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Managing Circularity in Industrial Ecosystems: Introducing the Concept of Circular Maturity and its Application in NLMK Group

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Abstract. The primary objective of this research endeavor is the conceptualization and operationalization of the 'Circular Maturity' construct within the context of industrial ecosystems. A comprehensive evaluative framework is developed, designed to assess circularity in alignment with thresholds that are environmentally, socially, and economically acceptable, commonly encapsulated as ESG results. This framework incorporates a multifaceted system for the governance of circularity, integrating diverse measures, functions, principles, strategies, business models, and circular solutions across various stages of the value chain. Utilization of information, finances, resources, human capital, platforms, and collaborative mechanisms is envisaged to mitigate external risks and challenges. Key driver projections, namely circular potential, circular activity, and circular efficiency are formulated for the governance of circularity and the enhancement of circular maturity at the corporate level. The applicability and efficacy of the proposed framework are validated through a case study involving the industrial ecosystem of Novolipetsk Metallurgical Combinate (NLMK) in Russia.

Keywords: Circular maturity; Circularity; Industrial ecosystem; NLMK

1. Introduction

As Earth's biocapacity approaches its limits, and with climate policies and regulations on carbon emissions tightening globally (Berawi, 2020), coupled with the volatility in prices and demand for fossil resources, it becomes crucial to transition from a linear to a circular model of production and consumption in industrial ecosystems (Khaykin and Babkin, 2022). Numerous studies have considered circularity in industrial ecosystems at different levels (Krmela, Šimberová, and Babiča, 2022; Ilyina, 2022; Kulibanova *et al.*, 2022; Shkarupeta and Ilyina, 2022), proposing approaches to assessing circularity (Khan *et al.*, 2023; Kuzior, Arefiev, and Poberezhna, 2023; The Circularity Gap Report, 2022; Vinante *et al.*, 2021; Bogdanovich-Irina, Kistaeva-Natalia, and Egorova-Svetlana, 2020; Mayer *et al.*,

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2019; Haas *et al.,* 2015) and circular maturity (Uztürk and Büyüközkan, 2022), as well as analyzing mechanisms of transition from linear economy to closed-loop economy (Pichlak and Szromek, 2022; Doszhan *et al.,* 2022; Gileva and Shkarupeta, 2022; Surovitskaya, 2021; Umarova, 2021; Liu and Stephens, 2019).

On the other hand, however, no comprehensive studies have been carried out on circularity management in industrial ecosystems aimed at improving their circular maturity at the corporate level. For this reason, the given problem requires careful, further thorough exploration.

Managing circularity in industrial ecosystems is understood as an array of measures ensuring positive dynamics of circular maturity in industrial ecosystems, accounting for the risks and challenges of the external environment based on specific functions, principles, strategies, business models, circular solutions, and technologies introduced at different stages of the value chain using information, finances, resources, human capital, platforms, and collaborative mechanisms to achieve a high circularity index, a complex of long-term ESG effects, ultimately creating a mature circular ecosystem. We thoroughly explored the concept of industrial ecosystems based on sustainable business models incorporating eco-innovation and circularity in the context of the transition to Industry 5.0 in our earlier papers (Babkin, and Shkarupeta, 2022; Babkin *et al.,* 2022; Babkin *et al.,* 2021).

Circular maturity serves as a metric to quantify the level of circular development within an industrial ecosystem. It is defined as an aggregate indicator that characterizes the degree of circularity in the ecosystem, taking into account the adoption of circular principles, factors, strategies, and circular business models. Key drivers projected to influence circular maturity in an industrial ecosystem include circular potential, circular activity, and circular efficiency.

In general, the existing techniques for assessing circularity allow classifying metrics related to the generally accepted principles, such as resource consumption and recovery (Zaytsev *et al.,* 2021), circular product design, and waste generation. Sufficient metrics are yet to be devised for certain areas (for example, employee training, economic indicators, etc.). In addition, existing studies assessing the circular maturity of industrial ecosystems at the corporate level have certain limitations. This primarily concerns the system of indicators for assessing the circular maturity of ecosystems. Integral indicators describe recycling and symbiosis within the ecosystem from different perspectives but do not consider the dynamics of circularity in industrial ecosystems (Umarova, 2021). As a result, different estimates may be obtained for the circular maturity of industrial ecosystems. Furthermore, the framework for assessing the circularity of an industrial ecosystem should be equipped with a predictive function determining the circularity relative to the environmentally, socially, and economically acceptable thresholds (ESG results), answering four key questions:

- What is the general level of circular maturity in industrial ecosystems?
- How does the circular maturity vary over time in an industrial ecosystem?
- Which factors make the smallest and the greatest contribution to the final index of circular maturity in the industrial ecosystem?
- What are the challenges facing sustainable ESG practices in industrial ecosystems, and what methods are available for resolving them?

2. Methods

The research methodology is based on existing theoretical approaches to developing industrial ecosystems, the nature and the evolution of the circular economy and the areas under its umbrella, integration of modern literature and cooperation with experts, a framework for developing industrial ecosystems, techniques, and procedures for assessing circular maturity at the national, sectoral and corporate levels. The study fundamentally relies on the dialectical approach, also using the systemic, complex, interdisciplinary, cross-industry, project, value, holistic approaches, analysis based on the tools available from the WEF Strategic Intelligence Platform, content analysis, comparative analysis, method of taxonomic components, method of strategic maps, integral method, linear normalization, computational data analysis, desk research, analysis of published research, qualitative and quantitative data analysis, data-driven management by exception, ranking, triangulation of aggregated data with other established sources, benchmarking, etc.

The framework we have developed for assessing the circular maturity of an industrial ecosystem at the corporate level includes several stages shown in Figure 1.

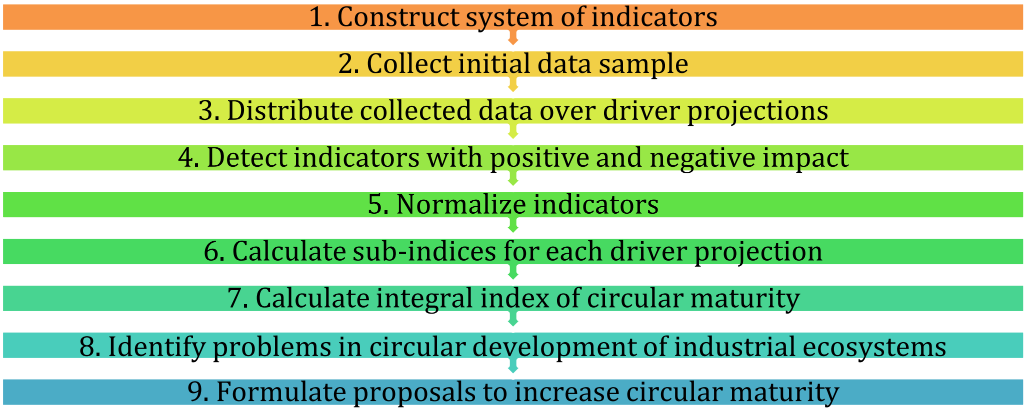

Figure 1 Framework for assessing the circular maturity of the industrial ecosystem at the corporate level

Stage 1. Constructing a system of indicators.

The proposed system of indicators for assessing the circular maturity of the industrial ecosystem at the corporate level (Table 1) includes 13 indicators distributed over three driver projections: circular potential, circular activity, and circular efficiency.

Table 1 System of Indicators for assessing the circular maturity of the industrial ecosystem at the corporate level

Driver projection	Indicator	Notation	Unit
1 Circular potential	1.1 Total investments	X1	million USD
	1.2 Investment projects in environmental protection	X2	million USD
	1.3 Cost of employee training	X3	million USD
	1.4 Number of training conducted: employee training	X4	thousand sessions
2 Circular activity	2.1 Current environmental protection costs	X5	million USD
	2.2 Labor productivity	X6	tons of steel per capita
	2.3 Number of suppliers with measures to improve environmental compliance	X7	%
	2.4 Environmental audits for suppliers of raw materials and equipment	X8	units
3 Circular efficiency	3.1 Lost time injury frequency rate	X9	coefficient
	3.2 Share of recycled water in total water consumption	X10	%
	3.3 Specific atmospheric emissions	X11	kg/ton of steel
	3.4 Recycling of secondary raw materials	X12	%
	3.5 Specific energy intensity	X13	Gcal/ton

Source: developed by the authors on the basis of (The Circularity Gap Report, 2022)

The approach based on identifying three driver projections allows us to balance low scores with respect to one projection with high scores with respect to another projection. The three projections compensate for a relatively large number of indicators and improve the analytic capabilities of the technique developed.

The framework for assessing circularity is validated during Stage 2 (Collect initial data sample) and Stage 3 (Distribute collected data over driver projections), with a focus on the case of the NLMK Group in Section 4 of the study. The validation results suggested that the framework's multi-dimensional approach was capable of capturing the intricacies of circular practices within a large industrial corporation.

Stage 4. Detect indicators with positive and negative impacts.

Higher values of some indicators correspond to a higher level of circularity in industrial ecosystems, and these indicators are regarded as positive (X1, X2, X3, X4, X5, X6, X7, X8, X10, X12). Higher values of other indicators correspond to a lower level of circularity in industrial ecosystems, and these indicators are regarded as negative (X9, X11, X13). Inverse values of negative indicators should be used for normalization.

Stage 5. Normalization of the indicators is carried out by one of the following methods: decimal scaling, minimax normalization, Z-score normalization, mean normalization. If the goal is to maintain the original data distribution while scaling down, decimal scaling would be appropriate. For a dataset with extreme values, Z-score normalization might be more suitable to ensure that these values do not disproportionately influence the analysis.

Stage 6. The calculation of sub-indices for each driver projection is carried out according to (1) on the basis of arithmetic averages of the corresponding normalized indicators, and all indicators have equal significance.

$$SI_{circ} = \frac{1}{n}\sum_{i=1}^{n}\frac{\tilde{x}_i^t - \tilde{x}_i^{min}}{\tilde{x}_i^{max} - \tilde{x}_i^{min}}, \quad (1)$$

where SI_{circ} is the sub-index of circularity for each of the three estimated projections;

n is the number of indicators;

$\tilde{x}_i^t$ is the value of the ith indicator in the tth industrial ecosystem;

$\tilde{x}_i^{min}$ is the minimum value of the ith indicator;

$\tilde{x}_i^{max}$ is the maximum value of the ith indicator.

Stage 7. Calculating the integral index of circular maturity.

All projections also have equal weight for estimating the integral index of circular maturity of industrial ecosystems (2):

$$I_{circ}{}^{t} = \frac{m\ p.circ}{N} P_{circ}{}^{t} + \frac{m\ a.circ}{N} A_{circ}{}^{t} + \frac{m\ e.circ}{N} E_{circ}{}^{t}, \quad (2)$$

where $I_{circ}{}^{t}$ is the integral index of circularity in industrial ecosystems;

N is the total number of estimated indicators;

$m_{p.circ}$, $m_{a.circ}$, $m_{e.circ}$ are the corresponding numbers of indicators in each of the three driver projections;

$P_{circ}{}^{t}$ is the sub-index of the tth industrial ecosystem with respect to the Circular Potential projection;

$A_{circ}{}^{t}$ is the sub-index of the tth industrial ecosystem with respect to the Circular Activity projection;

$E_{circ}{}^{t}$ is the sub-index of the tth industrial ecosystem with respect to the Circular Efficiency projection.

3. Results and Discussion

The proposed framework for assessing the circular maturity of the industrial ecosystem at the corporate level was validated using the data for the industrial ecosystem of the NLMK Group for 2016–2020. The NLMK group was chosen for study for several reasons. As one of the largest international producers of steel, NLMK Group is aware of its responsibility to society, nature, and future generations. The sustainable development of the NLMK Group is regulated by a range of internal documents. The NLMK production facilities are part of a closed-loop economy: 100% of the products can be involved in recycling and reprocessing, and 35% of the NLMK steel is produced with ferrous scrap. Closed-loop water supply is organized at fourteen NLMK enterprises. The goal of the 2022 Strategy is to maintain the share of recycled water supply in terms of production growth at the level of at least 96% (NLMK, 2022).

The data for calculating the circular maturity of the industrial ecosystem of the NLMK Group are given in Table 2. The source of initial data for calculating the circular maturity was the environmental, social, governance (ESG) databook.

Table 2 Data for calculating the circular maturity of the industrial ecosystem of the NLMK Group

Indicator	2016	2017	2018	2019	2020
X1	558.60	592.00	680.00	1,080.00	1,124.00
X2	54.00	33.00	80.00	78.00	82.00
X3	3.36	4.50	4.81	5.47	19.17
X4	53.40	55.40	52.50	52.90	52.90
X5	73.00	90.00	95.00	124.00	101.00
X6	482.05	501.96	503.33	448.49	461.00
X7	30.00	69.00	80.00	41.00	38.00
X8	21.00	36.00	39.00	34.00	13.00
X9	0.85	1.12	0.77	0.86	1.25
X10	96.30	96.40	96.50	96.60	96.60
X11	19.97	19.55	18.95	20.19	19.80
X12	90.00	91.00	93.00	99.00	99.00
X13	5.60	5.49	5.47	5.64	5.55

Source: compiled by the authors on the basis of (NLMK, 2021)

We computed the arithmetic mean, considering both the positive and negative influence of the variables, and obtained the following values for the circularity sub-indices and the integral circularity index of the NLMK Group's industrial ecosystem (Table 3).

Table 3 Sub-indices of circular maturity and the integral circularity index in the industrial ecosystem of the NLMK Group

Sub-index	2016	2017	2018	2019	2020
Sub-index of circular potential	0.185	0.283	0.316	0.528	0.784
Sub-index of circular activity	0.230	0.743	0.858	0.507	0.234
Sub-index of circular efficiency	0.231	0.402	0.800	0.545	0.565
Integral index of circular maturity	0.215	0.476	0.658	0.527	0.528

The sub-index of circular activity exhibits the greatest volatility, with the maximum reached in 2018 (0.858) and the minimum in 2016 (0.23). The maximum level of circular activity was observed for the NLMK Group in 2017 and 2018. The main factor in the negative trend of the declining sub-index of circular activity was a sharp reduction in the number of environmental audits conducted for suppliers of raw materials, materials, and equipment: from 39 in 2018 and 34 in 2019 to 13 in 2020. The sub-index of circular efficiency also decreased from 0.8 in 2018 to 0.565 in 2020. In this case, the factors were an increase in lost time injury frequency rate (LTIFR) from 0.77 in 2018 to 1.25 in 2020, an increase in atmospheric emissions from 18.95 kg/ton of steel in 2018 to 20.19 kg/t of steel in 2019 and 19.8 kg/t of steel in 2020, increase in energy intensity from 5.47 Gcal/ton in 2018 to 5.64 Gcal/ton in 2019 and 5.55 Gcal/ton in 2020.

The sub-index of circular potential exhibited consistent positive dynamics during 2016–2020. This is explained by the growth in investments, both total, for environmental protection and for employee training. The circular maturity of the NLMK Group's industrial ecosystem exhibited growth from 2016 to 2018. The maximum circularity index of NLMK Group's industrial ecosystem was observed in 2018, subsequently decreasing in 2019. The level of circular maturity was maintained at the same level in 2020.

The following factors accelerate circularity in the NLMK Group's industrial ecosystem: increasing investments, investment projects in environmental protection, costs of employee training, current environmental protection costs, the share of recycled water in total water consumption, and recycling of secondary raw materials. The following factors hinder the circular development of the NLMK Group: reduction in the number of employees, number of training conducted, labor productivity, number of suppliers with measures to improve environmental compliance, environmental audits of suppliers, increase in LTIFR, and energy intensity of products. A decrease in the circular maturity of the NLMK Group's industrial ecosystem was observed in 2019 and 2020 due to external challenges, such as export duties on metal products, volatility of raw materials markets, and unscheduled repairs at the Lipetsk site aimed at debottlenecking to increase the production capacity. The ongoing COVID-19 pandemic, disrupting the supply chains, including investment projects, has required additional resilience from the NLMK Group.

An effective system for managing circularity in industrial ecosystems is essential to address the negative trends and issues mentioned above and to accelerate circularity (Figure 2).

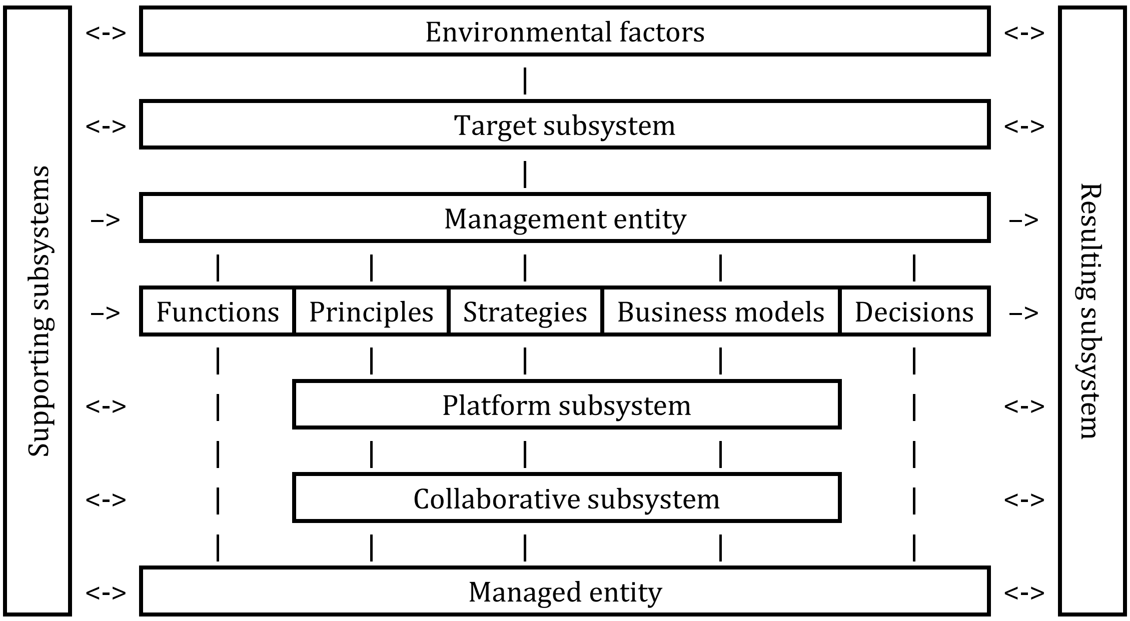

Figure 2 System for managing circular development in industrial ecosystems

Support subsystems for managing circularity in industrial ecosystems include information, financial, natural resources, human capital, and stakeholders. A favorable environment promoting growth is also an important part of the support subsystem for managing circularity in industrial ecosystems.

The environmental subsystem includes an increased load on the Earth's biocapacity, depletion of natural resources, and a considerable ecological footprint. Other major factors affecting circularity in industrial ecosystems include economic sanctions, altering the supply chains, and hindering access to technologies, but also stimulating import substitution and innovations to replace imported goods in industrial sectors and post-pandemic recovery of industrial ecosystems. The observed reduction in greenhouse gas emissions due to the COVID-19 pandemic is projected to have only a moderate impact on long-term emission trends. Nevertheless, there is a concurrent trend of tightening climate policies and regulations, particularly regarding carbon emissions.

The target subsystem for managing circularity in industrial ecosystems is intended to provide an environmentally safe and socially equitable space, growth of social welfare, minimize waste and losses, replenish resources based on more environmentally friendly supply chains, create a mature circular ecosystem, etc. The circular ecosystem is understood in this study as a network of organizations cooperating and interacting to promote a favorable environment for collective transformations enabling entire value chains (or individual industries or regions) to adopt circular practices.

Management subsystem (entities managing circularity in industrial ecosystems) includes the actors of the circular ecosystem, as well as the management of industrial ecosystems, industrial and eco-industrial parks, clusters, etc. The Managed subsystem (i.e., the object controlled to improve circularity in the industrial ecosystem) is the circularity evolution in industrial ecosystems. The levels at which circularity is managed in industrial ecosystems include the macro level (global, all sectors and industries), meso-level (national/state, sector, industry), micro-level (company level including corporations, multinational companies with multiple branches around the world, integrated structures, production facilities/divisions and assembly lines for products/processes).

Classical functions have been chosen for the system managing circularity in industrial ecosystems, including goal setting, planning, organization, motivation, coordination, regulation, monitoring and evaluation, and control. The principles for managing circularity in industrial ecosystems include: the elimination of waste and pollution, circulation of products and materials at their highest cost, environmental restoration, resource and impact decoupling, improving efficiency. The stages of managing circularity in industrial ecosystems include: design, sourcing, production, logistics, markets and sales, consumption, recycling of disposed products, reverse logistics. Strategies for managing circularity in industrial ecosystems include: recycling, efficient resource use, integration of renewable energy sources, restoration, reconstruction and recycling of products and components, prolonging the product life, product as service, sharing models, modifying the consumer behavior.

The circular business models in the management system include the holistic circular business model canvas, the ReSOLVE framework, the ENVISAGE model, the GRID business model, hybrid types of circular business models, industrial symbiosis, as well as five business models with respect to the value chain (circular supplies, product life extension, reusing waste, sharing platforms, product as a service). The following circular solutions can be used for managing circularity in industrial ecosystems (The Circularity Gap Report, 2022): efficient design and use of information and communication technologies (ICTs) and digital technologies, circular healthcare system, durable consumer products, effective design and use of consumer products, circular consumables, chemical-free practices, reduction of transportation and travel, vehicle design improvement, resource-efficient technologies, natural solutions for production, reduction of excess consumption, circular raw materials, infrastructure, vehicles, durability of machinery, equipment, vehicles, design improvements of vehicles. Three large groups of technologies can be used to accelerate circularity in industrial ecosystems: digital, physical, and biological technologies.

The system for managing circularity in industrial ecosystems must take into account the risks, including the tightening of climate policies in the world, carbon emission regulations, high costs of circular solutions (short-term losses for long-term benefits), decrease in fossil resource exports, volatile prices for fossil resources, etc.

It seems reasonable to establish a digital platform for accelerating the circular economy in the Russian Federation as part of the platform subsystem for managing circularity in industrial ecosystems. Such a platform has already been created at the global level. Since 2018, the Platform for Accelerating the Circular Economy (PACE) has become a global collaboration platform for key public and private decision-makers to share vision best practices and scale the circular economy together. Nearly 100 leaders from governments, companies and civil society across continents and sectors have joined the PACE Leadership Group to help accelerate the transition to a circular economy globally. Collaborative subsystem for managing circularity in industrial ecosystems allows for the creation and development of formal and informal communities based on the quintuple helix innovation model (academia + industry + government + society + environment). The resulting subsystem is intended for achieving the goals of managing circularity in industrial ecosystems, i.e., reaching a high level of the circularity index, as well as establishing a mature circular ecosystem. Effects of managing circularity along the value chain include direct ESG effects (economic, social, environmental), spillovers at the macro level, as well as the processing of critical raw materials, use of biological resources in the industrial sector, product life extension, and overproduction at the meso- and micro-levels.

The findings of this study align with and extend the existing body of research on circularity in industrial ecosystems. For instance, the emphasis on the role of environmental audits resonates with studies that highlight the importance of supplier engagement in achieving circularity. However, unlike some studies that report a stable or increasing trend in circular activities, this research identifies fluctuations in circular maturity levels attributed to both internal and external factors. The decline in circular activity and efficiency sub-indices corroborates findings from other studies that point to the challenges posed by external economic and environmental factors.

4. Conclusions

The study's primary contribution resides in its novel system for managing circularity in industrial ecosystems, distinguishing it from existing mechanisms in the industrial economy. This system's potential for generating synergistic effects is considerable, provided that orchestrated measures are systematically and coherently implemented across national, sectoral, and corporate levels. However, the framework is not without limitations. Its complexity and sensitivity to normalization methods render the estimates volatile. To enhance the framework's robustness, it is advisable to expand the sample size and extend the study to other industrial ecosystems beyond the NLMK Group. While the study focuses on the NLMK Group in Russia, the framework and findings have broader implications. The challenges and opportunities associated with managing circularity are not confined to any single geographic or industrial context. Therefore, the framework could serve as a blueprint for similar assessments in other industrial ecosystems globally. Future research directions include the development of a strategic management framework focused on sustainable ESG practices within the context of circular industrial ecosystems. Additionally, there is a need to refine managerial practices to better align with sustainable ESG goals. Such future inquiries could also explore the applicability of the framework across various sectors, such as construction and retail, thereby broadening its scope and utility processes.

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References

Babkin, A., Glukhov, V., Shkarupeta, E., Kharitonova, N., Barabaner, H., 2021. Methodology for Assessing Industrial Ecosystem Maturity in the Framework of Digital Technology Implementation. *International Journal of Technology*, Volume 12(7), pp. 1397–1406

Babkin, A., Shkarupeta, E., Kabasheva, I., Rudaleva, I., Vicentiy, A.A., 2022. Framework for Digital Development of Industrial Systems in the Strategic Drift to Industry 5.0. *International Journal of Technology,* Volume 13(7), pp. 1373–1382

Berawi, M.A., 2020. Managing nature 5.0: The role of digital technologies in the circular economy. *International Journal of Technology,* Volume 11(4), pp. 652–655

Bogdanovich-Irina, S., Kistaeva-Natalia, N., Egorova-Svetlana, E., 2020. Environmental Indicators as a Tool For Balanced Development of The Economy. *π-Economy,* Volume 13(6), pp. 7–19

Doszhan, R.D., Zhuparova, A.S., Kozhakhmetova, A.K., Semerkova, L.N., 2022. Economic Feasibility of Sustainable Innovations. *Models, Systems, Networks In Economics, Technology, Nature And Society,* Volume 3, pp. 42–59

Gileva, T.A., Shkarupeta, E.V., 2022. Reframing Strategic Management of Enterprise Development in the Digital Environment: Stages and Tools*. π-Economy,* Volume 97(5), pp. 28–42

Glukhov, V.V., Babkin, A.V., Shkarupeta, E.V., 2022. Digital Strategizing of Industrial Systems on The Basis of Sustainable Eco-Innovation and Circular Business Models in The Transition to Industry 5.0. *Economics and Management,* Volume 28(10), pp. 1006–1020

Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How Circular is The Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in The European Union and The World in 2005*. Journal of Industrial Ecology*, Volume 19(5), pp. 765–777

Ilyina, E.A., 2022. Circular Economy: Conceptual Approaches and Mechanisms of Their Implementation. *Organizer of Production*, Volume 30(3), pp. 21–30

Khan, M.A.-A., Cardenas-Barron, L.E., Trevino-Garza, G., Cespedes-Mota, A., 2023. Optimal Circular Economy Index Policy In A Production System With Carbon Emissions. *Expert Systems with Applications*, Volume 212, p. 118684

Khaykin, M.M., Babkin, A.V., 2022. Problems of Economic Security of An Industrial Enterprise Under Conditions of Modern Geopolitical Realities. *Organizer of Production*, Volume 30(4), pp. 165–176

Krmela, A., Šimberová, I., Babiča, V., 2022. Dynamics of Business Models in Industry-Wide Collaborative Networks for Circularity. *Journal of Open Innovation: Technology, Market, and Complexity,* Volume 8(1), p. 3

Kulibanova, V.V., Theor, T.R., Ilyina, I.A., Sharakhina L.V., 2022. Development of the ESG Agenda in The Russian Federation at The Regional Level. *π-Economy*, Volume 15(5), pp. 95–110

Kuzior, A., Arefiev, S., Poberezhna, Z., 2023. Informatization of Innovative Technologies For Ensuring Macroeconomic Trends in The Conditions of a Circular Economy. *Journal of Open Innovation: Technology, Market, and Complexity*, Volume 9(1), p. 10–20

Liu, Z., Stephens, V., 2019. Exploring Innovation Ecosystem from The Perspective Of Sustainability: Towards A Conceptual Framework. *Journal of Open Innovation: Technology, Market, and Complexity,* Volume 5(3), p. 48

Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P., Blengini, G.A., 2019. Measuring Progress Towards A Circular Economy: A Monitoring Framework For Economy ‐ Wide Material Loop Closing in The EU28. *Journal of industrial ecology*, Volume 23(1), pp. 62‐76

NLMK, 2021. ESG databook – 2021. Available Online at: https://nlmk.com/download_file.php?FILE_ID=139439&ELEMENT_ID=111273&NAME=ESG+датабук+–+2021&PAGE_URL=%2Fru%2Fsustainability%2F, Accessed on February 05, 2023

NLMK, 2022. Sustainability Annual Report 2022. Available Online at: https://nlmk.com/upload/iblock/a67/NLMK_OUR_2022.pdf, Accessed on September 30, 2023

Pichlak, M., Szromek, A.R., 2022. Linking Eco-Innovation and Circular Economy—A Conceptual Approach. *Journal of Open Innovation: Technology, Market, and Complexity*, Volume 8(3), p. 121

Shkarupeta, E.V., Ilyina, E.A., 2022. Digital Circular Economy: Concept, Model, Strategy, Framework, Technology. Organizer of Production, Volume 30(4), pp. 9–17

Surovitskaya, G.V., 2021. The Potential of "End-To-End" Digital Technologies to Improve Quality Management Systems. *Models, Systems, Networks In Economics, Technology, Nature and Society,* Volume 3, pp. 60–70

The Circularity Gap Report, 2022. Five Years Of The Circularity Gap Report. Available Online at: https://www.circularity-gap.world/2022, Accessed on February 05, 2023

Umarova, D.T., 2021. Foreign Experience of Scientific and Technological Integration. *Models, Systems, Networks In Economics, Technology, Nature And Society*, Volume 4, pp. 26–40

Uztürk, D., Büyüközkan, G., 2022. 2-Tuple Linguistic Model-based Circular Maturity Assessment Methodology: A Case for Agriculture. *IFAC-PapersOnLine*, Volume 55(10), pp. 2036–2041

Vinante, C., Sacco, P., Orzes, G., Borgianni, Y., 2021. Circular Economy Metrics: Literature Review and Company-Level Classification Framework. *Journal of Cleaner Production*, Volume 288, p. 125090

Zaytsev, A., Dmitriev, N., Rodionov, D., Magradze, T., 2021. Assessment of the Innovative Potential of Alternative Energy in the Context of the Transition to the Circular Economy. *International Journal of Technology*, Volume 12(7), pp. 1328–1338