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ECONOMIC MONITORING OF THE CIRCULAR TRANSFORMATION AS A CHALLENGE FOR MECHANICAL ENGINEERING

Andrija Popović[1], Zorana Stanković[2], Andreja Todorović[3], Milena Rajić[4]

[1]Innovation Center, University of Niš

[2] Faculty of Mechanical Engineering, University of Niš

[3]Innovation Center, University of Niš

[4] Faculty of Mechanical Engineering, University of Niš

Abstract. *This paper critically evaluates the role of mechanical engineering in the economic monitoring of the circular economy transformation. The transition from a linear "take-make-dispose" model to a circular one is imperative for sustainability, requiring significant adaptation in mechanical engineering practices. The research investigates the methodologies and institutional frameworks that underpin this transformation, assessing their efficacy and identifying areas for enhancement. By examining the latest scientific literature and employing various indicators and evaluation methods, the study outlines the practical and strategic benefits of embracing circular economy principles. It underscores the necessity of robust monitoring mechanisms and the crucial role of institutions in fostering the transition, with a particular focus on the European Union's regulatory approach. This paper provides a comprehensive understanding of the state of circular economy implementation in mechanical engineering and suggests future directions for its development, monitoring, and integration into policy and educational frameworks.*

Key words: *Circular Economy, Mechanical Engineering, Methodological Approach, Institutional Framework, Managerial Approach, Industrial Organization*

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Corresponding author: Andrija Popović
Innovation Center, University of Niš
E-mail: andrija.m.popovic@gmail.com

1. INTRODUCTION

The impact of social, industrial, and technological development and the traditional linear economic models, characterized by a "take-make-dispose" approach, on the global economy and ecosystem is becoming increasingly significant. Climate change, loss of biodiversity, and ongoing resource extraction are causing higher volatility in the global economy and raising concerns about the sustainability of the current way of life [1-4]. Within this context, mechanical engineering, a field pivotal in industrial and manufacturing processes, and economics, the field crucial to determining the effectiveness of those processes, confront the urgent need for adaptation toward sustainable practices. This adaptation is necessary not only for environmental sustainability but also for overall long-term economic viability and competitiveness [5].

It has become abundantly clear that linear economic system has inherent flaws and limitations, and due to its heavy reliance on the continuous extraction and processing of raw materials and disposal of end-of-life products, it is unsustainable [6]. In the field of mechanical engineering, this unsustainability manifests through inefficient resource use, high energy consumption, and the generation of substantial waste, particularly in the manufacturing sector, while the wider economic consequences of its unsustainability at the global level are the lack of resources, price volatility, uncertainty, and increasingly economic crisis [7-9].

As an alternative economic model that relies on the new technologies of Industry 4.0, the circular economy not only offers a solution to the current challenges but also offers numerous operational and strategic benefits at both the macro and microeconomic levels [8, 10-13]. Compared to the linear model, the circular economy prioritizes the efficient utilization of resources, minimizing waste, and encouraging the regeneration of products and materials [2,14]. This approach is particularly relevant in mechanical engineering, where products are designed with longevity in mind, easy repair and remanufacturing, and end-of-life options that prioritize recycling or reuse [4]. The transition towards a circular economy constitutes a significant opportunity from both environmental and economic perspectives, facilitating innovation and generating novel business models.

Effective implementation of the circular economy demands comprehensive monitoring mechanisms at both macro and micro levels. These mechanisms are essential to track progress, identify bottlenecks, and ensure that circular practices are seamlessly integrated into all economic system elements, from mechanical engineering practices and processes to overarching policies [2,15-17]. Monitoring encompasses various aspects, including material flow analysis, assessment of resource efficiency, and evaluation of the environmental and economic impacts of circular practices. Therefore, it is imperative to establish comprehensive monitoring mechanisms to ensure the successful implementation of circular economy practices.

Even though monitoring mechanisms are essential for the evaluation of circular economy development, institutions also play a crucial role in transitioning towards and monitoring a circular economy. Policymaking, providing incentives for sustainable practices, setting industry standards, and fostering collaboration among stakeholders are some of the ways that institutions interact and support the circular economy implementation. For mechanical engineering, institutional support is vital for research and development, facilitating the adoption of circular principles and integrating them into educational and professional training [4]. Potentially, the clearest and most developed approach to accelerating the implementation of the circular economy can be seen in the approach of the European Union. This top-down approach means that changes in national regulations, strategies, and policies are introduced and implemented before they affect subordinate local regulations. Therefore, it is of crucial importance to understand, assess, and improve the capacity and role of these institutions in leading this transformative transition towards a circular economy [14,18].

This paper aims to delve into the economic monitoring of circular transformation as a challenge for mechanical engineering. It will explore the methodologies and institutional frameworks that support this transformation, assess their effectiveness, and identify areas for improvement. The paper will draw upon various studies to provide a comprehensive understanding of the current state of circular economy implementation in mechanical engineering and the future directions for its monitoring and development.

2. LITERATURE REVIEW

The following review examines the latest scientific literature related to the circular economy, particularly emphasizing its impact on mechanical engineering. It offers an in-depth overview of current research and theories, highlighting the necessity of transitioning from conventional linear economic models to a circular economy. This transition is not only crucial for environmental sustainability but also represents a strategic objective at various levels - global, regional, national, and personal.

In their works, Kalmykova et al. [19] and Ghisellini et al. [7] offered comprehensive and insightful reviews of the circular economy by carefully and thoroughly examining its development and revealing its fundamental principles in order to understand its theoretical foundation better. Their research integrates a vast spectrum of existing ideas and practices into a coherent framework and, crucially, progresses the conversation by introducing practical tools and strategies. These innovations are meant to empower businesses to seamlessly adopt circular economy principles, significantly enriching both overall historical comprehension and the pragmatic implementation of these concepts. At the same time, the Ellen MacArthur Foundation [8] has made significant strides in understanding the circular economy and its importance from the standpoint of businesses and civil society. Their research explores the economic and business incentives for transitioning towards a circular economy. This pivotal report underscores not just the immediate advantages but also the long-term imperatives of this transformation, thereby casting a compelling vision for a sustainable future.

In addition to detailed overviews, multiple foundational works set the stage for a deeper understanding of the circular economy's complexities. Sousa-Zomer et al. [4] offer a critical analysis of the obstacles encountered when transitioning business models from a linear to a circular framework. Their work sheds light on the many-sided nature of this shift, revealing the particularities involved in redefining value creation and supply chain dynamics in a circular context. This paper becomes a cornerstone for understanding the initial resistance and the innovative solutions required in adopting circular principles. Furthermore, Lewandowski’s [5] contribution complements the previous references by demonstrating how traditional business models can be restructured to align with circular economy principles. His insights bridge the gap between theory and practice, offering a pragmatic yet innovative approach to rethinking economic activities. His work serves as a guiding framework for businesses and policymakers, showing the feasibility and advantages of integrating circular economy concepts into existing business structures. In addition to its foundational importance, the Ellen MacArthur Foundation [8] goes beyond a historical perspective and provides a strong rationale for transitioning towards circular models. This report is pivotal in mapping out the journey from the early theoretical concepts of the circular economy to its practical applications. It not only clarifies the economic and environmental imperatives of this transition but also paints a vision of a sustainable and resilient future.

From the foundational understanding of the circular economy and its importance stems the research on transitioning from linear to circular models which reflects a multidisciplinary effort to understand and implement these changes across various sectors. The work of de Boer et al. [6] offers a macroscopic view of this transition, discussing the global environmental and socio-economic impacts. Their analysis underscores how the circular economy can address critical global challenges like climate change, resource scarcity, and social inequality, offering a holistic perspective on the required systemic changes. Complementing this global perspective, McCarthy et al. [20] delve into the macroeconomics of the circular economy. Their research bridges the gap between theoretical understanding and real-world economic implications, demonstrating how circular economy practices can lead to economic growth, job creation, and a more resilient economy. This paper is crucial for understanding the broad economic effects of transitioning to a circular economy and how it can be integrated into national and global economic strategies.

In the realm of practical applications, Suzanne et al. [21] discuss the challenges and opportunities of integrating circular economy principles into production planning. This research is particularly relevant for mechanical engineering, as it highlights how traditional production processes can be re-engineered for sustainability. Similarly, Vunnava and Singh's work [22] on mechanistic engineering models offers valuable insights into the tools and methods required to enable a circular economy transition, emphasizing the role of technology and innovation in this process.

The practical challenges and strategies for businesses, especially in the manufacturing sector, are further explored by Riesener et al. [23] and Chen et al. [24] These papers provide a comprehensive overview of the hurdles businesses face in this transition and propose potential solutions and strategies. They discuss how circular economy principles can be implemented in manufacturing processes, product design, and supply chain management, offering a roadmap for businesses looking to embark on this transformative journey.

The cumulative knowledge presented in these works offers a comprehensive understanding of the circular economy's theoretical foundation, global impacts, and practical applications. However, the transition towards a circular economy is particularly impactful in the field of mechanical engineering, where design, manufacturing processes, and lifecycle management play critical roles. The application of circular economy principles in this sector requires a delicate understanding of the unique challenges and opportunities it presents. As we dive deeper into the methodological frameworks and indicators for monitoring the circular economy, it is essential to scrutinize existing frameworks and their applicability to the mechanical engineering sector. This sector, with its complex manufacturing processes and lifecycle management, requires a subtle approach to monitoring and evaluating circular economy practices.

Delving into the methodological aspect, Tikhonov [25] highlights the need for approaches tailored to mechanical engineering in the circular transition. To enable sustainable product development, a fundamental shift in the system is required. This includes a holistic approach to design, material selection, and end-of-life management. These frameworks should track not only the flow of materials, but also evaluate product durability and reparability. This concept is further elaborated by Lewandowski [5], who discusses the restructuring of business models to fit into a circular economy framework.

Drawing on this, Sassanelli et al. [26] present a systematic review of circular economy performance assessment methods, advocating for frameworks that gauge a company's circularity level. Similarly, Haupt and Hellweg [27] propose environmental-impact-based indicators, broadening the scope of circular economy monitoring to include comprehensive environmental considerations. Potting et al. [28] contribute to this discourse by developing a framework that gauges innovation's role in circular economy transitions, highlighting its significance in mechanical engineering.

Transitioning to the role of policies and institutions, López Ruiz et al. [29] shed light on how regulatory frameworks significantly influence the adoption of circularity in the construction and demolition sectors, a finding equally relevant to mechanical engineering. Fischer and Pascucci's [12] investigation into the Dutch textile industry offers insights into how institutional frameworks can facilitate or impede the adoption of circular economy principles. Extending this perspective, Rizos et al. [30] discuss the challenges and opportunities for SMEs within the circular economy, providing valuable insights applicable to the mechanical engineering sector.

Further broadening the discussion, Schulz, Hjaltadóttir, and Hild [31] advocate for a comprehensive understanding of the circular economy from an institutional viewpoint. They emphasize the transformative potential of circular economy practices. Glückler and Lenz's [32] framework analyses the interplay between regulation and institutions at a regional scale, offering a dynamic view of how such interactions shape the effectiveness of circular economy policies, a perspective crucial for mechanical engineering firms.

This section highlights the complex connection between economics, mechanical engineering, and the circular economy. The methodological and policy frameworks, along with institutional factors discussed here, collectively influence the adoption and effectiveness of circular economy concepts in this field. These insights not only guide present practices but also pave the way for future innovations and strategies in mechanical engineering. However, the analysis shows a clear lack of unified and dedicated research providing a unique perspective on the economic monitoring of the circular transformation in mechanical engineering.

Having established the significance of these frameworks and influences in mechanical engineering, the next section of this paper will further illuminate the methodological frameworks used on macro and micro economic levels, particularly in the field of mechanical engineering and for businesses embarking on this transformative journey.

3. METHODOLOGICAL FRAMEWORK FOR MEASURING AND ASSESSING THE DEVELOPMENT OF THE CIRCULAR ECONOMY

As previously mentioned, advancing the realization of the circular economy requires thorough measurement and assessment of its implementation. One of the main challenges of this task is the lack of universally accepted methodological frameworks, indicators, or metrics. Additionally, the complex relationship between technical, environmental, economic, and social aspects inherent in circular processes presents a significant obstacle [17]. Despite these challenges, evaluating the development of the circular economy is of crucial importance. The ability to track progress, identify areas requiring improvement, and shape policies and strategies for an efficient transition to the circular economy is vital [2,3].

Having in mind the importance of evaluation, various international regulatory bodies have begun to deal with presenting non-financial information, including key elements necessary for evaluating the circular economy. The most recognizable approach is that of the European Commission [33] through Directive 2014/95/EU, based on methodological frameworks such as the Guide to Corporate Social Responsibility [34], the Environmental Management and Audit Scheme [35], and the Global Reporting Initiative [36], among others. This directive and the presented frameworks provide guidelines for selecting and measuring indicators. However, even when 80% of the top 250 multinational companies use these standardized formats in their Corporate Sustainability Reports, the presented information still lacks uniformity [17]. This reality highlights the need for further research on which aspects of circularity organizations currently measure and communicate in their reports and what additional information they need to include to accurately represent their level of adoption of the circular economy. Also, it is necessary to build national indicators based on this information, providing a basis for comprehensive analysis.

In the following lines, we will illuminate the dense network of technical, economic, ecological, and social dimensions embedded in circular processes and identify the most appropriate methodological approaches, methods, and indicators that can be applied.

3.1 Criteria for Evaluation of the Development of the Circular Economy

Although promoted by international and national institutions and the academic community, the circular economy still represents a very young and extremely challenging concept in terms of definition and measurement [16,19]. This is precisely why there is no generally accepted definition of the circular economy, and therefore, the criteria for its evaluation are not standardized.

The definition of the circular economy that holds sway at present is that put forth by the Ellen MacArthur Foundation [8]. It states that the circular economy can be defined as "an industrial system that is restorative or regenerative by intention and design. It replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models." [8, p.7]. Additionally, Kirchherr et al. [37] in their comprehensive literature review identified 114 definitions and proposed a unifying concept defining the circular economy as " an economic system that replaces the ‘end-of-life’ concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks), and macro level (city, region, nation, and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers." [37, p. 229].

These definitions provide a foundation for establishing evaluation and monitoring criteria and monitoring the development of the circular economy that aims to reflect the primary goals of circular economy strategies. These criteria include [38,39,40]:

- Reducing the use of natural resources
- Reducing the level of harmful gas emissions
- Reducing waste and loss of valuable materials
- Increasing the share of renewable or recycled resources
- Increasing the utility, value, and durability of products

The sustainability and efficiency of any framework for evaluating the development of the circular economy depend on its validity, reliability, and usefulness [40], as well as the criteria that establish the basis for its evaluation. Therefore, it is necessary to determine whether the analyzed methodological frameworks, indicators, or tools accurately measure progress toward the circular economy, provide consistent results in different contexts, and are practical for application.

3.2 Circular Economy Evaluation Indicators

One of the crucial open questions regarding the circular economy is the definition of indicators and tools for measuring and evaluating the circular economy. "What gets measured, gets managed" - a quote from Peter Drucker, reveals the trap for a targeted transition to a sustainable, circular economy [41, p. 1]. Considering that this concept is based on a paradigm closely correlated with sustainable development, tools for measuring the circular economy are mainly based on its contribution to sustainable development. However, policymakers are increasingly seeking comprehensive aggregate indicators related to composite indices as a useful tool that can be easily interpreted and communicated to the public [42, p. 2].

In the course of our analysis, we will commence by exploring the indicators at the national or macro level. For this purpose, indicators and the methodological framework of the European Union will be used as a representative example due to its pioneering significance in the implementation of the circular economy. Afterward, our attention will be directed towards assessing the circular economy, particularly at the micro and company levels. Our presentation will highlight the vital indicators recognized in scientific and professional circles, thereby providing a clear insight into their significance. Our discussion will encompass quantitative, analytical, and composite indicators, illustrating how they can be used in various facets of the circular economy.

3.2.1 Indicators for Measuring the Circular Economy at the National Level

Based on a significant number of research and exploratory studies and reports, it can be observed that the model of the circular economy has experienced rapid promotion and significant application only in a small number of the world's most developed countries. Many of these countries are a part of the European Union, and therefore, the indicators and tools for evaluating the circular economy at the national level will be identified with the indicators presented in the Framework for Monitoring the Circular Economy in the European Union [43]. It is imperative to measure the circular economy on a national level as it promotes sustainable development. In this aspect, governments hold significant responsibility in establishing and executing policies that facilitate the shift from linear economic models to those founded on circular economy principles [42]. Based on various data, some countries have developed specific approaches to monitor progress towards the development of the circular economy at the national level (macro level). Interestingly, almost all these initiatives are based on material flow calculations and waste management data [44, p. 46]. At the macro level, the main focus is on the (material) exchange between the economy and the environment, international trade, and material accumulations in national economies, not on flows within the economy. Macroeconomic indicators describe the characteristics of a country or a larger region mainly in relation to interactions with the rest of the world through trade flows [45, p. 6].

European Union policy for waste and the circular economy has evolved over the past 30 years through a series of environmental action plans and circular economy policies aimed at reducing impacts on the environment, improving human health, and creating an efficient economy [44, 46]. The latest document in the series that monitors the measurement of the development of the circular economy in the European Union is the Methodological Framework for Monitoring Progress in Implementing Measures for the Circular Economy from 2018 [47]. This framework includes ten key indicators that cover four broad areas such as production and consumption, waste management, secondary raw materials, and competitiveness and innovation. The data of indicators and sub-indicators are based on official statistics from Eurostat, the Joint Research Centre, and the European Patent Office [42, p. 3]. However, not all of the indicators are relevant to the field of mechanical engineering. Thus, building on the Garcia-Bernabeu et al. [42] overview, in Table 1, we are emphasizing the most important macroeconomic indicators relevant to the mechanical engineering field.

Table 1 List of Circular Economy Macro-Indicators Relevant to the Mechanical Engineering

No.	Indicator	Data Source	Reference Area	Coverage - Time	Relevant to the Field of Mechanical Engineering	Importance to Mechanical Engineering
Production and Consumption						
1.	**EU self-sufficient for raw material**	European Commission	Only EU aggregate		**Yes**	Determines the availability and sustainability of materials essential for mechanical engineering within the EU.
2.	**Green Public Procurement**				**No**	
3.	**Waste Generation**				**Yes**	
3a.	**Generation of municipal waste per capita (Kg per capita)**	Eurostat	All EU Member States	>10 years (2000)	**Yes**	Indicates the societal impact of waste, reflecting on the efficiency and environmental footprint of mechanical engineering processes.
3b.	**Generation of waste excluding major mineral wastes per GDP unit (Kg per thousand euro)**	Eurostat	All EU Member States	>10 years (2004)	**Yes**	Provides insight into the relationship between economic activity and waste production, relevant for sustainable mechanical engineering practices.
3c.	**Generation of waste excluding major mineral wastes per domestic material consumption (percentage)**	Eurostat	All EU Member States	>10 years (2004)	**Yes**	Measures the intensity of waste generation in relation to material usage, a key factor for resource-efficient mechanical engineering.
4.	**Food Waste (millions of tons)**				**No**	
Waste Management						

5.	**Recycling Rate**				**Yes**	
5a.	**Recycling rate of municipal waste (percentage)**	Eurostat	All EU Member States	>10 years (2000)	**Yes**	Reflects the effectiveness of recycling systems, which mechanical engineering can enhance through design and process optimization.
5b.	**Recycling rate of all waste excluding major mineral waste (percentage)**	Eurostat	All EU Member States	5 to 10 (2010)	**Yes**	Gauges the overall efficiency of waste recycling, crucial for understanding and improving circular practices in mechanical engineering.
6.	**Recycling/recovery for specific waste streams**				**Yes**	
6a.	**Recycling rate of overall packaging (percentage)**	Ministries of Environment	All EU Member States	>10 years (2000)	**Yes**	Relevant for evaluating the sustainability of packaging materials often used in products.
6b.	**Recycling rate of plastic packaging (percentage)**	Ministries of Environment	All EU Member States	>10 years (2000)	**Yes**	Crucial for mechanical engineering, as it impacts material selection and sustainability of plastic components.
6c.	**Recycling rate of wooden packaging (percentage)**	Ministries of Environment	All EU Member States	>10 years (2000)	**Yes**	Indicates the efficiency of wood recycling, a material commonly used in mechanical engineering.
6d.	**Recycling rate of e-waste (percentage)**	Eurostat	All EU Member States	5 to 10 (2010)	**Yes**	Directly relevant to mechanical engineering due to the need for sustainable disposal and recycling of electronic components.
6e.	**Recycling of biowaste (Kg per capita)**	Eurostat	All EU Member States	>10 years (2000)	**No**	
6f.	**Recovery rate of construction and demolition waste (percentage)**	Eurostat	All EU Member States	5 to 10 (2010)	**Yes**	Important for mechanical engineering in the context of sustainable construction and infrastructure development.
			Secondary Raw Materials			
7.	**Contribution of recycled material to raw materials demand**				**Yes**	
7a.	**End-of-life recycling input rates (EOL-RIR) (percentage)**	European Commission	Only EU aggregate	2016	**Yes**	Assesses how effectively materials are recycled at the end of a product's life, crucial for mechanical engineering product design.
7b.	**Circular material use rate (percentage)**	Eurostat	All EU Member States	>10 years (2010)	Yes	Measures the extent to which materials are reused and recycled, integral to sustainable mechanical engineering.
8.	**Trade in recyclable raw materials (tonnes)**	Eurostat	All EU Member States	>10 years (2004)	**Yes**	Provides insights into the market dynamics of recyclable materials, affecting material selection and supply chains in mechanical engineering.
			Competitiveness and Innovation			
9.	**Private investments, jobs and gross value added related to CE sectors**				**Yes**	
9a.	**Gross investments in tangible goods (percentage of GDP at current prices)**	Eurostat	All EU Member States	>10 years (2012)	**Yes**	Reflects the investment in physical assets, important for assessing the growth and development of the mechanical engineering sector.
9b.	**Persons employed (percentage of total employment)**	Eurostat	All EU Member States	>10 years (2012)	**Yes**	Indicates the employment landscape in mechanical engineering, showing its impact on the job market.
9c.	**Value added at factor cost (percentage of GDP at current prices)**	Eurostat	All EU Member States	>10 years (2012)	**Yes**	Reveals the economic contribution of mechanical engineering to the broader economy.
10.	**Number of patents related to recycling and secondary raw materials**	European Patent Office	All EU Member States	>10 years (2000)	**Yes**	Highlights innovation in mechanical engineering, particularly in sustainable practices and materials.

The list of indicators and sub-indicators for evaluating various criteria of the circular economy, as presented in Table 1, reflects the degree of its development in the European Union. The list also includes two indicators, green public procurement and food waste, although their full implementation will only commence in the coming years. The majority of indicators and sub-indicators pertain to waste management, considering that waste is one of the key challenges to sustainable development. Additionally, a portion of the indicators focuses on competitiveness and innovation, which are crucial for further socio-economic development [3]. Most of the macroeconomic indicators are also relevant to the field of mechanical engineering and gather data from that field as well.

3.2.2 Indicators for Measuring the Circular Economy at the Company Level

Despite the widespread dissemination and availability of circular economy theory, there remains a notable deficiency in empirical methodologies for assessing its practical impact, as well as a paucity of established metrics and indicators for this purpose [48]. The transition towards a circular economy necessitates comprehensive tools for evaluating its progression, necessitating metrics that address both the macro-level (national) and micro-level (company-specific) dimensions. While data at the macro level are relatively accessible, facilitating national-level circular economy assessment, companies encounter significant obstacles in evaluating their circular economy practices, particularly beyond the scope of waste generation and recycling. Consequently, the development of an effective measurement framework at the enterprise level is imperative for a holistic analysis of circular economy practices. Presently, the circular transition is in its nascent stage, predominantly within the most advanced economies. Even within those economies, approximately 28% of companies have yet to initiate any circular economy-related activities, and only about 8 to 12% of companies are substantially engaged in transitioning towards a circular economy [49, p. 4]. Therefore, measurement at the enterprise level should be viewed through a system of measurement of companies that have implemented the concept of the circular economy. Literature in this field recognizes over 100 indicators at the enterprise level [50, p. 522], and thus, measurement at the micro level has a limiting factor related to the choice of measurement tools. Indicators for measuring the circular economy must be relevant, so the list of proposed tools highlights 28 micro indicators [50, p. 523]. As shown in Table 2, micro indicators of the circular economy can be divided into three groups, namely [51]:

- Quantitative indicators – numerical measures of circularity
- Analytical tools – qualitative measures of circularity
- Composite indicators – combine quantitative indicators and analytical tools for assessing the circularity of products or enterprises

From the perspective of focus on the circular economy, indicators can be grouped into nine categories: Extension of lifecycle, Resource efficiency, "End-of-Life" management, Waste management, Recycling, Remanufacturing, Reuse, Disassembly, and Multidimensional indicators.

Most micro indicators are categorized in recycling, remanufacturing, or lifecycle management. Very few are in reuse, disassembly, waste management, life extension, or resource efficiency [50, 51].

Table 2 List of Circular Economy Micro-Indicators Relevant to the Mechanical Engineering

Indicator	**CE Focus Category**	**Decision Criteria**	**Sustainability Dimension**	**Product Life Cycle Phase**	**Access to Data**	**Control Over the Indicator**	**Measurement Principle**	**Importance to Mechanical Engineering Field**	**Importance Evaluation**
Quantitative Indicators									
RDI	Recycling	Rec	Environmental	PD	I/E	C/M/L	Degree of recycling desirability	High	Essential for sustainable material and design choices
RPI	Recycling	Rec	Ecological	C	E	C/M	Extent of material reuse potential	High	Influences material selection and lifecycle management
CEI	Recycling	Rec	Economic	C	E	C/M/L	Economic value at end-of-life	Medium	Balances economic and environmental aspects of material recovery
MCI	Recycling/ Waste Management	Rec/LE/WM	Environmental	C	I/E	C/M/L	Product circularity based on material flows	High	Drives design for longevity and material efficiency
MRS	Recycling	Rec	Environmental	PD	I	C/M	Recyclable material fraction	High	Directly relates to product sustainability and waste reduction
EVR	Resource Efficiency	RE	Eco/ Environmental	PD	I/E	C/M	Eco-cost to value ratio	Medium	Evaluates environmental impact versus product value
VRE	Resource Efficiency	RE	Eco/ Environmental/ Social	PD	I	C/M/L	Resource efficiency by weight and policy	Medium	Encourages mass and policy-based resource-efficient design
eDIM	Disassembly	D	Ecological	PD	I	C	Disassembly time	High	Critical for end-of-life management and recyclability
EDT	Disassembly	D	Ecological	PD	I/E	C	Effective disassembly time	High	Vital for maintenance, repair, and disassembly processes
LI	Life Extension	LE	Environmental	C	I/E	C/M/L	Material longevity in the product cycle	High	Focuses on designing durable and long-lasting products
Analytical Tools									
PLCM	Recycling/ Remanufacturing	Rec/Rem	Ecological	C	I	C/M	Circular value of parts and product	High	Measures the economic value of circularity in product design
CC	Recycling/Reuse	Rec/Reu	Ecological	C	E	C/M	Recycled content of the product	High	Assesses recycled content, informing sustainable design choices

EPVR	End-of-Life	EOL	Eco/ Environmental/ Social	C	E	C/M	End-of-use management options	Medium	Guides sustainable end-of-life product strategies
SDEO	End-of-Life	EOL	Eco/ Environmental/ Social	C	E	C/M	Sustainable design performance at end-of-life	Medium	Influences design for end-of-life considerations
PR-MCDT	End-of-Life	EOL	Eco/ Environmental/ Social	C	E	C/M	Remanufacturing feasibility	Medium	Assists in decision-making for product recovery options
REPRO2	Remanufacturing	Rem	Ecological	PD	I	C	Remanufactured product design aid	High	Facilitates eco-design in product remanufacturing
TPQ	Resource Efficiency	RE	Environmental	PD	I	C	Material/component quality for resource efficiency	High	Enhances material selection and product quality assessment
EZWP	Waste Management	WM	Eco/ Environmental/ Social	C	I	C/M/L	Zero-waste management development	Medium	Encourages development of waste management practices
CDG	Multidimensional Indicators	Rem	Eco/ Environmental	PD	I	C/M	Circular economy design improvement	Medium	Provides guidelines for circular design, relevant to product innovation
Composite Indicators									
DSTR	Remanufacturing	Rem	Eco/ Environmental	C	I	C/L	Economic and ecological viability of remanufacturing	High	Evaluates the sustainability of remanufacturing processes
RI	Recycling	Rec	Environmental	C	I	C/L	Recycling and recovery rates	High	Defines efficiency in product recycling and material recovery
SICE	Recycling/ Waste Management/ Reuse	Rec/WM/Reu	Environmental	C	I/E	C/M/L	Sustainability and functional performance	Medium	Integrates sustainability into the functional assessment of products

Abbreviations: PD - Product Development; C – Consumption; I – Internal; E – External; C/M/L - Company/Market/Legislation; Rec – Recycling; LE - Life Extension; WM - Waste Management; RE - Resource Efficiency; D – Disassembly; Rem - Remanufacturing; EOL - End-of-Life; Eco – Ecological; Env – Environmental; Soc – Social;

The selection of tools for measuring the progress towards a circular economy within an enterprise is influenced by various factors, as reflected in the comprehensive table, which includes both quantitative and analytical indicators. Data sources for these metrics may be internal or external to the company, impacting the applicability and scope of each indicator. Table 2 showcases a set of 28 most relevant indicators, underscoring those that are important for the field of Mechanical Engineering. By selecting particular indicators, a company not only aligns itself with the principles of a circular economy but also signals its commitment to specific dimensions of sustainability.

The predominance of quantitative indicators, especially those focusing on recycling and resource efficiency, underscores their technical importance to Mechanical Engineering.

However, their numerical strength does not equate to overarching significance. Analytical tools and composite indicators offer insights into areas that quantitative measures cannot encapsulate alone, such as the design for disassembly and remanufacturing, the longevity of materials in the product life cycle, and the strategic end-of-life management of products.

Furthermore, Table 2 suggests that the relevance of indicators extends beyond raw data collection, with a significant number being influenced by external factors such as market trends and regulatory frameworks. The legislative context, in particular, can exert considerable influence on the feasibility and effectiveness of certain indicators. Therefore, a judicious combination of various indicators is recommended to gain a holistic understanding of an enterprise's circular economy maturity. This multi-layered approach ensures that mechanical engineering considerations are fully integrated into the assessment, leading to a more accurate and actionable measurement of circularity at the company level.

3.3 Circular Economy Evaluation Methods

In addition to the previously explained indicators, the assessment of the transitioning success toward a circular economy can be performed through the application of various evaluation methods. These methods are of crucial importance as they enable the identification of successes and challenges in the implementation of circular economy models. They also serve as a basis for continuous improvement of practices, policies, and strategies that lead to sustainable development. However, in the existing literature on the circular economy, there is a lack of interest in evaluating the performance of the circular economy and a lack of methods that could measure and simultaneously assess all variables involved in the circular system [3,38-40].

There are various methods for evaluating the development of the circular economy. Several popular methods used to evaluate the circular economy include Life Cycle Assessment (LCA), Material Flow Analysis (MFA), Input-Output Analysis (IOA), Ecological Footprint (EF), and Circular Economy Indicator (CEI) [26,40]. These methods are used in different contexts and for different purposes, but all of them provide clear and measurable information about circularity.

Table 3 Comprehensive Overview of the Circular Economy Evaluation Methods

Method	Description	Application in Circular Economy	Advantages	Limitations	Relevance to Mechanical Engineering	Importance Evaluation	References
Life Cycle Assessment (LCA)	Evaluates environmental implications of products/services throughout their life cycle.	Analyzes end-of-life alternatives and environmental footprint.	Comprehensive environmental impact assessment.	Focuses mainly on environmental aspects and can be cost-intensive.	High	Crucial for sustainable design and impact assessment.	[26,38,40,52,53]
Material Flow Analysis (MFA)	Quantifies flow and stocks of materials within a system.	Measures circularity rate and resource use efficiency.	Detailed insights into resource efficiency and waste management.	Challenges with data availability and system assessment capacity.	Medium	Useful for material use optimization in production processes.	[54-57]
Input-Output Analysis (IOA)	Studies economic interdependencies and impacts.	Explores resource efficiency and waste reduction potential.	Connects economic activities with environmental/social impacts.	Requires socio-cultural considerations; complex.	Medium	Useful for understanding economic interactions and resource flows.	[40,58-60]
Ecological Footprint (EF)	Measures land and water area required for	Assesses environmental demand versus	Encourages awareness of ecological limits and sustainability.	May not capture all aspects of circularity.	Low to Medium	Indirectly promotes sustainable practices.	[26,40]

	resource consumption and waste absorption.	ecological capacity.					
Circular Economy Indicator (CEI)	Measures circularity within organizations or systems.	Evaluates performance strategies of the circular economy.	Specific insights into circular practices.	Complex calculation; extensive data needed.	Medium to High	Important for assessing and enhancing circularity in designs/processes.	[26,40]
Multi-Criteria Decision Making (MCDM)	Evaluates decisions based on multiple criteria.	Assesses performance of complex circular systems.	Allows evaluation of conflicting criteria.	Still developing; research needed for method refinement.	Medium	Aids complex decision-making with sustainability trade-offs.	[26,61-63]
Fuzzy Logic	Handles uncertain information in decision-making.	Manages uncertainties in sustainability assessments.	Suitable for complex, vague information.	Integration with other performance measures is limited.	Low to Medium	Supports decisions in complex, uncertain scenarios.	[64]
Design for X (DfX)	Design approach for aspects like disassembly, end-of-life, recycling.	Develops guidelines for circular product design.	Strategic design guidelines for sustainability.	Ongoing research needed to address limitations.	High	Directly relates to sustainable, circular product design.	[26,65-68]
Data Envelopment Analysis (DEA)	Analyzes efficiency in operations of decision-making units.	Assesses energy efficiency in recycling and other processes.	Efficiency analysis across multiple entities/processes.	Specific application to circular economy needs further exploration.	Low to Medium	Used for evaluating production efficiency and benchmarking.	[11,69,70]

Table 3 presents a comprehensive overview of various Circular Economy Evaluation Methods, each vital for assessing the transition towards a circular economy. These methods offer diverse approaches to evaluate circularity. They not only provide clear and measurable insights into the circular economy but also identify challenges and successes in implementing circular models.

The table also highlights each method's unique advantages, limitations, and specific relevance and importance in the context of mechanical engineering. This relevance ranges from high, as seen in LCA and DfX, which directly relate to sustainable design and product development, to medium and low in other methods, where the focus shifts more towards economic and ecological aspects. Despite these variations, all methods collectively contribute to a deeper understanding and continuous improvement of practices, policies, and strategies leading to sustainable development.

Moving forward, understanding the previous indicators and evaluation methods is integral to developing effective institutional frameworks. The following section will explore the structural and policy dimensions that govern the application of circular economy practices, emphasizing the interplay between practical methodologies and institutional environments that shape their implementation and efficacy.

4. INSTITUTIONAL FRAMEWORK FOR THE DEVELOPMENT OF THE CIRCULAR ECONOMY

The successful implementation of circular economy practices relies not only on the establishment of reliable monitoring mechanisms but also on the effective functioning of various institutions, which form the backbone of the necessary changes in economic, political, and social decision-making. Institutions, defined as multiple configurations of economic, political, and social decision-makers, are essential in providing the infrastructure for much-needed changes [71]. These institutions comprise regulatory frameworks, business agreements, norms of behavior, and other factors that significantly influence industrial and societal transformations, molding social interactions, setting expectations, and delineating acceptable actions within the evolving ecosystem. For mechanical engineering, institutional support is critical for research and development and for incorporating circular principles into educational and professional structures [8]. The European Union’s top-down approach exemplifies a clear and developed strategy for accelerating the circular economy by enforcing changes in national regulations, strategies, and policies at a higher level before these trickle down to local regulations. It is essential to understand, assess, and enhance the capacity and function of these institutions to lead the transformative shift towards a circular economy [72-74].

Elaborating on the research done independently by Shulz et al. [31], Geissdoerfer et al. [75], and North [76], Table 4 details the institutional framework through a three-level approach: Regulatory, Normative, and Cognitive. In the context of mechanical engineering, institutions across all three levels play unique and vital roles in guiding the industry toward circular practices. The new comprehensive framework, represented in Table 4, outlines the roles of these institutions in facilitating the transition towards a circular economy.

Table 4 Institutional Framework and Circular Transformation

Institutional Level	Type of Institution	Specific Actions	Role of Institutions	Significance for Circular Economy	Implications for Mechanical Engineering	Factors for Success
Regulatory	**Government Bodies**	Enactment of environmental regulations, subsidies, and tax incentives for sustainable practices	Enforce rules through a system of laws, sanctions, and rewards	Create and enforce laws that promote circular practices like waste reduction, recycling, and resource efficiency	Mandate product design for disassembly, establish material selection standards, incentivize sustainable engineering processes	Strong legal framework, enforcement capabilities
	International Organizations	Harmonization of standards, development of international agreements	Influence behavior through regulation and management on a global scale	Promote collaboration between countries for a global circular economy approach	Encourage adherence to international standards and enable global market access for circular products	Global cooperation, cross-border policy alignment
Normative	**Industry Associations**	Establishment of industry-specific sustainability standards	Act through norms and values that define acceptable behavior in society	Shape social norms and values to favor sustainable consumption and production	Establish industry standards for sustainability, create a professional culture valuing circular principles	Industry-wide adoption, benchmarking
	Community Groups	Advocacy for sustainable local practices, community-based initiatives	Provide guidelines for social conduct through community engagement	Influence local economies and consumer behavior towards circular practices	Support local sourcing and community-focused circular initiatives in mechanical engineering	Community engagement, local initiatives
Cognitive	**Academic Institutions**	Integration of circular economy concepts into educational programs	Shape the way individuals interpret the world, encompassing shared conceptions, beliefs, and mental models	Influence perceptions and understanding of circular economy, affecting willingness to adopt circular practices	Integrate circular economy principles in educational curricula, promote circular design principles	Education and research, knowledge dissemination
	Media Outlets	Information dissemination, awareness campaigns	Influence perceptions and understanding of circular economy on a wide scale	Raise public awareness and knowledge about the benefits and practices of the circular economy	Enhance the public and professional understanding of the implications of circular economy for mechanical engineering	Public awareness, informative media

This structure in Table 4 demonstrates the critical importance of a multi-level, collaborative approach to implementing the circular economy within mechanical engineering and highlights the necessity for institutions to adapt and coordinate across different levels to ensure success. At the Regulatory Level, there is a call for enforcing design and material standards that facilitate sustainability. The Normative Level emphasizes the cultivation of an industry ethos that embraces and champions circular methods. The Cognitive Level focuses on shaping the educational and perceptual landscapes to foster a mindset aligned with circular practices. Collectively, these levels create a robust foundation for Mechanical Engineering to actively participate in and drive the shift towards a more sustainable and circular economy.

Challenges in the circular transition largely stem from the dynamic and increasingly challenging socio-economic environment. However, institutional and regulatory barriers represent key obstacles that determine the dynamics and speed of implementation and development of the circular economy. The dynamic relationship between institutions at various levels and socio-economic and technological development shapes the way in which activities are stimulated, conflicts are managed, and paths of circular transformation are defined [31,75]. It is an objective fact that the institutional framework defines the way in which a strategic approach to the implementation and development of the circular economy is created and carried out at the level of the national economy and regional integrations.

5. DISCUSSION AND ANALYSIS

The circular economy, characterized by its restorative and regenerative design, offers a sustainable alternative to the traditional linear "take-make-dispose" model, which is crucial for addressing climate change, biodiversity loss, and resource depletion concerns. The mechanical engineering sector plays a pivotal role in the current paradigm shift towards circular economy. However, this transition poses inherent challenges due to the entrenched linear methodologies.

The adoption of circular economy principles necessitates rigorous and systematic monitoring to ensure the seamless integration of these practices into mechanical engineering processes. The complexity of the task is underscored by the lack of universally accepted methodological frameworks and metrics to track progress, identify bottlenecks, and inform policy adjustments. For instance, the European Commission's Directive 2014/95/EU serves as a guiding beacon, yet the variation in reporting practices among leading multinational corporations reveals a discrepancy in monitoring approaches, emphasizing the need for a standardized yet flexible evaluation system that reflects the circular economy's many-sided nature [17, 33-36].

Mechanical engineering's transition to circularity must be supported by robust evaluation methods like Life Cycle Assessment (LCA) and Material Flow Analysis (MFA), which offer comprehensive insights into the environmental impact of products and the efficiency of resource use [26, 40, 52-57]. These methodologies are not merely academic exercises but are instrumental in reshaping the sector's approach to design, production, and end-of-life management, thus reflecting the circular economy's core objectives of minimizing waste and maximizing resource utilization [14].

Furthermore, institutions provide the framework for the circular economy's uptake by setting strategic directions, formulating policies, and fostering collaborations that encourage sustainable practices within mechanical engineering. The European Union, with its methodical top-down approach, exemplifies the influence of strong institutional leadership on national policies, which in turn impact the mechanical engineering sector's regulatory environment. These institutions, therefore, must not only devise strategies but also adapt and synchronize with the evolving socio-economic and technological landscapes to encourage the industry's compliance with circular principles [14, 18, 71-74].

Mechanical engineering stands at a juncture where institutional support is not just beneficial but essential for innovation and integration of circular principles into both educational curricula and professional practices. The sector requires a strategic institutional framework that spans regulatory, normative, and cognitive domains, fostering an industry culture that values sustainability, encourages resource-efficient design, and supports professional development aligned with circular economy objectives [4, 8, 31].

The journey toward a circular mechanical engineering sector is fraught with challenges. The transition demands a rethinking of traditional business models, a reconfiguration of production processes, and a recalibration of the workforce's skills and knowledge. As highlighted by Sousa-Zomer et al. [4] and Lewandowski [5], the sector must overcome resistance to change, develop innovative solutions, and align with new business models that are both ecologically and economically viable.

The challenges are further compounded by the requirement for a cohesive and concerted effort from various societal actors, including governments, businesses, and individuals, to commit to sustainable practices. The sector's progress hinges on the successful navigation of these socio-economic and regulatory hurdles, which requires a continuous reassessment and fine-tuning of both strategies and operations [31, 75].

6. CONCLUSION

In this thorough analysis of the integration of circular economy principles in mechanical engineering, we must acknowledge the limitations of our research and data sources, and emphasize the potential applications of our findings. While the research has explained the theoretical and practical implications of a circular transformation, it is constrained by the nascent nature of circular economy metrics and the uneven adoption of practices across industries and regions.

The reliance on current literature and existing frameworks like the European Commission's Directive 2014/95/EU may not capture the full spectrum of circular economy activities, particularly in less developed economies or industries at the periphery of the circular movement. Furthermore, the application of methods such as LCA and MFA, while comprehensive, could benefit from a more refined approach that includes emerging technologies and innovative practices in mechanical engineering that are not yet mainstream or fully understood.

The potential users of this research span policymakers, academic researchers, and mechanical engineering practitioners. Policymakers can leverage these findings to craft refined and supportive regulatory environments that encourage circular practices. Academics may build upon this foundational research to address gaps in circular economy metrics and develop more comprehensive and adaptable evaluation tools. Practitioners in the mechanical engineering field can apply this knowledge to drive innovation and implement sustainable practices that align with the principles of the circular economy.

This study highlights the need for further exploration and refinement of circular economy principles in mechanical engineering. It highlights the urgency of developing a more cohesive, cross-sectoral, and interdisciplinary approach to monitoring and evaluation. By recognizing the limitations of our current frameworks and seeking to innovate beyond them, we can foster a more resilient, sustainable, and circular future.

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