ECONOSCITECH INTEGRATION

ISSUE 10 PART II

INTERNATIONAL SCIENTIFIC ELECTRONIC JOURNAL

TASHKENT STATE UNIVERSITY OF ECONOMICS

American University of Technology
Powered by Arizona State University®

ISSN: 3060-5075



Acceptance of articles
PUBLISHED MONTHLY

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ISSN INTERNATIONAL STANDARD SERIAL NUMBER DENMARK

CONTACT: +998 94 3540880 https://econoscitech-integration-journal.uz

2026



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In accordance with Resolution No. 384/6 dated April 10, 2026, issued by the Presidium of the Supreme Attestation Commission under the Ministry of Higher Education, Science and Innovation of the Republic of Uzbekistan, this journal is included in the list of recommended international scientific publications for publishing the primary research findings of doctoral dissertations in the field of Economic Sciences.

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Electronic publication. Issue 10. PART II
500 pages. Approved for publication in October 2026.

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UDC 338.45:656.2
INTEGRATED ASSESSMENT OF THE ECONOMIC DEVELOPMENT OF RAILWAY ROLLING STOCK MANUFACTURING AND REPAIR ENTERPRISES: A WEAKEST-LINK-SENSITIVE AGGREGATION APPROACH

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Abstract. This paper examines the challenge of aggregating heterogeneous indicators into a single composite measure of the economic development of railway rolling stock manufacturing and overhaul enterprises. The study demonstrates that conventional linear composite indices may insufficiently reflect structural imbalances characteristic of such enterprises, including dependence on a single major customer, limited production localization, and relatively low financial autonomy. This limitation arises because the additive aggregation approach allows strong performance in one dimension to compensate fully for weak performance in another. To address this methodological issue, a weakest-link-sensitive aggregation function is proposed, combining the geometric mean of criterion-specific desirability values with their minimum value. The mathematical properties of the proposed function are compared with those of alternative aggregation methods, and a growth-to-quality conversion coefficient is introduced. The proposed approach is illustrated using synthetic data representing four hypothetical enterprises. Sensitivity analysis indicates that the resulting enterprise ranking remains stable when the weakest-link weight varies between 0.2 and 0.8. The findings provide a methodological basis for a more balanced assessment of enterprise economic development, with particular attention to structural constraints and the consistency of performance across evaluation criteria.

Keywords: composite index, aggregation, weakest-link principle, desirability function, railway rolling stock manufacturing, overhaul, economic development, sensitivity analysis.

Аннотация. В статье рассматривается проблема агрегирования разнородных показателей в единый композитный индекс экономического развития предприятий по производству и капитальному ремонту железнодорожного подвижного состава. Обосновано, что традиционные линейные композитные индексы могут недостаточно полно отражать структурные диспропорции, характерные для таких предприятий, включая зависимость от одного крупного заказчика, ограниченный уровень локализации производства и относительно низкую финансовую автономию. Данное ограничение обусловлено тем, что аддитивный подход к агрегированию допускает полную компенсацию низких значений одних критериев высокими значениями других. Для решения этой методологической задачи предложена функция агрегирования, чувствительная к наиболее слабому звену и объединяющая геометрическое среднее значений желательности отдельных критериев с их минимальным значением. Математические свойства предложенной функции сопоставлены с характеристиками альтернативных методов агрегирования. Дополнительно введён коэффициент преобразования количественного роста в качественное развитие. Предложенный подход проиллюстрирован на синтетических данных четырёх условных предприятий. Анализ чувствительности показывает устойчивость полученного ранжирования предприятий при изменении весового коэффициента наиболее слабого звена в диапазоне от 0,2 до 0,8. Полученные результаты формируют методологическую основу для более сбалансированной оценки экономического развития предприятий с учётом структурных ограничений и согласованности результатов по отдельным критериям.

Ключевые слова: композитный индекс, агрегирование, принцип слабого звена, функция желательности, производство железнодорожного подвижного состава, капитальный ремонт, экономическое развитие, анализ чувствительности.

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INTRODUCTION

Enterprises engaged in the manufacturing, overhaul, and modernization of railway rolling stock occupy a distinctive position within the transport economy. Demand for their products and services is derived primarily from railway traffic volumes and the age structure of railway operators' fleets. Their production assets are often specialized for the 1,520 mm railway gauge and may have limited alternative uses outside the industry. Moreover, railway rolling stock typically remains in operation for several decades, meaning that a substantial proportion of the economic value generated by these enterprises arises throughout the product life cycle, particularly through major overhauls, spare parts provision, and modernization rather than exclusively through new rolling stock production.

These characteristics indicate that the economic development of such enterprises cannot be adequately assessed on the basis of production output alone. For example, an enterprise may increase the number of locomotive sections undergoing overhaul while simultaneously experiencing challenges related to production localization, order stability, and financial autonomy. Consequently, an increase in production volume does not necessarily indicate a corresponding improvement in the overall quality and sustainability of enterprise development.

A comprehensive assessment of economic development therefore requires the integration of multiple criteria into a single composite measure. The selection of an appropriate aggregation method is particularly important because it directly influences the interpretation of the resulting index. The weighted arithmetic sum, one of the most widely used aggregation methods in composite indicator construction, is characterized by full compensability: lower performance in one dimension can be offset by higher performance in another, provided that the relevant weights and indicator values permit such compensation.

For railway rolling stock manufacturing and repair enterprises, this characteristic may limit the ability of a composite index to reflect structural constraints. Such constraints may include dependence on a single major customer, limited localization of higher-value production activities, and insufficient internal financial resources for reinvestment. These factors represent potentially important weaknesses that may be insufficiently reflected in an assessment based exclusively on compensatory aggregation.

Accordingly, the purpose of this study is to provide a theoretical and methodological justification for an aggregation function that is sensitive to the weakest evaluation criterion, compare its mathematical properties with those of alternative aggregation functions, and examine its performance using synthetic data representing hypothetical railway rolling stock manufacturing and repair enterprises.

LITERATURE REVIEW

The methodology of composite indicator construction has been systematically presented in the handbook developed by the Organisation for Economic Co-operation and Development (OECD) and the Joint Research Centre (JRC) of the European Commission. The handbook outlines ten principal stages, ranging from the development of a theoretical framework to the presentation and interpretation of results. It emphasizes that normalization, weighting, and aggregation methods should be selected in accordance with the conceptual objectives and analytical purpose of the composite index [10].

Nardo et al. examined methodological approaches and analytical tools for constructing composite indicators, demonstrating that the selection of aggregation methods can substantially influence the resulting rankings of countries or other evaluated entities [9]. The issue of compensability was examined by Munda and Nardo, who emphasized the importance of non-compensatory aggregation approaches when evaluation criteria represent distinct and potentially incommensurable dimensions [8].

Within the framework of multi-criteria decision analysis, the weighted product method, based on a weighted geometric mean, represents an aggregation approach with limited compensability under appropriate normalization conditions [4]. In contrast, the maximin criterion evaluates alternatives according to their lowest-performing dimension, providing a strongly non-compensatory approach that prioritizes the weakest evaluation criterion [6].

Desirability functions offer a methodological foundation for transforming heterogeneous performance indicators into comparable dimensionless values and subsequently aggregating them. Harrington introduced a desirability-based transformation that maps individual indicators onto a dimensionless scale associated with qualitative performance categories. Individual desirability values can then be combined using a geometric mean, under which a zero value for any criterion results in a zero overall desirability score [3]. Derringer and Suich subsequently extended the desirability function approach to the simultaneous optimization of multiple response variables [2].

In the field of enterprise performance measurement, Kaplan and Norton's balanced scorecard broadened the scope of evaluation beyond conventional financial indicators by incorporating additional dimensions of

organizational performance. However, the balanced scorecard does not inherently prescribe a single composite aggregation function for integrating all performance dimensions into one index [5].

Entropy-based weighting methods have also been applied in studies of industrial performance and manufacturing competitiveness. Such methods derive criterion weights from the informational characteristics and variability of the underlying data, thereby reducing reliance on exclusively subjective expert judgments. Nevertheless, the resulting weights remain sensitive to the structure and distribution of the dataset [15].

In railway economics, life-cycle cost analysis provides an established framework for evaluating procurement alternatives, maintenance strategies, and the long-term economic performance of railway assets, including applications involving performance-based maintenance arrangements [1]. The broader macroeconomic significance of railway transport has also been examined by Lapidus and Macheret, who analyzed its role in economic development and the functioning of transport systems [7].

Despite these contributions, the reviewed literature provides limited integrated consideration of aggregation methods specifically designed to assess the economic development of railway rolling stock manufacturing and repair enterprises. In particular, the relationships among order stability, localization depth, life-cycle efficiency, and financial autonomy, as well as the implications of fully compensatory aggregation for evaluating these dimensions, require further methodological examination.

The present study addresses this research gap by proposing a weakest-link-sensitive aggregation approach that incorporates both the overall level of criterion performance and the influence of the lowest-performing dimension. This approach is intended to provide a more balanced representation of enterprise economic development and support the identification of structural priorities for sustainable performance improvement.

RESEARCH METHODOLOGY

Let an enterprise be assessed on K criteria, each represented by a desirability $D_k \in (0; 1]$ obtained from the Harrington transformation of the underlying indicators and their geometric aggregation within the criterion. Four aggregation functions are compared: the weighted arithmetic mean $A = \Sigma\, w_k \cdot D_k$; the weighted geometric mean $G = \Pi\, D_k^{w_k}$; the minimum $M = \min(D_k)$; and the proposed chain-sensitive function $I_f = (1 - \lambda)\cdot G + \lambda \cdot M$, where $\lambda \in [0; 1]$ is the weight of the weakest link. The functions are compared by five properties: boundedness, monotonicity, degree of compensation, sensitivity to the weakest criterion, and continuity with respect to small changes in D_k.

To describe the relation between quantitative growth and qualitative development, a growth-to-quality conversion coefficient is introduced: $K_s = \Delta I_f / \Delta \ln Q$, where ΔI_f is the change in the integral index over the period and $\Delta \ln Q$ is the logarithmic growth of output. $K_s > 0$ indicates that growth is accompanied by qualitative improvement, $K_s \approx 0$ indicates growth without development, and $K_s < 0$ indicates growth at the expense of quality. The approach is tested on synthetic data for four conditional enterprises designed to represent typical structural profiles: balanced (E1), customer-dependent (E2), shallow-localised (E3) and financially constrained (E4). The data are constructed by the author within ranges typical of the industry and serve to demonstrate the behaviour of the functions, not to describe any real enterprise. Sensitivity analysis varies λ from 0 to 1 and examines the stability of the ranking.

The desirability of each indicator is obtained by the Harrington transformation $d = \exp(-\exp(-y))$, where y is a linear rescaling of the indicator such that the satisfactory threshold corresponds to $y = 0$ ($d = 0.37$) and the good threshold to $y = 1.5$ ($d = 0.80$); values below the satisfactory threshold are truncated at $y = -1$ ($d \approx 0.07$) to prevent a single extreme observation from annihilating the index. Within a criterion the indicator desirabilities are combined by the weighted geometric mean with entropy weights $w_j = (1 - E_j)/\Sigma(1 - E_k)$, where E_j is the normalised Shannon entropy of the j-th indicator across the enterprises compared; an indicator that takes the same value for all enterprises receives a zero weight because it does not discriminate among them. The degree of compensation of an aggregation function is measured here by the marginal rate of substitution between the weakest criterion and any other criterion: the increase in another criterion required to offset a 0.05 decrease in the weakest one while keeping the index unchanged.

Artificial intelligence tools were used to a limited extent (approximately 10%) to support language refinement, grammatical correction, proofreading, and technical editing of the manuscript. AI-assisted tools were not used to generate research findings, conduct the scientific analysis, or formulate the study's conclusions. The author retains full responsibility for the originality, accuracy, scientific integrity, and final content of the research.

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ANALYSIS AND RESULTS

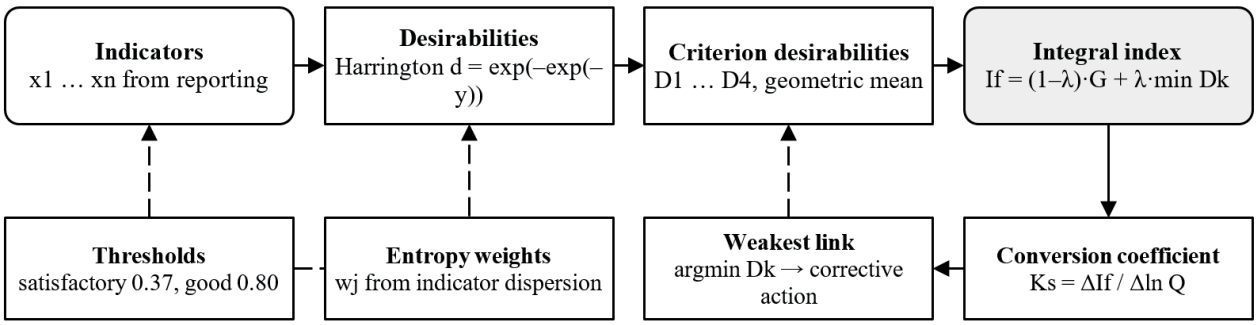
The properties of the four aggregation functions are summarised in Table 1. The arithmetic mean is fully compensatory and insensitive to the weakest criterion; the minimum is fully non-compensatory but discontinuous in its ranking behaviour, because it ignores all criteria except the worst; the geometric mean is partially compensatory and penalises low values, but a moderately low criterion can still be masked by high values elsewhere. The chain-sensitive function inherits the boundedness and monotonicity of its components, is continuous, and its degree of compensation is controlled by a single interpretable parameter (Table 1).

Table 1
Properties of the compared aggregation functions

Property	Arithmetic mean A	Geometric mean G	Minimum M	Chain-sensitive If
Boundedness in (0; 1]	yes	yes	yes	yes
Monotonicity in each Dk	yes	yes	weak	yes
Degree of compensation	full	partial	none	adjustable by λ
Sensitivity to the weakest criterion	low	medium	complete	medium to high
Continuity of the index	yes	yes	yes	yes
Use of all criteria in ranking	yes	yes	no	yes
Interpretability of the parameter	weights only	weights only	none	λ = weight of the weak link

Source: compiled by the author.

The structure of the proposed assessment is shown in Figure 1. Indicators are transformed into desirabilities, aggregated within criteria by the geometric mean, and the criterion desirabilities are then combined by the chain-sensitive function; the weakest criterion is reported alongside the index, and the conversion coefficient links the index dynamics to output growth (Figure 1).



Output: index value, development type, weakest criterion, growth-to-quality conversion

Solid arrow – direct computational link; long dash – parameters and feedback

Figure 1. Structure of the integral assessment of enterprise development[1]

Synthetic criterion desirabilities for the four conditional enterprises are given in Table 2 together with the values of the four aggregation functions. E1 is balanced at a good level; E2 has a very high level on three criteria but a low order-stability desirability, reflecting dependence on one customer; E3 is weak on value-added depth; E4 is weak on financial autonomy but strong elsewhere. The arithmetic mean ranks E2 first, because its three strong criteria outweigh the weak one; the geometric mean reduces the gap but still places E2 above E1; the minimum ranks E2 last. The chain-sensitive function with λ = 0.3 ranks E1 first and moves E2 below the good-level threshold of 0.63, which corresponds to the economic meaning of the profiles: an enterprise dependent on a single customer cannot be considered more developed than a balanced one, however strong its other results (Table 2).

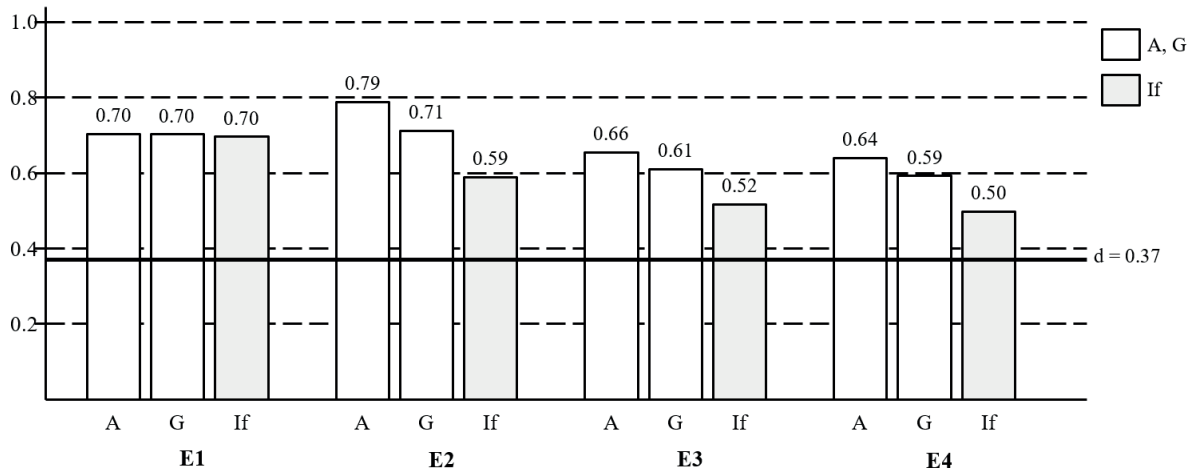
1 Author's development

Table 2
Criterion desirabilities of conditional enterprises and the values of aggregation functions (synthetic data)

Enterprise	D1 orders	D2 value added	D3 life cycle	D4 finance	A	G	M	If (λ=0.3)
E1	0.72	0.70	0.68	0.71	0.703	0.702	0.68	0.696
E2	0.30	0.95	0.95	0.95	0.788	0.712	0.30	0.589
E3	0.78	0.30	0.74	0.80	0.655	0.610	0.30	0.517
E4	0.80	0.76	0.72	0.28	0.640	0.592	0.28	0.498

Source: author's calculation; the data are synthetic.

The marginal rates of substitution make the difference between the functions tangible. For the arithmetic mean a 0.05 decrease in the weakest criterion of E2 is offset by a 0.05 increase in any other criterion regardless of their levels. For the geometric mean the offset required grows with the gap between the criteria: at the profile of E2 a 0.05 decrease in D1 from 0.30 to 0.25 must be compensated by an increase of roughly 0.06 in each of the other three criteria, which is already impossible because they are close to the upper bound of the scale. For the chain-sensitive function with λ = 0.3 the same decrease requires an increase of about 0.10 in each of the other criteria, that is, no compensation is feasible within the scale, and the enterprise is forced to address the weak link itself. This is precisely the behaviour expected from a development index for enterprises whose structural problems are concentrated in one dimension (Figure 2).



Dashed horizontal lines – grid; bold line – satisfactory threshold of the Harrington scale

Figure 2. Values of the aggregation functions for the conditional enterprises (λ = 0.3)[2]

The sensitivity of the ranking to λ is examined in Table 3. For λ = 0 the ranking coincides with that of the geometric mean (E2 > E1 > E3 > E4); already at λ = 0.2 E1 overtakes E2, and in the whole range 0.2–0.8 the ranking E1 > E2 > E3 > E4 is stable, so the choice of λ within this range affects the index values but not the order of enterprises. What changes with λ is the qualitative grade: E2 leaves the good zone (If < 0.63) at λ = 0.2 and approaches the satisfactory threshold at λ = 0.8, while E3 and E4 fall below the satisfactory level of 0.37 only at λ ≥ 0.8, where the function is dominated by the minimum and differences are determined almost entirely by the worst criteria. The base value λ = 0.3 therefore lies within the stable region and is recommended for practical use; λ may be raised when the regulator wishes to penalise imbalances more strongly (Table 3).

2 Author's development

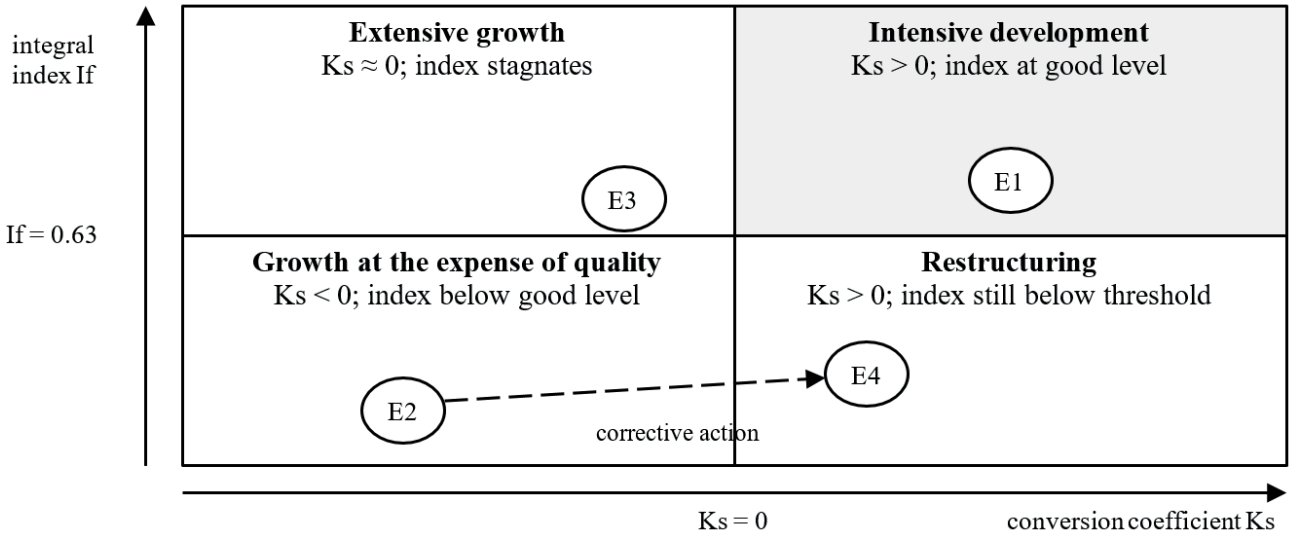
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Table 3
Sensitivity of the integral index and ranking to the weakest-link weight λ

λ	E1	E2	E3	E4	Ranking
0.0	0.702	0.712	0.610	0.592	E2 > E1 > E3 > E4
0.2	0.698	0.630	0.548	0.529	E1 > E2 > E3 > E4
0.3	0.696	0.589	0.517	0.498	E1 > E2 > E3 > E4
0.5	0.691	0.506	0.455	0.436	E1 > E2 > E3 > E4
0.6	0.689	0.465	0.424	0.405	E1 > E2 > E3 > E4
0.8	0.684	0.382	0.362	0.342	E1 > E2 > E3 > E4
1.0	0.680	0.300	0.300	0.280	E1 > E2 > E3 > E4

Source: author's calculation.

The joint interpretation of the index level and the conversion coefficient is illustrated in Figure 3. Four development types are distinguished: intensive development (index at a good level, Ks > 0), extensive growth (index growing slowly relative to output, Ks ≈ 0), growth at the expense of quality (Ks < 0 with rising output) and decline (index and output both falling). For E2 in the synthetic example, a 20 per cent increase in output accompanied by a fall of the order-stability desirability from 0.30 to 0.25 gives Ks ≈ -0.20, that is, growth at the expense of quality, even though three of the four criteria remain at a very good level (Figure 3).



Solid arrow – axis; long dash – expected trajectory after corrective action

Figure 3. Development types by the level of the integral index and the growth-to-quality conversion coefficient (positions of conditional enterprises are illustrative)[3]

CONCLUSION AND RECOMMENDATIONS

The choice of an aggregation method constitutes a fundamental methodological consideration in assessing the economic development of railway rolling stock manufacturing and repair enterprises. Conventional linear composite indices may insufficiently reflect structural imbalances characteristic of such enterprises, whereas the proposed weakest-link-sensitive aggregation function, which combines the weighted geometric mean of criterion-specific desirability values with their minimum, incorporates information from all evaluation criteria while explicitly accounting for the lowest-performing dimension. The proposed function is continuous and non-decreasing, and its degree of compensability can be adjusted through a single interpretable parameter.

3 Author's development

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The illustrative analysis based on synthetic data demonstrates that the proposed function changes the relative ranking of a customer-dependent enterprise and a structurally balanced enterprise, reflecting the economic characteristics represented by their respective profiles. Furthermore, sensitivity analysis indicates that the resulting ranking remains stable when the weakest-link weight, λ, varies between 0.2 and 0.8. The proposed growth-to-quality conversion coefficient complements the composite index by distinguishing quantitative expansion accompanied by qualitative improvements from output growth associated with declining development quality.

For practical implementation, it is recommended that the composite index be calculated annually using data from enterprises' statutory financial and operational reports. The lowest-performing criterion should be disclosed alongside the overall index to improve transparency and facilitate the identification of priority areas for improvement. A baseline value of $\lambda = 0.3$ is proposed for initial application, accompanied by periodic sensitivity analyses to assess the robustness of the resulting evaluations.

In addition, the growth-to-quality conversion coefficient may be considered by railway operators and relevant regulatory authorities as a supplementary performance indicator when developing and evaluating multi-year framework contracts. Its application should take into account the availability of reliable data, sector-specific conditions, and the contractual responsibilities of the parties involved.

Further research should focus on calibrating the Harrington desirability thresholds using empirical data from railway rolling stock manufacturing and repair enterprises in Uzbekistan. Additional studies should examine the behavior and robustness of the proposed index over a complete railway fleet renewal cycle, including changes in production demand, maintenance requirements, investment conditions, and enterprise financial performance.

Overall, the proposed methodological approach provides a basis for a more comprehensive assessment of enterprise economic development by combining aggregate performance measurement with explicit consideration of structural constraints. Its practical application may support more balanced managerial decisions, targeted investment planning, and the long-term sustainable development of railway rolling stock manufacturing and repair enterprises.

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Proofreader: Xondamir Ismoilov

Layout and Designer: Hasan Maqsudov

2026. № 10/2

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