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Evaluation of the Potential for the Development of the Circular Industry in the Region: A New Approach

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Abstract: The construction of circular economic models in industry represents a critical mechanism for achieving sustainable development goals. However, data on the development of the circular economy, derived from diverse metrics and assessment methodologies, often yield contradictory results. In light of this, the study suggested a new approach to evaluating the potential for circularization. This approach entails identifying key factors influencing circularization and assessing their suitability for the implementation of circular models of different levels. The study identified factors and indicators of the potential for industrial circularization at the regional level. The paper proposed a classification of circular economy models that simultaneously take into account the length of the production cycle and the degree of proximity to the circular economy. The rating method is employed to evaluate the potential of a region for the successful implementation of circular economy models. The rating is calculated by constructing both a general integral circularization potential index and individual sub-indices. The application of this methodology enabled the development of a ranking of Russian regions based on their potential for industrial circularization. To make recommendations, the analyzed regions were divided into four groups, according to an evaluation of the circularization potential.

Keywords: circular economy; industrial development; circularity capacity; circular economy evaluation; life cycle assessment; circular business models; region; circularity indicators; r-imperatives; level of circularity



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1. Introduction

In contemporary global contexts, the transition to a circular economy (CE) has emerged as a pivotal development strategy for industrialized nations. Shifting from linear to circular business models is essential to decouple economic growth and resource consumption. This transformation facilitates sustainable development by reconfiguring resource and energy flows from linear to circular systems [1]. The adoption of circular economy principles offers a multitude of benefits, including reduced energy and resource consumption—partly achieved by utilizing waste as an energy source [1–3]—as well as decreased waste generation and increased rates of recycling and reuse [4–6]. Furthermore, circular models enhance business efficiency and competitiveness [7–9], contribute to climate change mitigation efforts [10], and generate comprehensive positive impacts on sustainable development, particularly in social and environmental dimensions [11,12].

However, in practice, the development indicators of the circular economy often fall short of their potential or present ambiguous results. For instance, the overall recycling rate has shown limited progress globally, even in Europe, which is considered a leader

in circular economy implementation. Despite its advanced position, Europe recycles less than 50% of its total waste [13]. Similarly, in Russia, the share of disposed and neutralized production and consumption waste in 2022 accounted for 45.7% of the total waste generated nationwide, with significant regional disparities observed [14].

Moreover, the outcomes of integrating circular economy principles with Industry 4.0 and digital transformation reveal contradictory trends. On the one hand, numerous studies highlight the potential of digital technologies to facilitate the transition to circular models, emphasizing their role in optimizing resource use, enhancing supply chain efficiency, and enabling innovative business models [15–17]. Digital solutions, such as the Internet of Things, Artificial Intelligence, and blockchain, are often regarded as critical enablers of the circular economy, providing tools for tracking, monitoring, and managing resources more effectively [18–20].

On the other hand, empirical evidence suggests that the rapid growth of the digital economy has exacerbated environmental pressures. Data from the Digital Economy Development Report indicate that the expansion of digital technologies has led to increased resource consumption and a disproportionate rise in waste generation compared to recycling rates [21]. Contrary to initial expectations, digitalization has not achieved significant dematerialization; instead, it has contributed to higher energy and water consumption, further straining natural resources [21]. These findings underscore the gap between theoretical assumptions and practical outcomes, revealing that many earlier projections regarding the environmental benefits of digitalization remain unfulfilled.

This divergence between expectations and reality highlights the need for a comprehensive evaluation of the circular economy. Such an evaluation is essential to identify gaps, establish clear priorities, and develop coherent strategies for advancing CE principles in alignment with sustainable development goals.

Numerous scientific studies have explored the evaluation of the circular economy from various methodological perspectives and at different levels of analysis. A synthesis of existing literature reveals that the primary focus of these studies is on assessing the current status and progress of circularization across various levels of the economic hierarchy, including micro (firm-level), meso (industrial or regional), and macro (national or global) scales. A significant proportion of the approaches, methods, and evaluation tools developed in this field are aimed at measuring the outcomes of circularization and the effectiveness of transitioning to circular models.

Sergienko, Smaznova, and Razumova introduced a waste generation indicator to evaluate the circularity of a country's economy. This indicator is calculated as the ratio of the mass of waste generated by industries to both the population and the country's GDP, providing a measure of resource efficiency and waste management [22].

At the regional level, Jia and Zhang developed a system index based on the 3R principles—Reduce, Reuse, and Recycle—to assess circular economy performance. This framework emphasizes the importance of minimizing resource use, maximizing reuse, and enhancing recycling efforts [23].

On a micro-level scale, Matos et al. explored indicators of circularity by categorizing them according to their focus areas, sustainability dimensions, target profiles, data availability, and their influence on companies. This approach provides a detailed understanding of how circular economy practices can be analyzed at the organizational level [24].

Belhadi et al. suggested a model to evaluate the level of circular economy and Industry 4.0 integration through a standardized index that incorporates the interactions between different dimensions and practices and allows organizations to be grouped into three categories: “beginner”, “ongoing”, and “performing” [25].

Guryeva offered a comprehensive evaluation framework for the circular economy, addressing macro, meso, and micro levels. At the macro level, the assessment is based on indicators from the List of National Indicators of Sustainable Development Goals. The meso level incorporates 12 indicators grouped into six indices, focusing on environmental, economic, and social aspects of enterprise activity. The micro level relies on a survey of 30 questions, structured into three blocks (environmental, economic, and social) to assess organizational practices [26].

In addition to universal indicators, some researchers emphasize the importance of tailoring assessment methods to the specific contexts of individual countries.

For instance, China pioneered the development of national circular economy indicators to monitor its progress. These indicators, applicable at macro, meso, and micro levels, cover key aspects such as production, efficiency, resource consumption and integrated use of resources, waste disposal, and pollutant emissions [27].

In Russia, Bobylev and Solovyova proposed a set of indicators to evaluate the circular economy, including water and energy intensity of GDP, industrial and consumer waste generation and circulation, solid household waste generation per capita, the share of recycled and neutralized waste in the total volume of waste generated during production and consumption, and overall resource efficiency, measured in both absolute terms and per unit of GDP [28].

Despite these advancements, there is no consensus among researchers on how to define and categorize micro, meso, and macro levels. Different studies adopt varying approaches to delineating these hierarchies, reflecting the complexity and multifaceted nature of circular economy assessment. Similarly, the sets of indicators used to assess the circular economy (CE) vary significantly across studies, reflecting diverse methodological approaches and priorities. Despite this variability, a common focus of this body of research remains on evaluating the level of economic circularization.

Another significant cluster of research focuses on evaluating the circular economy (CE) through its components and the effects and consequences arising from circularization.

For example, Kulakovskaya et al. propose an integrated approach to assess the environmental and economic impacts of CE implementation at the value chain level. Their methodology combines material flow analysis, life cycle assessment, life cycle cost calculation, and scenario development, offering a comprehensive framework for evaluating circularity [29].

Walzberg et al. conducted a systematic analysis of circularity metrics, identifying methods borrowed from various scientific disciplines. These include industrial ecology (e.g., life cycle assessment, environmentally extended input–output analysis, material flow analysis, emergy, and exergy analysis), complex systems science (e.g., system dynamics, discrete event simulation, agent-based modeling, and operations research), and other circularity-specific metrics [30]. The authors highlight a predominant focus on producer-centric assessments (sustainable production) rather than consumer-centric evaluations (sustainable consumption). They also note the static nature of many existing methods, which often fail to capture market dynamics or social changes associated with CE transitions. While these methods are effective in assessing the sustainability of CE performance, they exhibit limitations in evaluating the transitional components of circular economy implementation.

Numerous research studies have explored various metrics for assessing the circular economy (CE) [31,32], encompassing different levels and domains of evaluation [33,34].

Iacovidou et al. categorized these metrics by value domains, identifying and analyzing environmental, technical, economic, and social indicators [32]. Saidani et al. developed a taxonomy of 55 CE indicators, organizing them into 10 categories based on criteria such as the levels of CE implementation (micro, meso, macro), CE loops (maintain, reuse, remanufacture,

recycle), performance (intrinsic, impacts), the perspective of circularity (actual, potential), and their degree of transversality (generic, sector-specific) [35]. Parchomenko et al. proposed a framework comprising 63 CE metrics and 24 features relevant to CE, identifying three clusters of metrics frequently assessed together: resource efficiency, materials stocks and flows, and product-centric metrics [36]. At the micro level (single firm or product), Kristensen and Mosgaard reviewed 30 CE indicators and found that the majority focused on recycling, end-of-life management, and remanufacturing, while fewer addressed disassembly, lifetime extension, waste management, resource efficiency, or reuse [37].

In contrast, Kofos et al. shifted the focus from indicators and metrics to information tools that enhance CE visibility and improve stakeholders' confidence in environmentally related business data, particularly regarding product flows [38].

The applicability and relevance of these metrics depend on the specific objectives of a study and the availability of data for the corresponding indicators. This variability arises because the selection of indicators is closely tied to the researcher's focus and the context of the investigation.

Another significant area of research focuses on identifying and evaluating factors that act as drivers or constraints in the development of a circular economy (CE).

For instance, Aloini et al. identified 14 key drivers of the circular economy: (1) the legal and regulatory framework; (2) government tax and financial incentives; (3) the potential to enhance production efficiency; (4) opportunities for new business development and innovation; (5) environmental concerns; (6) strategic challenges requiring resolution; (7) skills and capabilities for CE implementation; (8) global pressures; (9) job creation potential; (10) consumer awareness of CE benefits; (11) communication and collaboration; (12) supply chain configuration; (13) recycling technologies; and (14) information and communication technologies [39].

Similarly, Kosolapova et al. examined CE drivers, including innovation, investment, digitalization, new business ecosystems, and institutional frameworks. To quantify the effects of the circular economy, the researchers utilized three key indicators: waste generation in production and consumption, energy intensity of the gross regional product (GRP), and water intensity of the GRP [40].

At the same time, it is reasonable to evaluate not only individual factors but also their collective impact to assess the potential for the development of a circular economy (CE). Given that the economy is a complex socio-economic system, it is essential to consider the factors influencing CE development in an interconnected and holistic manner.

Furthermore, as evidenced by the analysis of scientific literature, theoretical research predominantly explores approaches to assessing various types of circular development without linking them to specific circular models. However, at different stages of CE development, enterprises tend to adopt different types of circular models, each with its unique characteristics and implications. Therefore, a more nuanced approach that integrates specific circular models into the assessment framework is necessary to provide actionable insights for businesses and policymakers.

For example, during the initial stages of transitioning to circular production, organizations often adopt circular models that do not significantly alter their operational processes or production cycles but help mitigate negative environmental impacts by reintroducing a portion of used resources into the production cycle. This highlights the importance of aligning the evaluation of circularization potential with specific circular economy (CE) models, as the choice of the model directly influences the feasibility and effectiveness of circular practices.

Currently, numerous concepts exist, within which researchers identify the most significant circular models. These concepts are frequently presented in the form of R-imperatives,

which use the prefix “re-” (from Latin, meaning “again”, “over”, or “back”) to encapsulate the essence of circular economy principles [41]. Initially, researchers focused on three R-imperatives: reduce, reuse, and recycle. Later, a fourth imperative—‘recover’—was added in some studies [42]. Over time, the number of R-imperatives expanded, leading to the development of new CE concepts, models, and practices [43,44].

In their research, Reike, Vermeulen, and Witjes analyzed 69 articles that identified various R-imperatives, ultimately compiling a list of 38 unique terms. Based on this analysis, they proposed a framework of 10 main circular models, known as the 10R concept [45].

A year earlier, Potting, Hekkert, Worrell, and Hanemaaijer, in their study on measuring circular innovations within production chains, also identified 10 R-imperatives [46]. While their models largely overlap with those proposed by Reike et al., there are differences between them, the main of which are the classification criteria. Potting et al. ranked the R-imperatives based on their proximity to the linear or circular economy, with R9 being closest to the linear model and R0 closest to the circular model. In contrast, Reike et al. used the length of production cycles as their ranking criterion, where R0 represents short cycles (the product remains largely unchanged) and R9 represents long cycles (the product undergoes significant transformation and loses its original functionality).

The theoretical analysis conducted in this study underscores the importance of considering the specific characteristics of circular economy models when assessing the potential for CE formation. By aligning evaluation frameworks with the unique features of these models, researchers and practitioners can better understand and facilitate the transition to a circular economy.

Despite the substantial body of research dedicated to evaluating the circular economy, several research gaps remain. First, the majority of studies focus on assessing the achieved level or outcomes of circularization. While these approaches provide valuable insights into the actual level of circular development, they often overlook the conditions under which these results were attained. Second, although significant research has been conducted on identifying factors that drive or constrain the transition to a circular economy, there is a lack of integrated, comprehensive evaluations of the potential for transitioning to circular practices within specific socio-economic systems. Third, existing studies rarely explore the relationship between the conditions for circularization and the specific models of the circular economy. Additionally, there is a lack of clarity regarding the levels at which CE evaluation should be conducted.

In summary, there is a scarcity of research directly focused on evaluating the potential for circularization. While measuring the circular economy is essential for its improvement—following Peter Drucker’s principle that “what gets measured gets managed”—existing methods predominantly assess the progress and outcomes of CE initiatives. However, this progress is heavily influenced by the potential for establishing a closed-loop economy within specific, geographically localized industrial systems, a topic that has not yet been comprehensively explored.

In light of these gaps, this study aims to develop a novel approach and toolkit for evaluating the potential for building a circular industry within meso-level socio-economic systems. The proposed framework will account for the readiness of territories to adopt various circular economy models, thereby providing a more holistic understanding of the conditions necessary for successful CE implementation.

The remainder of the article is structured as follows: Section 2 presents the theoretical model and research methodology; Section 3 discusses the main results, including the rating of the circularization potential of Russian regions calculated using the author’s methodology, as well as the evaluation of circularization potential for specific categories of CE models; and Section 4 provides conclusions and recommendations based on the findings.

2. Materials and Methods

2.1. Conceptual Framework and Theoretical Model of the Study

Building on the two variants of the 10R concepts discussed earlier, it is logical to develop an integrated methodology for evaluating the potential for circularization of regional industry. This methodology will assess the feasibility of implementing 11 circular models at the regional level, ranking them according to the length of the production cycle and their degree of proximity to the principles of a circular economy. In total, the following models were identified: R10 Re-mine, R9 Recover, R8 Recycle, R7 Re-purpose, R6 Remanufacture, R5 Refurbish, R4 Repair, R3 Reuse-Resell, R2 Reduce, R1 Rethink, R0 Refuse. Models were ranked simultaneously by the length of the production cycle and the degree of proximity to the circular economy. In this research, R10 is the long-cycle model closest to the linear economy, and R0 is, respectively, the short-cycle model closest to the circular economy.

The analysis reveals that for large industrial nations, where the transition to a circular economy is particularly relevant, it is advisable to evaluate the potential for circularization at the meso-level, specifically at the regional level. This choice is driven by the unique characteristics of industrial production in countries with significant regional differentiation in terms of territorial and climatic conditions, such as the United States, Canada, China, India, and Russia. In such large countries, where regions often span vast geographical areas, most circular interactions—especially those involving perishable industrial waste—occur primarily within regional boundaries. Furthermore, regions within these countries often exhibit distinct economic structures and possess a high degree of autonomy in implementing regulatory measures. This autonomy enables them to create institutional conditions conducive to the development of circular industries. Consequently, it is highly relevant to evaluate the availability of regional conditions necessary for implementing circular models.

To solve the research objective, the main factors that influence the circularization of production were identified (Figure 1).

When identifying the factors, the initial assumption was that the decision to transition from a linear to a circular production model is influenced by a multitude of factors. These include not only internal factors, such as financial, human, and technological conditions, but also external factors. While some external factors, such as federal taxes and fees, uniformly affect businesses across the country, others, such as regional support measures, vary significantly between regions. Importantly, these factors must be evaluated in a systemic manner, considering their interrelationships.

Drawing on the four main spheres of society—economic, political, socio-cultural, and environmental—we identified 12 key factors of the regional environment that collectively characterize the potential for implementing various circular economy models in the industrial sector (referred to as the potential for the circularization of regional industry). The selection of these factors was guided by their influence on the primary directions of production development: smart use and production, product life cycle extension, and the beneficial application of materials. Additionally, the factors were aligned with the circular economy models identified earlier during the development of the author's integrated approach.

Factors of the circularization potential of the regional industry:

1. Financial situation of enterprises. The transition to new business models or even the introduction of local changes in the business processes of companies requires significant financial investments, and organizations with unstable financial situations cannot afford it.
2. The economy of the region. It reflects the existing conditions in the region for the successful implementation of entrepreneurial activities in the field of industry.

3. Business modernization. This category includes conditions that encourage the company to modernize production.
4. Development of new markets. This demonstrates how active the region's enterprises are, which may be related to their willingness to develop new markets (for example, recyclables or industrial waste).
5. Digital technologies. Most digital technologies have a positive impact on improving the environmental friendliness of production, so companies that already use digital technologies are more likely to be ready to introduce new technologies that allow them to streamline their business processes.
6. Green technologies. This factor reflects the contribution of enterprises and regional authorities to technologies aimed at improving the environmental situation.
7. Transport accessibility. Manufacturing enterprises need to regularly carry out a huge volume of cargo transportation related to both purchases and sales; therefore, the quality of transport infrastructure is extremely important, especially when it comes to the delivery of perishable industrial waste.
8. Sustainable personnel. To implement the principles of sustainable development in an organization, it is necessary to have qualified personnel who are familiar with the principles and standards of ESG and are able not only to modernize the company's business processes but also to support their work.
9. Government support. The costs required to reform the business processes of companies based on the circular model of production are very high; therefore, to stimulate the transition to a circular economy, government support is needed.
10. Waste management. This category reflects the extent to which enterprises in the region are currently involved in recycling activities.
11. Changing the culture of production and consumption. This factor shows how many citizens have switched to responsible consumption (using recyclable products, reducing consumption, repairing purchased goods, etc.) and how many organizations have switched to responsible production (reducing or abandoning the use of non-renewable resources, introducing energy and resource-saving technologies, etc.).
12. Information field. To change the culture of production and consumption, an important factor is the popularization of the principles of sustainable production and eco-friendly consumption in the media.

The main directions of production development are smart use and production, product life cycle extension, and the useful application of materials.

It is important to note that different circular models affect the production circularization process in different aspects.

Circular models such as energy extraction and recycling contribute to the beneficial use of materials, but they do not globally affect the departure from traditional production value chains.

Reusing, repairing, restoration, and repurposing are more aimed at increasing the life of the product and its components. These circular models are at the average level of business process circularization.

Rethinking (by increasing efficiency), reduction, and complete abandonment of the use of non-ecological raw materials and/or components represent the highest level of business innovation, smart production and consumption.

Based on this, it is important to evaluate the readiness of regions to implement various types of circular models in the industrial sector. This will make it possible to find out which models of the circular economy should be focused on, and which ones are not yet available within the region's industry. For the circularization factors of the regional industry, indicators reflecting the degree of their development were selected (Table 1).

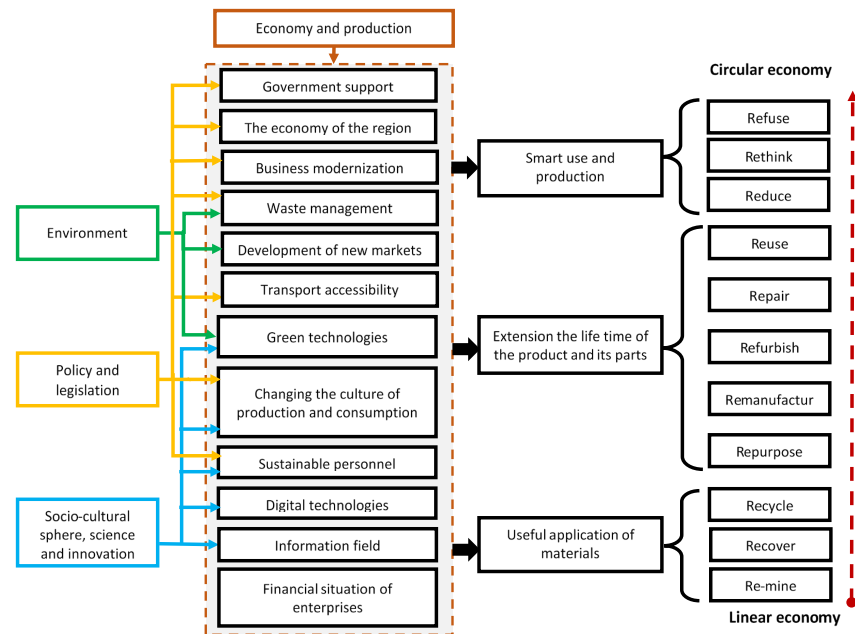


Figure 1. Factors of regional industry circularization.

Table 1. Indicators of industrial circularization potential.

Factor	Indicator	Unit of Measurement
The financial situation of enterprises	Net financial result of organizations' activities	million rubles
	Accounts payable of organizations	million rubles
	Cost of fixed assets (at the end of the year; at full book value)	million rubles
The economy of the region	The proportion of unprofitable organizations	% of the total number of organizations
	Surplus/deficit of consolidated budgets of the subjects of Russia	million rubles
	Gross regional product	per capita, rubles
	Migration growth rate	% per 10,000 people
	Unemployment rate	%
	Number of organizations per thousand people	units
Business modernization	The share of employees of organizations with wages below the minimum subsistence level of the working-age population (excluding small businesses)	%
	The degree of depreciation of fixed assets	%
Development of new markets	Existing technology parks	units
	Industrial production indices	% of the previous year
	Number of active businesses	units
	The number of "fading" enterprises	units
Digital technologies	Use of personal computers in organizations	% of companies
	Using servers in organizations	% of companies
	Using local computer networks in organizations	% of companies
	Using cloud services in organizations	% of companies
	The use of big data collection, processing, and analysis technologies in organizations	% of companies
	The use of Internet of Things technologies in organizations	% of companies
	The use of artificial intelligence technologies in organizations	% of companies
	The use of digital platforms in organizations	% of companies
	The level of innovation activity of organizations	%
	Advanced manufacturing technologies used	units
	Developed advanced production technologies	units

Table 1. Cont.

Factor	Indicator	Unit of Measurement
Transport accessibility	The density of paved public roads at the end of the year	km of track per 1000 km ² of territory
	The proportion of public roads of local importance that meet regulatory requirements	%
Green technologies	Special costs associated with innovations aimed at improving the environment per organization	million rubles
	The proportion of trapped and neutralized pollutants in the total amount of pollutants discharged from stationary sources	%
	Emissions of pollutants into the atmosphere coming from stationary sources	thousand tons
	The index of the physical volume of environmental expenditures for the conservation of biodiversity and the protection of natural territories	% of the previous year
Waste management	The share of municipal solid waste, including those that have been processed (sorted), in the total mass of municipal solid waste generated	%
	The share of waste allocated for disposal as a result of separate accumulation and processing (sorting) of solid municipal waste in the total mass of solid municipal waste generated	%
	The share of municipal solid waste sent for processing (sorting) in the total mass of municipal solid waste generated	%
	The share of disposed and neutralized production and consumption waste in the total volume of generated production and consumption waste	%
	Discharge of polluted wastewater into surface water bodies	million m ³
	Number of waste disposal enterprises	units
	Number of regional municipal solid waste management operators	units
	The number of enterprises that accept recyclables	units
	Number of landfills	units
	The volume of production of processing enterprises	tons
	The number of companies that post non-financial reports in the form of open data	% of companies
	Compliance with the SDGs by manufacturers	% of companies
	The volume of electronic waste	GB
Government support	Availability of support measures for enterprises operating under a circular business model	units
	Availability of support measures for enterprises initiating the transition to a circular business model	units
Sustainable personnel	Training of circular personnel	people
	Demand for sustainable staff	people
Information field	Public awareness about the circular economy	%
	Manufacturers' attitude towards recycled goods	%
	Attitudes towards recycled goods in the media	%
Changing the culture of production and consumption	The proportion of citizens using recyclable goods	%
	The share of enterprises producing recyclable goods	%
	Energy intensity of GRP	kilowatt- hour/ruble
	The proportion of citizens repairing their things	%
	The number of used goods sold or donated on internet sites per year	units per 10,000 people

The proposed indicators make it possible to reflect the availability of conditions for the implementation of circular models.

The core of the proposed methodology lies in analyzing the position of regions in terms of the availability of conditions for industrial circularization, based on 12 groups of factors identified through a review of scientific literature and industrial circularization practices. The proposed indicators are advisory in nature, and in cases where statistical data for certain indicators are unavailable, they may be excluded from the calculations.

To ensure a sufficient level of accuracy in the assessment, it is recommended to use at least 2–3 indicators for each group of factors. In future studies, the list of recommended indicators can be expanded as the statistical data on sustainable development within regions becomes more comprehensive.

2.2. The Relationship of Industrial Circularization Factors with Circular Models of Various Levels

Circular models of different types require distinct conditions not only for their initial adoption in production but also for their successful implementation, ensuring that enterprises remain competitive. Table 2 presents the distribution of key factors across various types and levels of circular models.

Table 2. Distribution of industrial circularization factors for different types of circular models.

Circular Model	Model Level	Key Factors
R0 Refuse	Short cycles	Changing the culture of production and consumption
R1 Rethink		
R2 Reduce		
R3 Reuse-Resell	Medium-high level cycles	Development of new markets
R4 Repair		
R5 Refurbish	Medium-low level cycles	Green technologies
R6 Remanufacture		Digital technologies
R7 Re-purpose		Business modernization
		Waste management
R8 Recycle	Long cycles	Information field
		Transport accessibility
R9 Recover		The economy of the region
		Government support
R10 Re-mine		Sustainable personnel
		The financial situation of enterprises

The proposed distribution of factors is pyramidal in nature. This implies that the successful implementation of circular models at higher levels (characterized by shorter production cycles) requires the prior development of conditions necessary for implementing circular models at lower levels. In Russia, however, the transition to a circular economy is still in its early stages, and only a limited number of companies are currently capable of operating under short-cycle circular models. Consequently, during the validation of the methodology, the potential for circularization was not assessed for models at this level.

2.3. Data and Algorithm for Evaluation of Circularization Potential

To evaluate the circularization potential in accordance with the author’s approach, it is necessary to have official statistical data on the indicators used. This study used data from Rosstat of Russia, including open data posted on the website “rosstat.gov.ru” (accessed on 28 September 2024) [47], the national set of SDG indicators [14], and the collection “Regions of Russia. Socio-economic indicators” [48]; data from the aggregator of organizations working with recyclables, Online Ecology LLC (Yaroslavl, Russia), were also used [49]. For the evaluation, it was necessary to determine how important a particular indicator is. To do this, a decision was made to use the entropy method, which allows an impartial assessment of the contribution of each factor [50]. The absence of fixed weights in the proposed methodology allows for its adaptation to assessments in countries with significant differences in economic, social, and environmental contexts. Analyzing the derived weights of factors also provides insights into the degree of uniformity in regional

development and helps identify indicators with the strongest regional differentiation (those with the highest weights). Adjusting these indicators, for instance, through targeted government support measures, could help create more uniform conditions for industrial circularization across different regions.

Before performing the calculations, the data for all selected regions were normalized (the indicators, the increase of which indicated the successful implementation of the concept of sustainable development, were evaluated using the standard normalization function using the Minimax linear scaling method, and for the inverse indicators, a numerical series was used in which all the numbers at the beginning were converted to negative ones). After normalization, the value of the Shannon entropy for each indicator was calculated directly, after which their weights were determined based on the values obtained. The final stage was the calculation of the final assessment of the circularization potential, taking into account certain weights.

Figure 2 shows a complete scheme of the proposed methodology for evaluating the potential for industrial circularization.

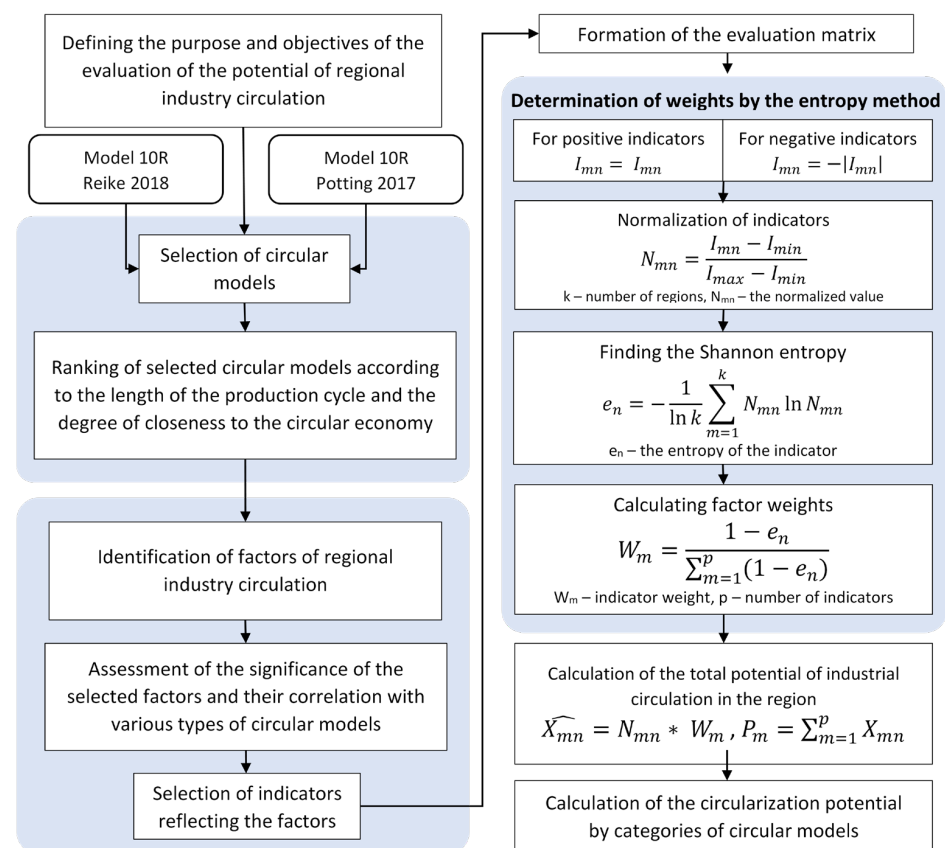


Figure 2. Methodology for evaluation of the circularization potential of the regional industry.

At the moment, it is not possible in Russia to obtain official statistics on a number of selected indicators. Therefore, the following indicators were excluded for testing the suggested methodology at the regional level: advanced production technologies developed, the volume of production of processing enterprises, the number of companies posting non-financial reports in the form of open data, compliance with the SDGs by manufacturers, the amount of electronic waste, as well as indicators related to factors such as government support, sustainable personnel, the information field, and changing the culture of production and consumption. All other indicators were used in the calculations. The proposed methodology has been tested in 82 Russian regions (Moscow, St. Petersburg, and Sevastopol were excluded from the sample because they showed values of indicators that

deviated significantly from the general sample); data for 2022 were used for all indicators (with the exception of the cost of environmental innovations and the proportion of employees of organizations with wages below the subsistence level, for which data from 2021 were used; the choice of this time interval was caused by the need to level out the impact of the lag since the benefits of investing in innovation do not begin to be fully disclosed until next year).

The implementation of this methodology makes it possible to assess the potential for the circularization of regional industry, taking into account the possibility of applying models of various types in practice.

3. Results

The calculation of the circularization potential for certain categories of circular models (related to long cycles and medium cycles of low and high levels) was carried out as follows:

1. The matrix of indicators was formed separately for the key indicators for each level.
2. The entropy weights were also estimated only for key indicators for this category of circular models.
3. To determine the potential for industrial circularization in the region for each group of circular models, all observations were divided into four groups: the first group included the first 20 regions with the highest potential assessment; the second group included regions occupying positions 21–40; the third group included regions from 41 to 60, and the fourth group included all remaining regions. This is due to the specifics of the evaluation, since during normalizing, indicators were evaluated in comparison with the best region, and when determining the degree of development of the circularization potential of the regional industry, it was decided to base it on the regions with the best values of indicators. This makes it possible to identify advanced and lagging regions based on the availability of conditions for industrial circularization. In order to increase the level of certainty about the magnitude of the circularization potential of the industry, a decision was made to abandon the use of an estimated scale with an odd number of categories (for example, the Likert scale), since it is quite difficult for a neutral category to determine the possibility of implementing circular models and, consequently, to understand whether the existing conditions are sufficient for the implementation of circular models of a higher level. According to the accepted four-point scale, all observations are divided into four almost equal groups. Since the number of analyzed regions during the testing of the methodology was 82, and since this number cannot be completely divided into 4, it was decided to increase the fourth group by two regions. In the future, if the number of regions is not a multiple of four, it is also recommended to increase the last group by the required number of regions. This is explained by the fact that the fourth group includes the subjects of Russia, in which industrial enterprises do not yet have sufficient conditions for the transition to circular models, and regional authorities need to focus more on improving the conditions for industrial circularization necessary for the functioning of lower-level circular models.
4. The subjects of Russia belonging to the first group for all types of models are considered the most suitable for the implementation of circular models of the corresponding category in industry. In regions where industry belongs to group 2, it is also possible to implement circular models of the appropriate type, but it will require more effort compared to the regions of the first group. For regions that have been assigned to groups 3 or 4, the widespread introduction of this type of circular model is currently impossible.
5. After assigning a region to group 3 or 4, the possibility of implementing higher-level circular models based on its industry is considered extremely unlikely.

Table 3 shows the rating of the regions of Russia in terms of the potential for industrial circularization from the largest to the smallest. To form general recommendations, all the analyzed regions were divided into 4 groups, according to a numerical assessment of the circularization potential. Due to the small number of regions, 20 regions were assigned to the first, second, and third groups, and 22 regions to the fourth.

Table 3. The potential of industrial circularization in the regions of Russia.

Region	Evaluation	Group	Region	Evaluation	Group
Moscow region	0.619	1	Volgograd region	0.362	3
Sverdlovsk region	0.501	1	Udmurt Republic	0.362	3
Republic of Tatarstan	0.499	1	Orenburg region	0.362	3
Leningrad region	0.475	1	Republic of Sakha (Yakutia)	0.353	3
Kemerovo region	0.473	1	Ulyanovsk Oblast	0.351	3
Krasnodar region	0.463	1	Arkhangelsk Oblast without AO	0.351	3
Tomsk region	0.460	1	Tambov region	0.350	3
Perm region	0.451	1	Kamchatka region	0.345	3
Chelyabinsk region	0.447	1	Omsk Oblast	0.345	3
Nizhny Novgorod region	0.446	1	Tver Oblast	0.344	3
Belgorod region	0.440	1	Smolensk Oblast	0.344	3
Novosibirsk region	0.438	1	Magadan region	0.340	3
Vologda Oblast	0.434	1	Pskov Oblast	0.339	3
Rostov region	0.430	1	Bryansk Oblast	0.338	3
Novgorod region	0.428	1	Penza region	0.335	3
Voronezh region	0.426	1	Kirov region	0.335	3
Irkutsk region	0.424	1	Chukotka AO	0.334	3
Kaluga Oblast	0.421	1	Orel region	0.333	4
Tula region	0.417	1	Republic of Buryatia	0.329	4
Yaroslavl Oblast	0.415	1	Kostroma Oblast	0.329	4
Tyumen region without AO	0.411	2	Kursk Oblast	0.326	4
Khanty-Mansiysk AO—Yugra	0.410	2	Amur region	0.323	4
Republic of Adygea	0.410	2	Transbaikal Territory	0.323	4
Krasnoyarsk region	0.408	2	Republic of Ingushetia	0.322	4
Vladimir region	0.407	2	Republic of North Ossetia-Alania	0.320	4
Stavropol Territory	0.405	2	Republic of Mari El	0.319	4
Samara region	0.405	2	Republic of Karelia	0.316	4
Republic of Bashkortostan	0.404	2	Republic of Khakassia	0.314	4
Yamalo-Nenets AO	0.400	2	Republic of Mordovia	0.313	4
Ivanovo region	0.393	2	Republic of Komi	0.312	4
Lipetsk region	0.384	2	Republic of Altai	0.306	4
Kaliningrad Oblast	0.383	2	Republic of Kalmykia	0.302	4
Chechen Republic	0.383	2	Republic of Crimea	0.300	4
Ryazan region	0.383	2	Astrakhan Oblast	0.298	4
Primorsky Krai	0.379	2	Jewish Autonomous Region	0.295	4
Murmansk region	0.378	2	Republic of Tyva	0.274	4
Kurgan region	0.373	2	Nenets AO	0.251	4
Saratov region	0.373	2	Republic of Dagestan	0.247	4
Sakhalin region	0.370	2	Kabardino-Balkar Republic	0.211	4

Table 3. *Cont.*

Region	Evaluation	Group	Region	Evaluation	Group
Chuvash Republic	0.370	2			
Altai Territory	0.367	3			
Karachay-Cherkess Republic	0.364	3			
Khabarovsk Territory	0.363	3			

The highest potential for industrial circularization is observed in the Moscow region, the Sverdlovsk region, and the Republic of Tatarstan. In these regions, any circular models of long cycles, as well as medium cycles of low and high levels, can be implemented. The lowest index values were recorded in relatively small and very remote regions of the Russian Federation, such as the Jewish Autonomous District, the Republic of Tyva, the Nenets Autonomous District, the Republic of Dagestan, and the Kabardino-Balkarian Republic. Currently, there are practically no conditions for industrial circulation in these regions. An important task was not only to find out the general potential of industrial circulation, but also to identify which circular models can be successfully implemented in the current conditions.

Based on the results of the analysis conducted separately for the key factors of circular models of long cycles and medium cycles of high and low levels, several groups of regions were identified. The first group includes the regions where most circular models can be implemented in industry (Table 4). Also, within the group, the subjects of the Russian Federation were divided into subgroups: the first subgroup included regions with the highest rates of development of key factors necessary for the implementation of circular models of long cycles. The second subgroup included those subjects whose potential for implementing circular models of long cycles was somewhat lower.

Table 4. Group 1—Regions with industries that have the conditions to implement most circular models.

Circular Models That Can Be Implemented in the Region	Region	Potential Groups
1.1 The most promising regions for the implementation of most circular models	Krasnodar region	1 1 1
	Moscow region	1 1 1
	Republic of Tatarstan	1 1 1
	Sverdlovsk region	1 1 1
	Chelyabinsk region	1 1 2
	Novosibirsk region	1 2 1
	Republic of Adygea	1 2 1
	Republic of Bashkortostan	1 2 1
	Samara region	1 2 2
1.2 Promising regions for the implementation of most circular models	Nizhny Novgorod region	2 1 1
	Rostov region	2 1 1
	Irkutsk region	2 1 2
	Yaroslavl region	2 1 2
	Krasnoyarsk region	2 2 1
	Primorsky Krai	2 2 2
	Stavropol Territory	2 2 2
	Tula region	2 2 2

The second group included regions where circular models of long cycles and low-level medium cycles can be implemented in industry (Table 5).

Table 5. Group 2—Regions with industries that have the conditions to implement circular models of long cycles and low-level medium cycles.

Circular Models That Can Be Implemented in the Region	Region	Potential Groups
2.1 Regions that are the most promising for implementing long-cycle and medium-cycle low-level models.	Belgorod region	1 1 3
	Voronezh region	1 1 3
	Leningrad region	1 1 3
	Vologda Oblast	1 1 4
	Kemerovo region	1 1 4
2.2 Regions that are promising for the implementation of long-cycle and medium-cycle low-level models	Khanty-Mansiysk Autonomous Okrug—Yugra	1 2 3
	Lipetsk region	1 2 4
	Perm region	2 1 3
	Kaluga region	2 1 4
	Novgorod Oblast	2 1 4
	Tomsk region	2 1 4
	Tyumen Oblast without AO	2 1 4
	Ivanovo region	2 2 3

The third group consisted of regions where it is currently possible to implement only circular long-cycle models in the industrial sector (Table 6).

Table 6. Group 3—Regions with industries that have the conditions to implement circular long-cycle models.

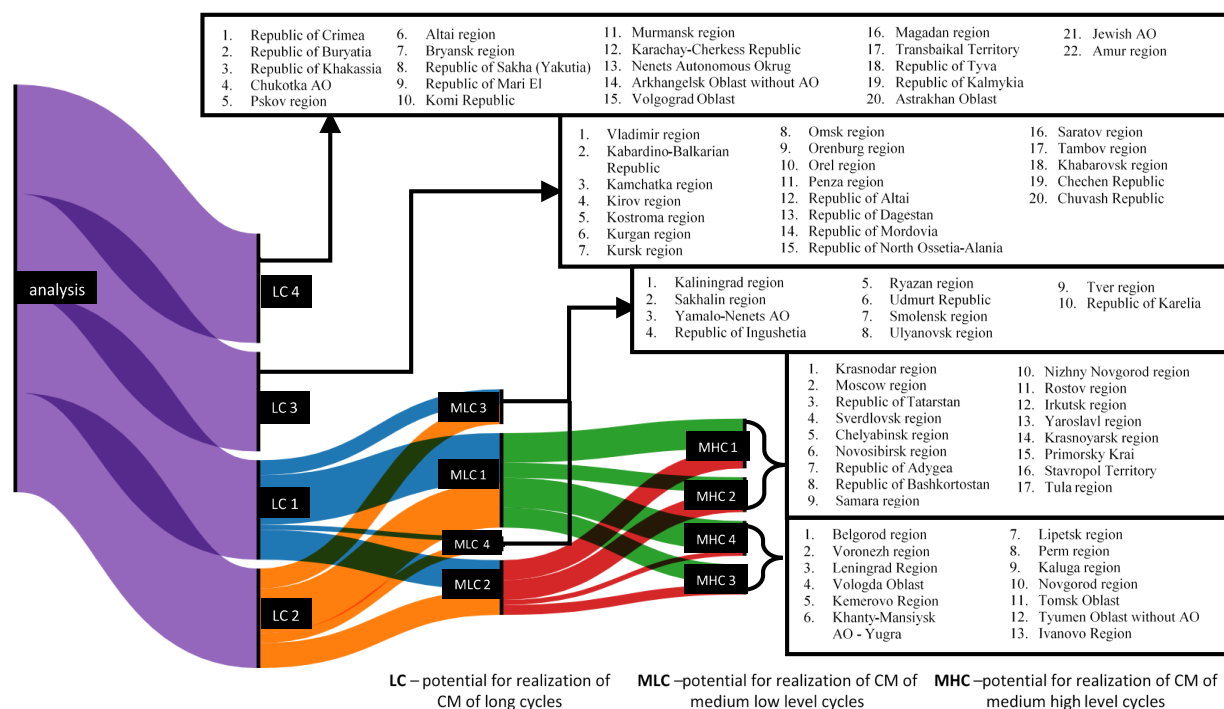
Circular Models That Can Be Implemented in the Region	Region	Potential Groups
3.1 Regions that are most promising for implementing long-cycle models	Kaliningrad region	1 3 4
	Sakhalin region	1 3 4
	Yamalo-Nenets Autonomous Okrug	1 3 4
	Republic of Ingushetia	1 4 2
3. Regions that are promising for implementing long-cycle models	Ryazan Oblast	2 3 1
	Udmurt Republic	2 3 2
	Smolensk Oblast	2 3 3
	Ulyanovsk region	2 3 4
	Tver region	2 4 3
	Republic of Karelia	2 4 4

The fourth group consisted of industrial regions, which currently do not have the conditions for the implementation of circular models (Table 7). This group included subjects whose potential for industrial circularization was significantly lower than the rest of the regions (belonged to groups 3 or 4).

According to the results of the study, at the moment it is possible to effectively introduce circular models into industry in 17 regions of Russia, which is 20.7% of the total number of analyzed regions. Figure 3 shows the distribution of the regions of Russia according to the potential for the introduction of circular models of various types in the industry.

Table 7. Group 4—Regions whose industry does not have the conditions for the implementation of circular models.

4.1 Regions Where the Implementation of Long-Cycle Models Poses Significant Challenges		4.2 Regions Where the Implementation of Long-Cycle Models Is Virtually Unfeasible	
Region	3 Group	Region	4 Group
Kirov region	0.361	Republic of Crimea	0.329
Republic of Dagestan	0.361	Republic of Buryatia	0.324
Penza region	0.361	Republic of Khakassia	0.323
Orel region	0.358	Chukotka AO	0.320
Vladimir region	0.356	Pskov region	0.319
Khabarovsk Territory	0.350	Altai Territory	0.318
Chuvash Republic	0.346	Bryansk region	0.315
Orenburg region	0.344	Republic of Sakha (Yakutia)	0.315
Kurgan region	0.343	Republic of Mari El	0.314
Kostroma region	0.340	Komi Republic	0.312
Tambov region	0.340	Murmansk region	0.307
Kursk region	0.340	Karachay-Cherkess Republic	0.301
Altai Republic	0.339	Nenets Autonomous District	0.291
Omsk region	0.336	Arkhangelsk region without AO	0.285
Kamchatka region	0.335	Volgograd region	0.279
Saratov region	0.332	Magadan region	0.279
Republic of North Ossetia-Alania	0.332	Trans-Baikal Territory	0.247
Chechen Republic	0.331	Republic of Tyva	0.245
Kabardino-Balkar Republic	0.331	Republic of Kalmykia	0.241
Republic of Mordovia	0.331	Astrakhan region	0.240
		The Jewish Autonomous Region	0.238
		Amur region	0.222

**Figure 3.** Distribution of regions of Russia according to the potential of introducing circular models of various types in industry.

4. Discussion and Conclusions

The proposed methodology for evaluating the circularization potential of regional industry enhances the understanding of how regional economic conditions can facilitate the transition to a circular industry. Unlike traditional approaches that focus on past outcomes of circularization, this methodology is forward-looking, emphasizing the creation of circularization potential. A distinctive feature of this approach is its ability to systematically assess both the factors influencing circularization and the specific models of the circular economy. By applying this methodology, stakeholders can make informed decisions regarding the most effective measures for transitioning to a circular economy.

The rating method is employed to assess the potential of a region for the successful implementation of circular economy models. The rating is calculated by constructing both a general integral circularization potential index and individual sub-indices. The integral index, based on 12 factors, provides a comprehensive evaluation of the overall conditions for adopting circular models in industrial enterprises. The sub-indices, on the other hand, enable a more detailed assessment of the potential for implementing circular models at various levels, offering insights into specific aspects of circularization.

The evaluation of a region's circularization potential enables policymakers to select optimal strategies for enhancing the sustainable development of industry, tailored to the existing conditions for implementing circular models. To provide general recommendations, the analyzed regions were categorized into four groups based on a numerical assessment of their total circularization potential. Due to the limited number of regions, 20 regions were assigned to each of the first three groups, while the fourth group included 22 regions.

As a result of this research, a scale for assessing the potential of regional industry circularization was developed, along with tailored recommendations for each group. Group 1 comprises regions with the most favorable conditions for adopting circular economy models. Recommended measures for these regions include raising awareness about various types of circular models (targeting both the general population and business representatives) and establishing regional support programs for enterprises operating on circular principles. Group 2 includes regions with relatively favorable conditions. For these regions, promoting responsible consumption and production through media campaigns, supporting "green" startups, and developing eco-techno parks are recommended. Group 3 consists of regions with relatively unfavorable conditions. In these areas, the primary focus should be on stimulating innovation activity among regional enterprises. Finally, Group 4 includes regions with the least favorable conditions. For these regions, measures should prioritize improving economic conditions and transport infrastructure, as well as training personnel for the circular economy through higher and vocational education programs. These recommendations are advisory in nature and are intended to highlight necessary measures rather than those deemed most effective. For regions with more favorable conditions, the emphasis should be on supporting and scaling circular models. Conversely, for regions with less favorable conditions, priority should be given to improving economic conditions and infrastructure, as the transition to circular models requires substantial investment and a high level of maturity in terms of understanding and commitment to the Sustainable Development Goals.

These recommendations provide a starting point for developing more detailed strategies tailored to each region's unique needs.

A limitation of this study is the lack of official statistical data for some indicators at the regional level. Consequently, future research directions include the development of alternative assessment tools for relevant factors and indicators to address these gaps.

The findings of this study align with those of similar research in several key aspects while also presenting unique features. This study identifies 12 primary factors influencing

the potential for implementing circular models in the industry, such as the financial stability of enterprises, digital technologies, government support, and others. These factors overlap with drivers of circularization identified in studies by researchers from various countries. For example, government support is highlighted in the works of Su et al. [51] and Aloini et al. [39]; innovation and digitalization are emphasized in studies by Salvador et al. [52] and Kosolapova et al. [40]; and environmental aspects (e.g., waste management) are addressed in research by Aloini et al. [39] and Geerken et al. [53]. However, this study places particular emphasis on regional conditions (e.g., regional economy, transport accessibility), which are not always explicitly addressed in other works focused on assessing circularization drivers at the national level.

The use of the entropy method in this study to determine indicator weights aligns with the multi-criteria approach described by Geerken et al. [53]. Both approaches aim for adaptability and account for diverse conditions. Similarly, the study by Calzolari et al. [54] describes composite indices as indicators of the circular economy, which resonates with the idea of an integrated evaluation proposed in this article. Another parallel is the classification of circular models by levels (e.g., short cycles, medium-high level cycles) in this study, which echoes the approach of Geerken et al. [53], where the potential of the circular economy is examined across five levels: national, primary, secondary, and tertiary sectors, individual sectors, and circular strategies.

This study also shares similarities with the work of Edirisinghe et al. [55], which evaluates the potential of the circular economy in industrial zones. Both approaches emphasize the importance of considering local conditions.

Unlike many other studies, this research focuses on the regional level and the industrial sector, making it more applicable for developing localized strategies for the circularization of regional industry.

In the proposed methodology, statistical data on the regions of the analyzed country form the basis for the evaluation. While this approach may partially limit the methodology—particularly in cases where all regions exhibit a high level of development, making it difficult to confidently assert the impossibility of implementing certain circular models—it remains a valuable analytical tool. It can be effectively used both for developing conditions conducive to industrial circularization within a country's regions and for conducting international comparisons. By incorporating data from multiple countries, the methodology enables the identification of regions with similar conditions across different nations, thereby highlighting the most promising areas for the implementation of circular models in industry.

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