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An Overview of Closed-Loop Economy Assessment Methods

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Abstract. The goals related to the transition to a closed-loop economy remain relevant due to the fact that this concept expands the boundaries of environmental sustainability through the ideas of transforming products and waste in the context of effective interaction between the safety of ecological systems and the stability of economic growth. Alongside the possibilities of the closed-loop economy, theoretical and methodological issues regarding the evaluation of the effectiveness of its practices are expanding. At present, there is no generally accepted way to measure a closed-loop economy as a whole, at individual levels (macro, meso, micro), or within the framework of various principles ("R"-strategies). The aim of the work is to systematize existing scientific research on the subject of closed-loop economy assessment, and to conduct their overview analysis. The article uses general theoretical methods of analysis, synthesis, comparison and classification, which meets the objectives of a descriptive review. Secondary data analysis is chosen as the main method. The study made it possible to trace trends, systematize approaches to assessing the closed-loop economy and gain an up-to-date understanding of the dynamics of scientific knowledge regarding methods of its assessment. We define reference points for categorization and structuring of indicators of the closed-loop economy and classify approaches to its assessment. The review identified a number of methodological problems: assessment methods should be based on generally accepted definitions and principles of the closed-loop economy, its established strategies and business models, as well as comply with national objectives and national strategies in the field of sustainable development and take into account industry and regional specifics. The assessment methods studied in the work are systematized and classified relative to the level of application of closed-loop economics practices (at the

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micro, meso, and macro levels), which can help strengthen the effective subjectivity of multi-level actors in the implementation of closed-loop economy projects.

Key words: closed-loop economy, circular economy, methodology for assessing circular economy, circular economy indicators.

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Introduction

The ideas of the transition from a linear type of production to new cyclical models remain relevant, despite the geopolitical turbulence, due to the need to solve existential problems to reduce the negative impact on the environment. The closed-loop economy (CLE), which is also referred to in foreign sources as the circular economy (CE), generally assumes two development vectors within the framework of the logical model "resources – products – renewable resources": 1) minimizing resource usage and recycling; 2) greening of production facilities and reducing the negative impact on the environment. From these positions, CLE expands the boundaries of environmental sustainability through the ideas of transforming products, waste and production chains, so that an effective interaction between the safety of ecological systems and the stability of economic development is found and implemented. However, in parallel with the possibilities of implementing CLE, theoretical and methodological issues regarding the evaluation of the effectiveness of practices within the framework of this concept are expanding.

Barriers to developing a unified approach to assessing CLE currently include:

1) dualism in approaches to CLE (minimizing resource consumption / minimizing negative environmental impact);

2) applicability of CLE practices at various levels:

– micro level (products, companies, consumers);

– meso level (industrial symbiosis, eco-industrial parks, industries);

– macro level (global, national, regional, urban economic systems);

3) essential content and list of the "R" principles in CLE, the most well-known of which are as follows: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover;

4) differences in methodological approaches to the assessment of the "R" principles;

5) complexity of determining the object of measurement and the differences in the systems considered and measured within the framework of CLE;

6) significant differences in biological and artificial cycles of materials and resources, where biological cycles are associated with the safe and efficient movement of renewable biotic resources to and from the biosphere, while artificial (anthropogenic) cycles involve the use of artificial materials and their compounds that are dangerous to the environment.

These barriers determine the main debatable issue: to what extent existing methodologies are suitable for assessing the environmental and economic effectiveness of CLE strategies in the measured systems. We should note that the generally accepted approach of attributing regional economic systems to the meso-level when considering CLE in foreign sources is changing to the macro level. This makes it possible to emphasize the level of subjectivity of the governing bodies responsible for the implementation of this direction in the economic system of a given facility.

The level of subjectivity for the implementation of CLE practices is an essential parameter, which is associated with the need to take into account specific territorial features (geographical, environmental, economic, social, institutional). CLE is particularly relevant for industrial regions (with a high proportion of the mining and manufacturing sectors in the structure of gross regional product). Industrial regions, being the basis for the development of the national economy, are top contributors to the degradation of ecological systems. A number of such regions are characterized by extensive industrial development, accompanied by the introduction of metal leaching technology, development of deep horizons and deposits with lower mineral content, which contributes to the aggravation of ecological and economic contradictions. These problems can be overcome only from the perspective of reflection of subjectivity, which must be taken into account at the stage of CLE assessment. This review paper aims to combine and systematize the accumulated knowledge in the field of closed-loop economics assessment, classifying existing methods according to the levels of CLE implementation.

Methods

The aim of the paper – to synthesize and systematize previous research on the subject of closed-loop economics assessment – involves using general theoretical methods of analysis, synthesis, comparison and classification, which meets the objectives of a descriptive review. Secondary data analysis is chosen as the main research method, the main purpose of which is to search for patterns, and also to systematize and classify the studied objects, methods or parameters. The research method allows us to solve a number of methodological tasks: to compare the results of previous studies on the assessment of CLE; to get an idea of the time dynamics of research; to conduct a comparative analysis of existing approaches to the assessment of CLE and propose their classification. The search for sources on circular economy (closed-loop economy) was carried out in the databases and information resources of Web of Science, Google Scholar, ResearchGate, ScienceDirect using various combinations of search queries, such as “circular economy assessment”, “circular economy index”, “circular economy measurement”, “circular economy indicators” by category “review article” and “research article”. The “open access” filter was used during the selection. The subject area was limited to economics, management, environmental sciences, and social sciences. A total of 43 indicators were obtained as a result of the analysis, which were included in the scientific review and systematized depending on the level of assessment for micro, meso, and macro indicators. The search results are selected manually based on the titles and abstracts. Significant selection criteria were concepts such as “analysis”, “evaluation” and similar expressions that indicated the potential measurement of one aspect or a subset of aspects within the circular economy.

Results

The studied methods of CLE assessment were systematized with respect to the level of application of these practices (micro, meso, and macro level), which can contribute to strengthening the effective subjectivity of multi-level actors in the development of practices and the implementation of CLE projects.

The macro level is currently represented by the fewest number of research papers, since the practices of CLE are at an early stage of development, which, accordingly, presupposes their approbation primarily at the micro and meso levels. The parameters of the CLE assessment at the macro level are proposed in the collection “Green Growth Indicators” of the Organization for Economic Cooperation and Development[1], which emphasizes the role of production and consumption in the economy, as well as the relationship between economy, natural resources and environmental policy. It is emphasized that increasing resource productivity and ensuring sustainable materials management require a comprehensive policy on waste, materials and products based on a 3R closed-loop economy. The ecological and resource-saving efficiency of the economy is assessed through indicators of carbon and energy productivity, which characterizes the interaction with the climate system and the global carbon cycle, as well as the ecological and economic efficiency of using energy resources in prduction and consumption; productivity of natural resources, which characterizes the environmental and economic efficiency of their use in production and consumption; multifactor productivity, which takes into account environmental parameters through the costs associated with environmental pollution.

Y. Qing and co-authors proposed an index system used to assess the development of a closed-loop economy in Shaanxi Province, including five parameters (Qing et al., 2011).

The article by M. Haupt, C. Vadenbo, and S. Hellweg presents an analysis of the material flows of the Swiss waste management system, with special attention paid to the physical composition of waste. Half of the solid household waste is recycled, and half is thermally treated with energy recovery. It is proposed to use the recycling rates (RRs), an indicator for circulating behavior of materials, as measure for the degree of circularity of an economy. The study provides an analysis of the recycling of solid household waste (paper, cardboard, aluminum, tinplate, glass, and polyethylene terephthalate) by splitting the RRs into closed- and open-loop collection rate and RRs. According to the proposed methodology, the coefficient measures the available secondary resources obtained as a result of recycling processes (Haupt et al., 2016).

(Smol et al., 2017) proposed indicators characterizing the closed-loop economy in regional politics. The authors draw attention to the relationship of CLE with eco-innovation, which implies that this aspect is reflected in the assessment methodology. The paper presents five group indicators based on eco-innovation factors, which can be identified from statistical data from Eurostat. This measurement method makes it possible to create a systematic and integrated approach to the concept at the regional level through the prism of the effectiveness of eco-innovations, taking into account the statistical specifics of national economic systems.

N. Kiani Mavi and R. Kiani Mavi evaluate the closed-loop economy at the macro level using the Malmquist index (Kiani Mavi, Kiani Mavi, 2019).

A. Pires and G. Martinho developed the Waste Hierarchy Index (WHI) to measure the hierarchy of municipal solid waste in the context of a closed-loop economy. Recycling and preparation for reuse, in the context of Eurostat’s regulatory sources, are considered as positive factors of a closed-loop economy, while incineration and disposal of waste are considered as negative factors. The authors are testing WHI at the local and national levels. The index allows calculating the hierarchy of waste, taking into account different types of recycling and incineration, these processes are

[1] Green Growth Indicators 2014. OECD. Available at: https://www.oecd.org/en/publications/green-growth-indicators-2013_9789264202030-en.html

assigned different weights depending on how waste operations correspond to a closed-loop economy (Pires, Martinho, 2019). The use of WHI is possible for specific materials and waste streams. However, WHI only considers operations that occur after the formation of waste, and does not include measures to prevent its formation. The possibility of applying the proposed methodology for assessing CLE directly depends on the national regulatory framework that defines the essence of these processes.

The work of I.-M. Garcia-Sanchez and co-authors describes a multivariate index, which is a two-stage composite business index of a closed-loop economy. Using a sample of 26,783 companies from 49 countries and 10 sectors for the period from 2014 to 2019, the authors summarized initiatives at the country and industry levels. The index is based on an analysis of data from the Thompson Reuters EIKON[2] database, and therefore its calculation and reliability of the estimate directly depend on the degree of disclosure of non-financial information (Garcia-Sanchez et al., 2021).

The tools of statistical analysis, the index method, and the analysis of relative indicators are used to evaluate CLE at the macro level (*Tab. 1*). This is due to the simplicity of calculations and the ability to select the studied parameters, which, in turn, makes it possible to adapt the methods to use any available set of official statistical data. The Malmquist index adds the ability to evaluate dynamic performance indicators, making it possible to differentiate performance change parameters related to cyclical processes. The need to apply

Table 1. Methodology for assessing a closed-loop economy at the macro level

Author(s)	Year	Methodological toolkit	Estimated indicators / parameters / description
Qing Y., Qiongqiong G., Mingyue Ch.	2011	Index method	– Social and economic development, – resource efficiency, – recycling and reuse of resources, – environmental protection, – pollution reduction
Haupt M., Vadenbo C., Hellweg S.	2016	Material flows analysis	Recycling rates (RRs)
Smol M., Kulczycka J., Avdiushchenko A.	2017	Relative statistical indicators	– Eco-innovation costs, – eco-innovation activity, – eco-innovative results, – resource efficiency results, – socio-economic results
Kiani Mavi N., Kiani Mavi R.	2019	Malmquist index	– Resource performance level, energy consumption, – greenhouse gas emissions, – waste volume, – renewable energy sources, – GDP
Pires A., Martinho G.	2019	Relative statistical indicators	The Waste Hierarchy Index (WHI) for solid household waste uses the following parameters: «PR» – preparing for reuse; «UpR» – up-cycling; «DR» – down-cycling; «CAD» – composting and anaerobic digestion; «BT» – biological treatment of mixed/residual municipal solid waste; «WtE» – incineration with energy recovery; «I» – incineration without energy recovery; «L» – landfill
Garcia-Sanchez I.-M., Somohano-Rodriguez F.-M., Amor-Esteban V., Frias-Aceituno J.-V.	2021	Statistical methods	CEBIX (Circular Economy Business Index at the national level) – consolidated business index of the closed-loop economy based on 17 environmental practices
Source: own compilation.			

[2] Available at: https://eikon.thomsonreuters. com/index.html

material flow analysis depends on the nature of the cyclic process in question, its parameters and its economic feasibility. The analysis of material flows makes it possible to optimize production processes, which, accordingly, leads to lower costs, but requires significant resources and involves difficulties in integrating with existing systems.

The methodological tools for assessing CLE at the meso level are more diverse. For example, N.B. Jacobsen's work is devoted to quantifying the effectiveness of industrial symbiosis, considered as a sub-branch of industrial ecology. It was established that industrial symbiosis can provide both significant and minor environmental benefits (Jacobsen, 2006).

The methodology presented by Z. Wen and X. Meng is based on the assumption that increased material exchange between combined enterprises in leading industrial production chains in eco-industrial parks leads to the creation of an industrial symbiosis system that is effective in strengthening the closed-loop economy (Wen, Meng, 2015).

The wastewater circonomics index was proposed in the work of B. Kayal and co-authors to measure cyclicity in the wastewater treatment industry. The index reflects the efficiency of reuse and recycling of the wastewater treatment process, taking into account its specific parameters. In this model, wastewater is transformed from waste into a resource. The novelty of the proposed index lies in the use of objectively substantiated weights reflecting the environmental benefits of the purification process (Kayal et al., 2019).

L.-L. Ding and colleagues proposed an approach based on the following hypothesis: industrial CLE seeks to maximize economic benefits while minimizing negative environmental impacts by restoring production, recycling, efficient waste management and the use of renewable sources. Using the analysis of the operating environment, the authors determine the effectiveness of the industrial circular economy. The extended Malmquist index is used for further analysis of dynamic changes. The economic result is represented by the industrial added value by sector (IAVS), which reflects the final product of industrial production activities in monetary form. Based on the availability of statistical data, the authors make assessments taking into account industrial labor and fixed assets as economic costs. An undesirable result in the model is industrial pollution, which is estimated based on the volume of industrial wastewater and solid industrial waste. Environmental management costs mainly consist of the costs of industrial wastewater treatment, wastewater treatment plants, and investments in environmental management due to industrial pollution. The indicators of environmental cleaning results were the volumes of treated industrial wastewater and solid industrial waste disposal (Ding et al., 2020).

S.V. Ratner, V.V. Iosifov, and P.D. Ratner (Ratner et al., 2020) proposed an approach to assessing the level of CE development at the regional and federal levels. The first subsystem of the circular economy (SS1) includes the production subsystem, the optimization of which consists in reducing resource intensity. The volume of GRP Y1 is taken as a positive result of the activity of the regional economic system, and the number of people in the region whose living is provided by this infrastructure Y2 is taken as a positive result of the activity of the communal infrastructure. The physical resources that it consumes – the amount of energy consumed by the region X1 and the amount of water consumed X2 – are considered as inputs to the production subsystem. The volume of emissions into the atmosphere from stationary sources Z1, the volume of untreated or insufficiently treated wastewater Z2, the volume of production and consumption waste Z3, and the area of disturbed land Z4 are selected as undesirable outputs.

The work of S.S. Gutman and M.S. Manakhova puts forward three groups of goals for the implementation of CE at the regional level (*Tab. 2*).

The article by C.-H. Wang and colleagues assesses suppliers for the implementation of a closed-loop economy. The index takes into account the economic, environmental and social losses associated with poor product quality. In the context of a closed-loop economy, poor quality leads to an increased number of defects, a shorter product life, and a reduced reuse of components (Wang et al., 2021).

Another industry-specific assessment methodology (for the construction industry) of CLE elements is proposed in the work of T. O'Grady and co-authors. The proposed index is evaluated through the design parameters of demolition, dismantling, and sustainability in construction. According to the authors, the indexation of the circularity of buildings should facilitate the transition from traditional demolition to a closed-loop economy and reduce the environmental impact at the stages of reconstruction. The researchers note that the possibility of using the technique varies depending on the regulatory framework governing the processes of waste disposal and reuse. The index ranges from 0 to 1, where a higher value indicates that the building has a high degree of disassembly and is built using sustainable components that can be disassembled several times (O'Grady et al., 2021).

N.Y. Titova proposed a circular economy system in accordance with the Sustainable Development Goals, based on a bibliometric analysis of 679 publications. The indicators used in these studies are divided into groups (economic, environmental, social), as a result of which a correspondence has been established between them according to the criteria of belonging to the assessment of the achievement of the UN Sustainable Development Goals and the principles of circular economy (Titova, 2022).

Table 2. Objectives of the circular economy at the regional level

Sector	Goals
Social sector	Creating new jobs and increasing the number of interns from universities in enterprises adhering to the principles of CE, due to support from the regional administrations (as an indicator of the employment prospects for the population). Creation of eco-parks, nature reserves, and eco-paths. Support for research and development (R&D) in the region. Development of landscaping of residential areas, taking into account environmental standards and garbage collection points. Encouraging people to engage in the separate sorting of garbage and organizing public events on this topic.
Environmental sector	Ensuring control over pollution of air, water bodies and soils by industrial facilities. Establishing the infrastructure for separate waste sorting in residential complexes and industrial facilities. Increased control over the organization of illegal landfills. Increasing the share of waste processed in the region. Introducing stricter environmental regulations. Reducing the share of primary resource usage. Reducing illegal deforestation in the region.
Economic sector	Support for the development and creation of industrial clusters. Funding from the R&D administration. Creating a secondary resource market. Raising tariffs for primary natural resources. Raising fines for environmental violations. Improving the economic sustainability of enterprises in the region.
Compiled according to (Gutman, Manakhova, 2021).	

T.T. Huyen Do and coauthors considered an integrated cyclic index to assess the potential effectiveness of using CLE in the wood production chain, taking into account carbon neutrality. The proposed index reflects five parameters of CLE and zero carbon emissions. The best-worst method was used to calculate the optimal weighting coefficients of the index components, and linear target programming was used to identify the maximum value in order to determine the preferred alternatives to CLE (Huyen Do et al., 2023).

F. Holly, S. Schild, and S. Schlund propose a C-METRIC evaluation model for measuring the work cycle of engineering companies, which includes 66 questions from 33 different fields of activity (Holly et al., 2023).

The work of A.G. de Andrade Monteiro and colleagues describes an indicator of the CE assessment for the chemical industry. The scope of the indicators in combination with technical cycles was based on the 3R principles in combination with measurements of waste generation, gas emissions and energy consumption (Monteiro et al., 2024).

The assessment of CLE at the meso level is more diverse in terms of methodological tools (*Tab. 3*). This is probably due to the greater availability of initial statistical data for this level, which are required for the use of most of these methodological tools. In addition, unlike macro-level tools, the possibility of using qualitative analysis (questionnaires, surveys) is obvious at the meso level. From our point of view, qualitative analysis tools are more appropriate at the meso level than at the macro and micro levels, due to the fact that at the meso level it is possible to form a sample or focus group that meets the necessary requirements to ensure the validity of the study: on the one hand, due to the qualitative selection of participants and the application of the requirements of homogeneity of social and professional characteristics of the respondents; on the other hand, the meso level retains the possibility of preserving the principle of the law of large numbers.

The most widespread group currently includes methods for assessing the parameters of a closed-loop economy at the micro level. For example, S.K. Das and co-authors proposed a multifactorial model for calculating the labor intensity of disassembly, reflecting the total operating costs of disassembling a product (Das et al., 2000).

P. Zwolinski and colleagues proposed taking into account constraints based on the profiles of recoverable products throughout the design process. Eight categories of criteria were proposed to determine the product profile (Zwolinski et al., 2006).

The research by J.Y. Park and M.R. Chertow develops tools for waste management as resources. The authors propose a quantitative tool that determines how resource-intensive specific materials are. The indicator of reuse potential describes how resource-intensive a material is due to its quality (Park, Chertow, 2014).

The end-of-life index allows developers to make informed decisions about design alternatives to ensure optimal end-of-life product performance (Lee et al., 2014).

The work of S. Huysman and colleagues puts forward a coefficient for calculating the environmental effect in terms of resource use. The approach of cumulative exergy extraction from the natural environment is applied. The indicator is based on estimated environmental impact values obtained using life cycle assessment methods (Huysman et al., 2015).

A. Van Schaik and M.A. Reuter have developed a recycling index based on simulation models, which includes waste disposal indicators (Van Schaik, Reuter, 2016).

Table 3. Methodology for assessing the closed-loop economy at the meso level

Author(s)	Year	Methodological toolkit	Estimated indicator / parameter / description
Jacobsen N.	2006	Statistical methods	Evaluating the effectiveness of industrial symbiosis
Wen Z., Meng X.	2015	Substance flow analysis (SFA). Resource performance indicators (RP). Questionnaires and field research	Assessing the impact of industrial symbiosis on the growth of CLE
Kayal B., Abu-Ghunmi D., Abu-Ghunmi L., Archenti A., Nicolescu M., Larkin C., Corbet S.	2019	Statistical methods, weighting factors	Wastewater Circonomics Index. Indicators that make up the index are based on the principles of reduction, reuse and recycling (3R)
Ding L.-I., Lei L., Wanga L., Zhang L.-F.	2020	Malmquist index. Data Envelopment Analysis (DEA). Cobb – Douglas Production Function	industrial added value by sector (IAVS (IAVS)
Ratner S.V., Iosifov V.V., Ratner P.D.	2020	Data Envelopment Analysis (DEA)	Comprehensive indicator of the level of development of the circular economy, calculated as the arithmetic average of four indicators of various types of efficiency
Gutman S.S., Manakhova M.S.	2021	Balanced scorecard (BSC)	Objectives for the implementation of CE at the regional level
Wang C.-H.	2021	Taguchi index	Supplier assessment: takes into account the economic, environmental and social losses associated with poor product quality
O'Grady T., Minunno R., Chong H.-Y., Morrison G.M.	2021	Statistical methods	The index includes parameters for the design for disassembly, deconstruction, and resilience (3DR) for the built environment. The index is based on the definition of the sub-indices of disassembly (DI), deconstruction (DE) and resilience (R) of the structure.
Titova N.Yu.	2022	Bibliometric analysis	A circular economy system in line with the Sustainable Development Goals
Huyen Do T.T., Ly T.B.T., Hoang N.T., Tran V.T.	2023	Best-worst method (BWM) and linear goal programming (LGP) techniques	Integrated circular economy index (ICEI). Its component indicators include: C1 – carbon emission reduction rate (Rc); C2 – internal renewable fuel substitution rate (RF); C3 – internal renewable electricity substitution rate (RE); C4 – thermal energy recovery rate (RH); C5 – economic efficiency rate
F. Holly, C. Schild, S. Schlund	2023	Survey	C-METRIC (Circular Manufacturing Evaluation and Rating for Industrial Circularity)
de Andrade Monteiro A.G. et al	2024	Life cycle concept, statistical methods	Indicators included in the model: emissions into the atmosphere, reduction of waste, % of waste used for recycling, % of waste used for electricity generation
Source: own compilation.			

The article by A.E. Scheepens and co-authors suggests an environmentally efficient value creation coefficient. To assess the potential negative environmental impact of business operations, an LCA-based eco-cost coefficient is applied (Scheepens et al., 2016).

E. Franklin-Johnson and co-authors use the longevity index to evaluate CLE. This method involves estimating the initial service life, the service life after repair, and the service life after recycling to assess the contribution of the resource to the durability of the material. The assessment is based on the assumption that the central element of a closed-loop economy is the creation of value through the conservation of materials. Thus, by measuring the contribution to the preservation of a material based on the amount of time during which the resource is used, it is possible to obtain an assessment of efficiency in a closed-loop economy (Franklin-Johnson et al., 2016).

The recycling index proposed by M.A. Reuter, A.V. Schaik takes into account new recycled material. The assessment methodology is based on the postulate that recycling is the basis of a closed-loop economy (Reuter, Schaik, 2016).

In the work of N. Adibi and co-authors, a resource indicator is proposed that includes the impact on the lifecycle through “critical parameters” such as waste recycling. The recyclability and criticality of resources are part of a multi-criteria indicator. The Global Resource Indicator evaluates all types of resources, including renewable and non-renewable, by the rate of regeneration (Adibi et al., 2017).

The circularity indicator is used at the product level to estimate costs in the value chain. The indicator of the cyclical ratio of the recycled economic value to the total cost of the product is used. The work is based on the hypothesis that the economic value of the product components is the basis for aggregation (Linder et al., 2017).

The assessment of end-of-life indicators, together with an analysis of preferred disassembly routes, allows developers to monitor product sustainability in terms of economic performance and environmental impact (Favi et al., 2017). The reuse index takes into account the possibility of a component being recycled in the same product or in similar products. The recovery index evaluates the ability of a component to be regenerated based on the various types of costs and revenues involved in the recovery cycle. The recycling index compares the difference between the cost of producing primary materials and the revenue generated by the recycling process. In particular, it takes into account the energy savings resulting from the material recycling process and the income from recycled materials. The Energy Recycling Index (with energy recovery) determines whether specific combinations of materials can be directly burned to produce energy.

S. Cayzer and co-authors have developed a prototype of the CLE indicators (CEIP). The approach has advantages such as speed, simplicity, and ease of use (Cayzer et al., 2017).

F. Di Maio and colleagues propose an indicator to assess the effectiveness of supply chain participants in terms of resource efficiency and compliance with a closed-loop economy, measuring both resource efficiency and CLE in terms of the market value of “scarce” resources. Circularity is defined as the percentage of the value of stressed resources incorporated in a service or product that is returned after its end-of-life (Di Maio et al., 2017).

The work of A.A. Mohamed Sultan and co-authors is also devoted to determining the priority of recycling expired products in a closed-cycle economy based on the Recycling Desirability Index (Mohamed Sultan et al., 2017).

V. Veleva, G. Bodkin, S. Todorova proposed a model that includes indicators for measuring the results of cyclical business strategies where employee engagement is considered as the most important strategy for identifying and implementing innovative approaches and initiatives in the field of sustainable development (Veleva et al., 2017).

The work of M.D. Bovea and V. Perez-Belis defines the guiding principles of design in accordance with the principles of a closed-loop economy (Bovea, Perez-Belis, 2018).

M. Ameli and co-authors present a multi-criteria mathematical model, which combines two tasks – choosing a design alternative and determining the end-of-life cycle option. To address the three main objectives of sustainable development (economic, environmental, and social), three goals are considered: maximizing producer profits, minimizing environmental impact, and maximizing social impact. Two restrictions are considered for the control of recovery and recycling coefficients, which are imposed by legislative acts. A simulation and optimization model is developed to formulate and solve the model (Ameli et al., 2019).

M. Niero and P.P. Kalbar proposed a methodology for assessing the circular economy at the product level, combining various types of indicators based on the circularity of the material, namely the assessment of material reuse and the indicator of circularity of the material, and characterizing the life cycle (climate change, depletion of abiotic resources, oxidation, solid impurities and water consumption). The choice of indicators is determined by the industry specifics of the product in question (Niero, Kalbar, 2019).

The multi-criteria decision-making tool was proposed by Y.A. Alamerew, D. Brissaud. The method is a circular economy assessment (PR-MCDT) tool for end-of-life product disposal strategies. The level designated by the authors for the application of the methodology is senior/middle management for strategic decision-making. The methodology takes into account technical, economic, environmental, business and social parameters (Alamerew, Brissaud, 2018).

M. Marconi, M. Germani, M. Mandolini, and C. Favi estimate the effective disassembly time of industrial products. It is determined based on the actual condition of the product and its components (deformation, rust, wear) using correction factors (Marconi et al., 2019).

EDiM is an indicator of the ease of disassembly to determine the time required based on the Maynard operation sequence (Vanegas et al., 2018). EDiM uses a checklist based on the sequence of actions and basic information about the product and the specifics of disassembly, classified into six groups.

The work of E. Lacovidou and co-authors is dedicated to evaluating the quality of materials, components, and products at various stages of the life cycle. The researchers have proposed a typology that makes it possible to distinguish between properties that promote or hinder their restoration, conversion, repair and recycling, which provides industry with a tool to improve the quality of waste streams and, consequently, increase the value of the secondary resources produced in order to achieve higher recycling rates (Lacovidou et al., 2019).

L. Cong and colleagues proposed a design method for end-of-use product value recovery. The hypothesis of the methodology is that the economic feasibility of recycling a product at the end of its life cycle largely depends on the design (Cong et al., 2019).

Sustainability indicators in CLE are presented in the work of E. Rossi and co-authors. They propose groups of indicators focused on three sustainability parameters – environmental, economic, and social – used in cyclical business models to account for innovations introduced by a circular economy (Rossi et al., 2020).

Table 4. Methods for assessing a closed-loop economy at the micro level

Author(s)	Year	Methodological toolkit	Estimated indicator / parameter / description
Das S.K., Yedlarajiah P., Narendra R.	2000	Multifactorial mathematical model	Disassembly Effort Index (DEI)
Zwolinski P., Lopez-Ontiveros M.-A., Brissaud D.	2006	Statistical methods	Remanufacturing Product Profiles (REPRO)
Park J.Y., Chertow M.R.	2014	Statistical methods	Reuse Potential Indicator (RPI)
Lee H.M., Lu W.F., Song B.	2014	Mathematical methods	End-of-Life Index
Huysman S., Debaveye S., Schaubroeck T., De Meester S., Ardente F., Mathieux F., Dewulf J.	2015	Life cycle assessment (LCA)	Recyclability benefit rate indicator
Van Schaik A., Reuter M.A.	2016	Simulation modeling	Recycling Indices (RI)
Scheepens A.E., Vogtlander J.G., Brezet J.C.	2016	LCA-based eco-costs value ratio	Eco-efficient Value Creation (EVR)
Franklin-Johnson E., Figge F., Canning L.	2016	Statistical methods	Longevity Index
Reuter M.A., Schaik A.V.	2016	Statistical methods	Recycling Index (RI). Recycling potential and efficiency should be quantified for products, collection systems, waste separation and recovery technologies, and supplies of materials
Adibi N., Lafhaj Z., Yehya M., Payet J.	2017	Life cycle assessment (LCA)	Global Resource Indicator
Linder M., Sarasini S., Van Loon P.	2017	Statistical methods	Product-level circularity metric
Di Maio F., Rem P.C., Balde K., Polder M.	2017	Assessment of the market value of "stressed" resources	Single Value-based Resource Efficiency Indicator (VRE)
Mohamed Sultan A.A., Lou E., Mativenga P.T.	2017	Statistical methods	Recycling Desirability Index
Veleva V., Bodkin G., Todorova S.	2017	Statistical methods	"Expanded Zero Waste" practice
Favi C., Germani M., Luzi A., Mandolini M., Marconi M.	2017	Index analysis	End-of-Life Index evaluation (EoL)
Cayzer S., Griffiths P., Beghetto V.	2017	A multidimensional approach with a single aggregated metric for each stage of the life cycle	CEIP metrics
Ameli M., Mansour S., Ahmadi-Javid A.	2018	Mathematical modeling	An optimization model for assessing sustainability at the design stage and identifying end-of-life alternatives
Niero M., Kalbar P.P.	2018	Multi-criteria Decision Analysis (MCDA)	Material circularity indicators and life cycle based indicators at the product level
Alamerew Y.A., Brissaud D.	2018	Multi-criteria decision-making method	Assessment of a closed-loop economy (PR-MCDT) for end-of-life product recycling strategies. CO2 emissions, SO2 emissions, energy consumption, net recovered value, logistical costs (cost of collection and transportation), cost of product disposal (incineration, recycling, landfill, etc.), number of employees, exposure of hazardous substances to employees during disposal, disassembly cost.
Marconi M., Germani M., Mandolini M., Favi C.	2018	Mathematical methods	Evaluation of the effective disassembly time of industrial products

End of Table 4

Author(s)	Year	Methodological toolkit	Estimated indicator / parameter / description
Vanegas P., Peeters J.R., Cattrysse D., Tecchio P., Ardente F., Mathieux F., Dewulf W., Duflou J.R.	2018	Maynard operation sequence technique (MOST)	Ease of Disassembly Metric (eDiM)
Bovea M.D., Perez-Belis V.	2018	Grouping of statistical indicators	A methodology that allows analyzing how much product development and design corresponds to the parameters of a closed-loop economy and what design principles would need to be included in order for the product to correspond to a closed-loop economy.
Lacovidou E., Velenturf A.P.M., Purnell P.	2019	Life cycle assessment (LCA)	Quality assessment at various stages of the life cycle of materials, components and products (MCP)
Cong L., Zhao F., Sutherland J.W.	2019	Scenario analysis, evaluation, Pareto efficiency analysis, Analytical Hierarchical process (AHP)	A cost-based recycling indicator to measure recyclability and evaluate constructive suggestions for material selection.
Rossi E., Bertassini A.C., Dos Santos Ferreira C., Do Amaral W.A.N., Ometto A.R.	2020	Grouping of statistical indicators	Material (reduction of raw material use, renewability, recyclability, reduction of toxic substances, reuse, restoration of production, number of recovered parts or components of the product, durability of the product, structure and diversity of stakeholders); economic (financial results, taxation, investment innovations); social (job creation, number of jobs created within the cyclical business model, income generated by jobs, employee participation in the cyclical model, customer mindset)
Source: own compilation.			

Micro-level techniques (Tab. 4) mainly focus on evaluating the effectiveness of design, taking into account the service life, life cycle and detailed disassembly processes, which implies that they are not universal and can only be used for specific industries for which they were originally developed.

Micro-level techniques in comparison with macro- and meso-level methods are characterized by more complex mathematical models, which is associated with greater availability of source data on the research object. Along with the potential for complicating the toolkit, more factors are needed to take into account all the circumstances of the system's functioning as a single object. However, not all relationships between system components can be quantified due to the lack of the required amount of information, especially for the use of predictive and simulation modeling.

In addition, more sophisticated qualitative analysis tools can be used at the micro level. In particular, the hierarchy analysis method is a procedure for finding the weighting coefficients of factors in the analysis of systems by the expert method. Separately, attention should be paid to the active use of life cycle assessment (LCA) in the CLE assessment toolkit. The method considers all stages of the product's life cycle, which makes it possible to identify the most critical stages in terms of environmental impact and ensures greater validity of decisions in product design, selection of materials, production technologies and disposal methods. LCA requires collecting a large amount of data on various stages of the life cycle. Some stages of LCA are related to subjectivity and depend on the criteria applied. From the point of view of human resource management efficiency, the

Maynard operation sequence technique (MOST) is of interest. There are 18 basic elements in MOST, which are designated by letters, for example: A (Action distance) – movement over a distance; B (Body motion) – movement of the body; G (Gain control) – gaining control over an object, capturing; P (Placement) – laying an object. The use of this technique to assess the disassembly of an object allows optimizing production processes in relation to actions within the framework of CLE. In our opinion, it is the MOST method that particularly emphasizes the specificity and non-universality of the currently used tools for estimating CLE parameters.

The multi-criteria nature of the presented tools is both an advantage and a disadvantage. On the one hand, the methods allow taking into account several criteria, involving the "human factor" in decision-making (hierarchy analysis method), and involving the use of mathematical tools and software. Along with this, the complexity of choosing the optimal solution is obvious, the potential conflict of criteria used to evaluate and compare alternative solutions, the complexity of the process of forming the model structure, the possible inconsistency of the results, and limitations on the number of criteria and objects.

Obviously, combinations of methodological tools will become promising in the future. Nevertheless, reaching consensus in this area is possible only after the final formation of the scientific doctrine of CLE (its essential concepts and principles).

Discussion

Attempts to systematize methodological approaches to CLE assessment and the assessment parameters have been carried out before. For example, J. Mesa and co-authors propose a classification of approaches to assessing CE in the context of sustainable development parameters, as well as approaches structured depending on the specifics of design, which allows adapting production processes to meet the goals of CLE – cycle deceleration processes and cycle closure processes (Mesa et al., 2018). A Parchomenko and co-authors applied multiple compliance analysis to evaluate 63 metrics and 24 features relevant to CE, such as recycling efficiency, longevity, and stock availability. The analysis revealed three main clusters of indicators: resource-efficiency cluster; materials stocks and flows cluster; and product-centric cluster. The authors also developed a visualization system for CE indicators that allows comparing individual indicators and integrating them into the most appropriate combinations (Parchomenko et al., 2019). In the study by H.S. Kristensen and M.A. Mosgaard considers 30 CLE indicators at the micro level. They are categorized into academic and practical ones and are categorized into three groups: individual quantitative indicators; analytical tools; and composite ones. The authors have identified nine categories of CE indicators: recycling, restoration, reuse, disassembly, lifetime extension, resource efficiency, waste management, end-of-life management, multidimensional indicators that are not included in other categories (Kristensen, Mosgaard, 2020). A set of indicators for assessing CLE for the microlevel, proposed by E. Rossi and co-authors, made it possible to see the need for an integrated approach and the development of multidimensional indicators for measuring CLE in the context of sustainability, since most CE assessment indicators focus on material flows and lifecycle completion strategies (Rossi et al., 2020). In the work of V. Elia and colleagues, the methods adopted for measuring environmental impact were analyzed and classified in order to identify the possibility of their use for quantifying compliance with the CE paradigm (Elia et al., 2017). A taxonomy of methods for assessing CLE is proposed, based on two parameters: indices (a synthetic indicator or a set of indicators) and measurement of material and energy flows, resource use, consumption, and life cycle-based parameters.

Thus, the classification proposed in our work complements scientific knowledge in the field of systematization of methodological approaches to the assessment of CLE.

Conclusion

The paper defines reference points for categorizing and structuring indicators of the closed-loop economy, classifies approaches to its measurement. We should note that the measurement of circularity is fraught with significant difficulties, requiring the development, application and validation of evaluation methods. At the moment, there is no generally accepted way to measure a closed-loop economy either as a whole, or at individual levels (macro, meso, micro), or within the framework of various CLE principles ("R" principles).

The aim of the work did not include identifying the advantages or disadvantages of existing methods, as such an attempt would be subjective. The methodological tools for assessing CLE are determined by regional and industry specifics, the geopolitical background of the study, and the goals and objectives set. Along with this, the presented methodological review made it possible to identify a number of methodological problems: the methodology for assessing CLE should include generally accepted definitions and principles of closed-loop economy and well-established closed-loop strategies and business models (currently these issues are debatable); the practical implementation of methodological tools should include the possibility of assessing compliance with common national objectives and national strategies in areas of sustainable development, as well as take into account industry and regional specifics. Despite this, the conducted research will make it possible to trace trends and systematize methodological approaches to assessing the closed-loop economy and gain an up-to-date understanding of the dynamics of scientific knowledge in this field.

References

Adibi N., Lafhaj Z., Yehya M., Payet J. (2017). Global Resource Indicator for life cycle impact assessment: Applied in wind turbine case study. *Journal of Cleaner Production*, 165, 1517–1528. DOI: 10.1016/j.jclepro.2017.07.226

Alamerew Y.A., Brissaud D. (2018). Circular economy assessment tool for end of life product recovery strategies. *Journal of Remanufacturing*, 9(18-19), 169–185. DOI: 10.1007/s13243-018-0064-8

Ameli M., Mansour S., Ahmadi-Javid A. (2019). A simulation-optimization model for sustainable product design and efficient end-of-life management based on individual producer responsibility. *Resources, Conservation and Recycling*, 140, 246–258. DOI: 10.1016/j.resconrec.2018.02.031

Bovea M.D., Perez-Belis V. (2018) Identifying design guidelines to meet the circular economy principles: A case study on electric and electronic equipment. *Journal of Environmental Management*, 228, 483–494. DOI: 10.1016/j.jenvman.2018.08.014

Cayzer S., Griffiths P., Beghetto V. (2017). Design of indicators for measuring product performance in the circular economy. *International Journal of Sustainable Engineering*, 10, 289–298. DOI: 10.1080/19397038.2017.1333543

Cong L., Zhao F., Sutherland J.W. (2019). A design method to improve end-of-use product value recovery for circular economy. *Journal of Mechanical Design*, 141(4). DOI: 10.1115/1.4041574

Das S.K., Yedlarajiah P., Narendra R. (2000). An approach for estimating the end-of-life product disassembly effort and cost. *International Journal of Production Research*, 38(3). DOI: 10.1080/002075400189356

De Andrade Monteiro A.G., Scur G., Mattos C.A., De Oliveira M.C. (2024) Circular economy in the Brazilian chemical industry: A proposal for a circularity index. *Cleaner Engineering and Technology*, 19(100730). DOI: 10.1016/j.clet.2024.100730

Di Maio F., Rem P.C., Balde K., Polder M. (2017). Measuring resource efficiency and circular economy: A market value approach. *Resources, Conservation and Recycling*, 122, 163–171. DOI: 10.1016/j.resconrec.2017.02.009

Ding L.-l., Lei L., Wanga L., Zhang L.-F. (2020) Assessing industrial circular economy performance and its dynamic evolution: An extended Malmquist index based on cooperative game network DEA. *Science of The Total Environment*, 731. DOI: 10.1016/j.scitotenv..139001

Elia V., Gnoni M.G., Tornese F. (2017). Measuring circular economy strategies through index methods: A critical analysis. *Journal of Cleaner Production*, 142(4), 2741–2751. DOI: 10.1016/j.jclepro.2016.10.196

Favi C., Germani M., Luzi A., Mandolini M., Marconi M. (2017). A design for EoL approach and metrics to favour closed-loop scenarios for products. *International Journal of Sustainable Engineering*, 10(3), 136–146. DOI: 10.1080/19397038.2016.1270369

Franklin-Johnson E., Figge F., Canning L. (2016). Resource duration as a managerial indicator for Circular Economy Performance. *Journal of Cleaner Production*, 133, 589–598. DOI: 10.1016/j.jclepro.2016.05.023

Garcia-Sanchez I.-M., Somohano-Rodriguez F.-M., Amor-Esteban V., Frias-Aceituno J.-V. (2021). Which region and which sector leads the circular economy? CEBIX, a multivariant index based on business actions. *Journal of Environmental Management*, 297, 113299. DOI: 10.1016/j.jenvman.2021.113299

Gutman S.S., Manakhova M.S. (2021). Formation of a system of indicators for assessing the implementation of the circular economy concept in the regions of the Russian Federation. *Sever i rynok: formirovanie ekonomicheskogo poryadka*, 2, 81–95. DOI: 10.37614/2220-802X.2.2021.72.007 (in Russian).

Haupt M., Vadenbo C., Hellweg S. (2016). Do we have the right performance indicators for the circular economy? Insight into the Swiss waste management system. *Journal of Industrial Ecology*, 21. DOI: 10.1111/jiec.12506

Holly F., Schild C., Schlund S. (2023). Development of an assessment model for measuring mechanical engineering companies' circularity and maturity levels. *Research Square*. DOI: 10.21203/rs.3.rs-3391466/v1

Huyen Do T.T., Ly T.B.T., Hoang N.T., Tran V.T. (2023). A new integrated circular economy index and a combined method for optimization of wood production chain considering carbon neutrality. *Chemosphere*, 311, Part 2. DOI: 10.1016/j.chemosphere.2022.137029

Huysman S., Debaveye S., Schaubroeck T. et al. (2015). The recyclability benefit rate of closed-loop and open-loop systems: A case study on plastic recycling in Flanders. *Resources, Conservation and Recycling*, 101, 53–60. DOI: 10.1016/j.resconrec.2015.05.014

Jacobsen N.B. (2006). Industrial symbiosis in Kalundborg, Denmark: A quantitative assessment of economic and environmental aspects. *Journal of Industrial Ecology*, 10(1-2), 239–255. DOI: 10.1162/108819806775545411

Kayal B., Abu-Ghunmi D., Abu-Ghunmi L. et al. (2019). An economic index for measuring firm's circularity: The case of water industry. *Journal of Behavioral and Experimental Finance*, 21, 123–129. DOI: 10.1016/j.jbef.2018.11.007

Kiani Mavi N., Kiani Mavi R. (2019). Energy and environmental efficiency of OECD countries in the context of the circular economy: Common weight analysis for Malmquist productivity index. *Journal of Environmental Management*, 247(2), 651–661. DOI: 10.1016/j.jenvman.2019.06.069

Kristensen H.S., Mosgaard M.A. (2020). A review of micro level indicators for a circular economy e moving away from the three dimensions of sustainability? *Journal of Cleaner Production*, 243. DOI: 10.1016/j.jclepro.2019.118531

Lacovidou E., Velenturf A.P.M., Purnell P. (2019). Quality of resources: A typology for supporting transitions towards resource efficiency using the single-use plastic bottle as an example. *Science of The Total Environment*, 647, 441–448. DOI: 10.1016/j.scitotenv.2018.07.344

Lee H.M., Lu W.F., Song B. (2014). A framework for assessing product End-Of-Life performance: Keviewing the state of the art and proposing an innovative approach using an End-of-Life Index. *Journal of Cleaner Production*, 66, 355–371. DOI: 10.1016/j.jclepro.2013.11.001

Linder M., Sarasini S., Van Loon P. (2017). A metric for quantifying product-level circularity. *Journal of Industrial Ecology*, 21(3), 471–795. DOI: 10.1111/jiec.12552

Marconi M., Germani M., Mandolini M., Favi C. (2018). Applying data mining technique to disassembly sequence planning: a method to assess effective disassembly time of industrial products. *International Journal of Production Research*, 57(1), 1–25. DOI: 10.1080/00207543.2018.1472404

Mesa J., Esparragoza I., Maury H. (2018). Developing a set of sustainability indicators for product families based on the circular economy model. Journal of Cleaner Production, 196, 1429–1442. DOI: 10.1016/j.jclepro.2018.06.131

Mohamed Sultan A.A., Lou E., Mativenga P.T. (2017). What should be recycled: An integrated model for product recycling desirability. *Journal of Cleaner Production*, 154, 51–60. DOI: 10.1016/j.jclepro.2017.03.201

Niero M., Kalbar P.P. (2019). Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level. *Resources, Conservation and Recycling*, 140, 305–312. DOI: 10.1016/j.resconrec.2018.10.002

O'Grady T., Minunno R., Chong H.-Y., Morrison G.M. (2021). Design for disassembly, deconstruction and resilience: A circular economy index for the built environment. *Resources, Conservation and Recycling*, 175. DOI: 10.1016/j.resconrec.2021.105847

Parchomenko A., Nelen D., Gillabel J., Rechberger H., Wien T. (2019). Measuring the circular economy – a Multiple Correspondence Analysis of 63 metrics. *Journal of Cleaner Production*, 210, 200–216. DOI: 10.1016/j.jclepro.2018.10.357

Park J.Y., Chertow M.R. (2014). Establishing and testing the "reuse potential" indicator for managing wastes as resources. *Journal of Environmental Management*, 137, 45–53. DOI: 10.1016/j.jenvman.2013.11.053

Pires A., Martinho G. (2019). Waste hierarchy index for circular economy in waste management. *Waste Management*, 95, 298–305. DOI: 10.1016/j.wasman.2019.06.014

Qing Y., Qiongqiong G., Mingyue Ch. (2011). Study and integrative evaluation on the development of circular economy of Shaanxi Province. *Energy Procedia*, 5, 1568–1578. DOI: 10.1016/j.egypro.2011.03.268

Ratner S.V., Iosifov V.V., Ratner P.D. (2020). Analysis and evaluation of the level of circular economy development in Russian regions. *Ekonomicheskii analiz: teoriya i praktika=Economic Analysis: Theory and Practice*, 19(2), 206–225. DOI: 10.24891/ea.19.2.206

Reuter M.A., Schaik A.V. (2016). Strategic metal recycling: Adaptive metallurgical processing infrastructure and technology are essential for a circular economy. *Annales des Mines – Responsabilite et environnement*, 82(62), 2–66. DOI: 10.3917/re1.082.0062

Rossi E., Bertassini A.C., Dos Santos Ferreira C., Do Amaral W.A.N., Ometto A.R. (2020). Circular economy indicators for organizations considering sustainability and business models: Plastic, textile and electroelectronic cases. *Journal of Cleaner Production*, 247. DOI: 10.1016/j.jclepro.2019.119137

Scheepens A.E., Vogtlander J.G., Brezet J.C. (2016). Two life cycle assessment (LCA) based methods to analyses and design complex (regional) circular economy systems. Case: Making water tourism more sustainable. *Journal of Cleaner Production*, 114, 257–268. DOI: 10.1016/j.jclepro.2015.05.075

Smol M., Kulczycka J., Avdiushchenko A. (2017). Circular economy indicators in relation to eco-innovation in European regions. *Clean Technologies and Environmental Policy*, 19, 669–678. DOI: 10.1007/s10098-016-1323-8

Titova N.Yu. (2022). An overview of methodological approaches aimed at assessing sustainable development and circular economy. *Vestnik Permskogo universiteta. Seriya: Ekonomika= Perm University Herald. Economy*, 17(3), 288–303. DOI: 10.17072/1994-9960- 2022-3-288-303

Van Schaik A., Reuter M.A. (2016). Recycling indices visualizing the performance of the circular economy. *World of Metallurgy – ERZMETALL*, 69(4/2016), 201–216.

Vanegas P., Peeters J.R., Cattrysse D. et al. (2018). Ease of disassembly of products to support circular economy strategies. *Resources, Conservation and Recycling*, 135, 323–334. DOI: 10.1016/j.resconrec.2017.06.022

Veleva V., Bodkin G., Todorova S. (2017). The need for better measurement and employee engagement to advance a circular economy: Lessons from Biogen's "zero waste" journey. *Journal of Cleaner Production*, 154, 517–529. DOI: 10.1016/j.jclepro.2017.03.177

Wang C.-H., Helmi Ali M., Chen K.-S. et al. (2021). Data driven supplier selection as a circular economy enabler: A Taguchi capability index for manufactured products with asymmetric tolerances. *Advanced Engineering Informatics*, 47. DOI: 10.1016/j.aei.2021.101249

Wen Z., Meng X. (2015) Quantitative assessment of industrial symbiosis for the promotion of circular economy: A case study of the printed circuit boards industry in China's Suzhou New District. *Journal of Cleaner Production*, 90, 211–219. DOI: 10.1016/j.jclepro.2014.03.041

Zwolinski P., Lopez-Ontiveros M.-A., Brissaud D. (2006). Integrated design of remanufacturable products based on product profiles. *Journal of Cleaner Production*, 14(15-16), 1333–1345. DOI: 10.1016/j.jclepro.2005.11.028

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