting mutual compensation between blocks, in contrast to traditional additive models, which provides a more correct reflection of structural balance. This is consistent with the provisions on the systemic nature of circular changes and clarifies the conclusions about the methodological incompatibility of existing approaches [10].

The social block, as in previous researches, remains the least formalized [15, 16, 18], however, its inclusion in the model allows to assess its contribution to overall performance. At the same time, its increased sensitivity to the quality of input data has been confirmed.

Scenario analysis complements existing approaches to the assessment of circular change by allowing comparison of different development trajectories [19, 20]. The results show that it should be used to compare development options, rather than as a forecast.

The originality of the results lies in the creation of an integrated methodological framework that combines composite assessment, structural decomposition, and scenario analysis. This makes it possible to overcome the fragmentation of existing approaches to circular transformation assessment and to strengthen both the theoretical interpretation and the practical applicability of the results. Overall, the results are consistent with existing research, but complement them by combining composite assessment, decomposition and scenario analysis in a single framework.

Practical significance. The proposed CEI-360 index can be used as a tool to support management decisions in the field of circular transformation of enterprises. It provides an annual assessment of performance, comparisons between enterprises and identification of imbalances between economic, environmental and social components. This allows determining priorities for investment, modernization and organizational changes. The scenario module allows comparing alternative development options in a single assessment system.

The research results should be interpreted taking into account the following limitations:

1) the sample covers a limited number of enterprises, so the results primarily demonstrate the efficiency of the approach, not its universality;

2) the social block is partly based on indirect indicators, which increases the uncertainty of its assessment;

3) the results of the scenario analysis depend on the adopted parameterization and reflect alternative development options;

4) the research is descriptive-analytical in nature and does not establish cause-and-effect relationships.

Further research should be directed at expanding the sample of enterprises and detailing the industry analysis. It is important to improve the quality of data and reduce the share of indirect indicators. A promising direction is also the verification of the CEI-360 index using independent indicators and checking its applicability for inter-enterprise and international comparisons.

4. Conclusions

1. A data panel for Ukrainian industrial enterprises for 2015–2025 was formed and the data quality profile for calculating CEI-360 was assessed ($\bar{Q}_b$: 0.886–0.921; $\bar{Q}_{j,2025}$: 0.881–0.934). This allowed to separate the performance of circular transformation from the assessment of data reliability, increasing the correctness of the interpretation of the results obtained.

2. The dynamics of circular transformation were identified, which includes growth, crisis decline (–15.7% in 2022) and recovery (up to 0.6678 in 2025). This confirms the ability of the CEI-360 index to capture turning points and development trajectories of enterprises.

3. The unevenness of inter-block changes is established and the structural imbalance is quantitatively assessed ($\bar{D}$: 0.234 to 0.065; $\bar{K}_{bal}$: 0.927 to 0.979), which made it possible to interpret the results as structurally balanced or asymmetric.

4. The role of structural balance is substantiated, where it is established that its consideration changes the assessment of performance (on average by 2%), which confirms the need to limit inter-block compensation.

5. Scenario modeling of the development of circular transformation is implemented, which showed the stability of the results (the same order of scenarios was preserved in all 24 variants) and the advantage of the *S2* scenario, which corresponds to the circular-cluster trajectory. This proves the suitability of the approach for comparing alternative development trajectories under conditions of uncertainty.

Conflict of interest

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

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that no artificial intelligence tools were used in the preparation of this manuscript.

Authors' contributions

Stanislav Suslikov: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review and editing; ***Volodymyr Kuchynskyi***: Supervision, Methodology, Validation, Writing – review and editing; ***Maryna Gliznutsa***: Formal analysis, Resources, Writing – review and editing; ***Iegor Vozniuk***: Investigation, Data curation, Resources, Visualization; ***Oleksandr Bratukh***: Data curation, Formal analysis, Writing – original draft.

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