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Circularity in Practice: Key Performance Indicators for Measuring, Managing, and Advancing Resource Efficiency

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***Abstract*— The transition towards a circular economy (CE) necessitates a fundamental re-thinking of how organizations measure, monitor and optimize sustainability per-formance. This paper explores the critical role of Key Performance Indicators (KPIs) in facilitating this transformation, providing a comprehensive taxonomy of circularity metrics across six domains: general, performance-based, material-related, energy-related, sustainability, and integrative indicators. The paper draws on recent academic and industry frameworks to present practical tools and meth-odologies for data collection, KPI implementation, and performance benchmark-ing. The role of digital technologies, including the Internet of Things (IoT), artifi-cial intelligence (AI), and blockchain, in facilitating high-resolution tracking and decision-making is emphasized. Furthermore, the paper addresses challenges in data integration, standardization, and sectoral applicability, particularly for small and medium-sized enterprises (SMEs). The discussion further explores chal-lenges in KPI adoption and identifies the need for optimization strategies. The ar-ticle's contribution lies in its provision of a structured approach for advancing sustainability and resource efficiency through robust KPI systems, by highlight-ing the synergies between measurement frameworks and circular business strate-gies. The analysis was supported by a pilot study conducted among representa-tives of the Polish small and medium-sized enterprise (SME) sector.**

Keywords— Circular Economy, Key Performance Indicators, Sustainability Metrics, Digital Technologies, Resource Efficiency

I. INTRODUCTION

The transition from a linear to a circular economy (CE) model poses considerable challenges for manufacturing companies, particularly in terms of operational restruc-turing, supply chain transformation, and the adoption of business models that priori-tize resource efficiency and waste reduction. In order to facilitate this transition, re-searchers have developed a comprehensive set of indicators over the years to meas-ure progress, identify inefficiencies, and guide strategic decision-making. These indi-cators facilitate businesses in tracking their transition effectively, ensuring alignment with sustainability goals while maintaining economic viability.

Recent research by Woźna et al. (Wozna et al., 2024) categorizes these indicators into six distinct groups—general, performance, material-related, energy-related, sus-tainability, and integrative—based on their analytical focus and application scope. indicators, provides a structured framework for small and medium-sized enterprises (SMEs) to select the most relevant tools for their specific sustainability objectives. By leveraging these tailored metrics, manufacturers can systematically assess their circu-larity performance, optimize resource flows, and accelerate their transition toward more sustainable and resilient business practices.

A. General Indicators

General indicators provide fundamental insights into circularity and are essential for understanding and implementing circular practices within SME operations. These tools cover a broad range of aspects, including measurement, calculation, and assessment of circularity metrics, enabling businesses to evaluate their resource efficiency and sustainability performance.

The Circular Economy Toolkit (CET) estimates material input per service provided, allowing companies to optimize resource use by shifting toward service-based consumption models (Welfens, Bleischwitz and Geng, 2017). The Circularity Index (CI) quantifies the proportion of recycled materials in total material use, offering a clear metric for circularity effectiveness (Griffiths and Cayzer, 2016). Meanwhile, the Circular Benefits Tool (CBT) assesses qualitative advantages of circular business models, helping firms identify strategic sustainability improvements (Saidani *et al.*, 2019).

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Economic aspects are addressed by the Circular Economic Value (CEV), which compares the financial benefits of circular materials versus traditional virgin resources (Fogarassy *et al.*, 2017). For product design, the Circularity Calculator (CC) evaluates recyclability and material efficiency, supporting sustainable design choices (de Pauw *et al.*, 2021). The Circularity Material Cycles (CIRC) tracks resource flows and recycling efficiency, aiding in material recovery optimization (Megevand *et al.*, 2022). Finally, the Closed Loop Calculator (CLC) measures closed-loop performance across product lifecycles, ensuring better lifecycle management (Kingfisher, 2014).

B. Performance Indicators

Performance indicators focus on evaluating the operational and strategic effec-tiveness of circular economy (CE) implementation within SMEs. These tools assess how well circular practices are adopted across different business functions, identify-ing strengths, weaknesses, and opportunities for optimization.

The Assessing Circular Tradeoffs (ACT) framework analyses trade-offs between various sustainability metrics, enabling businesses to make balanced decisions when implementing CE strategies (Vines et al., 2023). For the construction sector, the Build-ing Circularity Indicators (BCI) provide specialized metrics to evaluate material re-use, design for disassembly, and other CE-aligned practices, supporting sustainable construction management (Khadim et al., 2023).

Material efficiency is further examined through the Material Reutilization Part (MRP), which quantifies the effectiveness of reuse and recycling in product design, helping companies improve their resource recovery rates (Le et al., 2017). On an or-ganizational level, the Circle Assessment (CA) offers a qualitative evaluation of a company's adherence to CE principles, highlighting areas for improvement and benchmarking progress over time (Lei et al., 2021).

For comprehensive performance measurement, the Circularity Assessment Tool (CAT) employs quantitative metrics to evaluate overall CE performance, integrating environmental, economic, and operational factors into a unified assessment frame-work (Gulck et al., 2021).

C. Material-Related Indicators

Material-related indicators provide critical insights into resource flows, recycling ef-ficiency, and hazardous substance management within circular economy systems. These tools enable SMEs to track material inputs and outputs, optimize recovery processes, and minimize environmental impacts across product lifecycles.

The Indicators for Material Input for CE in Europe (IMCEE) measure material consumption relative to economic output (GDP), helping businesses and policymak-ers evaluate decoupling trends and material productivity at macro levels (Moraga et al., 2019). At the product level, End-of-Life Recycling Rates (EoLRRs) quantify the percentage of materials successfully recovered from discarded products, serving as a key metric for recycling system effectiveness (Blengini et al., 2018).

The Material Flow Analysis (MFA) tracks the physical movement of materials through production, use, and disposal phases, identifying opportunities to close mate-rial loops and reduce waste generation (Brunner and Paul, 2004). For energy-quality assessment in material systems, Exergy Analysis (EXA) evaluates usable energy ver-sus losses, supporting more efficient resource utilization (Rosen and Dincer, 2001).

Specialized tracking is provided by the Substance Flow Analysis (SFA), which monitors hazardous chemicals throughout their lifecycle to improve environmental safety and regulatory compliance (Brunner, 2012). This is particularly valuable for industries handling toxic or regulated substances.

D. Energy-Related Indicators

Energy-related indicators provide essential frameworks for analyzing and optimiz-ing energy flows within circular economy systems. These tools enable businesses to quantify energy consumption, evaluate efficiency improvements, and assess the environmental impacts of energy use across product lifecycles.

The Cumulative Energy Demand (CED) measures the total primary energy re-quired throughout a product's lifecycle, from raw material extraction to end-of-life processing (Huijbregts et al., 2017). This comprehensive metric helps identify energy-intensive phases where efficiency gains can yield significant benefits.

Embodied Energy (EE) calculations focus specifically on the energy consumed during material production and manufacturing (Brown and Ulgiati, 2004). By quanti-fying this "embedded" energy, businesses can make informed decisions about mate-rial selection and substitution to reduce overall energy footprints.

The Energy Analysis (EMA) takes a systems perspective, evaluating all energy in-puts in terms of their solar energy equivalent (Brown and Ulgiati, 2004). This ap-proach provides a common basis for comparing diverse energy flows and assessing their true environmental value.

Exergy Analysis (EXA) complements these tools by distinguishing between ener-gy's quantity and quality (Rosen and Dincer, 2001). It identifies thermodynamic inefficiencies in processes, highlighting opportunities to improve energy utilization and reduce waste.

For climate impact assessment, the Carbon Footprint (CF) tool tracks greenhouse gas emissions associated with energy use throughout value chains (World Resources Institute and World Business Council for Sustainable Development, 2011). This ena-bles targeted emission reduction strategies aligned with climate goals.

E. Sustainability Indicators

Sustainability indicators provide a holistic view of circular economy performance by evaluating environmental, economic, and social impacts. These tools help businesses align their circular strategies with broader sustainability goals while ensuring compliance with evolving regulations and stakeholder expectations.

The Circular Pathfinder (CP) serves as a strategic compass, analyzing product characteristics to determine circularity potential and guide sustainable innovation (van Dam *et al.*, 2017). By identifying key leverage points in product design and business models, this tool helps companies prioritize interventions with the highest sustainability returns.

For environmental performance tracking, the Environmental Protection Indicators (EPICE) offer a comprehensive framework to monitor ecological impacts across operations (Vavrova, 2020). These indicators enable businesses to measure their progress toward environmental targets while maintaining alignment with international sustainability standards.

At the macroeconomic level, Economy-Wide Material Flow Analysis (EWMFA) provides critical insights into national or regional resource productivity (Fischer-Kowalski *et al.*, 2011). This systems-level approach helps policymakers and business leaders understand material dependencies, identify critical resource flows, and develop strategies for sustainable economic development.

F. Integrative Indicators

Integrative indicators represent the most advanced tier of circular economy as-sessment tools, combining multiple analytical approaches to provide comprehensive, system-level insights. These sophisticated frameworks enable businesses to evaluate circularity performance across entire value chains while supporting strategic decision-making for sustainable transformation.

The Circularity Potential Indicator (CPI) serves as a powerful diagnostic tool, measuring how effectively products and processes can transition from linear to circu-lar models (Saidani et al., 2019). By assessing multiple dimensions of circular poten-tial, this indicator helps organizations prioritize investments in circular innovation where they will yield the highest returns.

For efficiency optimization, the Data Envelopment Analysis Model (DEA) applies advanced operational research techniques to identify best practices in resource utili-zation (Avkiran and Rowlands, 2008). This model is particularly valuable for benchmarking performance across facilities, supply chains, or industry sectors, re-vealing opportunities for circularity improvements.

The Evaluation Indicator System of Circular Economy (EISCE) offers a holistic scoring framework that assesses circular performance throughout all lifecycle stages (Papageorgiou et al., 2021). This comprehensive system enables businesses to track progress against circular economy KPIs while maintaining alignment with global sus-tainability standards.

As the gold standard for environmental assessment, Life Cycle Assessment (LCA) provides complete visibility into the environmental impacts of products and services from cradle to grave (ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework, no date). When integrated with circular economy strategies, LCA helps organizations make informed decisions that balance circularity objectives with broader environmental considerations

II. Methodology

In the article “Understanding Indicators for Circular Economy Application in Manufacturing” (Wozna et al., 2024), it is indicated that Key Performance Indicators (KPIs) play a crucial role in guiding organizations towards the implementation of a Circular Economy (CE). The authors of this study developed a comprehensive set of indicators to measure progress, identify inefficiencies, and support strategic decision-making within the CE framework. Based on this article, a detailed taxonomy of cir-cularity indicators was presented, dividing them into six key domains/categories: General, Performance-based, Material-related, Energy-related, Sustainability, and Integrated Indicators.

The authors emphasize that this structure provides a framework for SMEs to select the most appropriate tools for their sustainability goals. It was noted that a multidi-mensional approach, encompassing these various types of indicators, is essential to capture the full complexity of CE outcomes.

In light of the article’s identification and categorization of these indicators as es-sential tools for understanding and implementing circular practices, the indicators categorized in the publication were examined in a survey study. The survey aimed to investigate which of these specific, literature-recognized indicators are actually ap-plied by companies.

The conducted survey aimed to gather data on the use of Circular Economy (CE) and ESG reporting indicators in enterprises. A total of 93 respondents located in Po-land participated in the study. This study served as a pilot for a larger, full-scale re-search project extending beyond the borders of a single country.

Respondent and Company Profile:

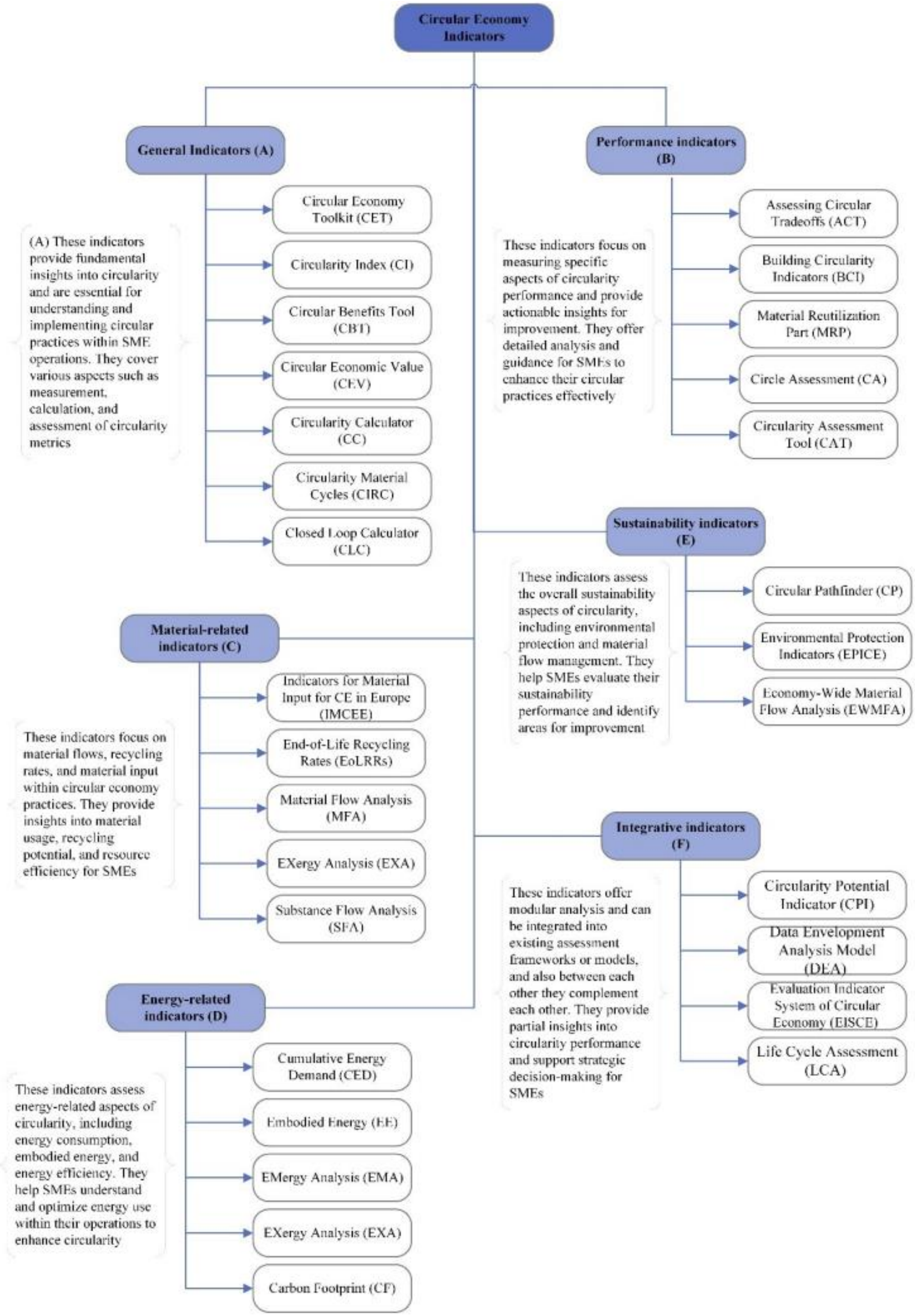
- Position: The largest group of respondents were Owners/Co-owners (45.2%). The second-largest group were Management Board Members/Directors (25.8%), fol-lowed by Specialists/Engineers (19.4%). The smallest groups were Departament Managers and ERP Consultants.
- Industry: The survey covered a variety of sectors, including manufacturing (steel structures, food, composites, robotics, machine relocations, industrial belts, com-pressors, recycling spare parts, industrial automation, welding, electrical), services (consulting, HR, cleaning, employee leasing, finance and insurance, water rent-al/filtration, air conditioning/heat pumps/ventilation, IT, industrial services), as well as construction.
- Market Reach: Respondents operated in both the Polish and European markets (43.3% each), with only 13.3% active on the global market.
- Company Size: 32.3% of the surveyed companies were micro-enterprises, 35.5% small, 22.6% medium-sized, and only 9.7% large enterprises.
- Annual Revenue (optional): 98% of respondents provided data regarding annual revenue. The most frequently indicated revenue bracket was up to 2 million EUR (35.5%), followed by 2–10 million EUR (22.6%), with the remaining respondents falling within the 10–50 million EUR and over 50 million EUR categories.

Use of CE/ESG Indicators:

Respondents were asked to indicate which indicators, within six categories, were used in their organizations:

a. General,
b. Performance,
c. Material-related,
d. Energy-related,
e. Sustainability,
f. Integrated indicators.

FIG. 1. GROUP CLASSIFICATION (WOZNA ET AL., 2024)



III. Results

Adopted CE/ESG Strategy:

The analysis of responses regarding implemented CE/ESG strategies or actions shows that 58.1% of respondents did not have a strategy or actions in place. 12.9% declared having a strategy (answer "Yes"), the same percentage indicated that a strategy was currently being implemented, while 16.1% answered "I don't know". These results suggest that formal CE/ESG strategies are still uncommon among re-spondents, particularly within the numerous micro and small enterprises.

Use of CE/ESG Indicators:

A significant portion of respondents (45%) selected “NONE FROM THIS CATEGORY” in all six categories. This means that 55% of respondents apply at least one of the indicators listed in the survey.

Indicator Use by Category:

- A. General Indicators: The most frequently indicated tools were the Circularity Calculator (9.6%) and the Closed-Loop Calculator (9.6%).
- B. Performance Indicators: Used by 38.7% of respondents. The most frequently indicated was the Building Circularity Indicators (25.8%). None of the respondents use Circular Economy Trade-Off Assessment indicators.
- C. Material-related Indicators: Used by 38.7% of respondents. The most com-monly indicated tool was Material Flow Analysis (29%). Other indicators included End-of-Life Recycling Rate Indicators (16.1%).
- D. Energy-related Indicators: Used by 38.7% of respondents. The most frequent-ly indicated were Cumulative Energy Demand and Carbon Footprint (both 12.9%).
- E. Sustainability Indicators: Applied by only 13% of respondents. Selected indi-cators included the Circular Pathfinder and Environmental Protection Indicators (each 6.5%).
- F. Integrated Indicators: This category of indicators was reportedly applied by 19% of respondents. Among the specific indicators selected from this group Circu-larity Potential Indicator (CPI) was used by 6.5% of respondents. The remaining respondents who reported using integrated indicators (accounting for the other 12.5% within this category) selected other options outlined in the taxonomy.

Correlation Between Strategy and Indicator Use:

Data analysis suggests that companies which declared having or implementing a CE/ESG strategy tend to use a wider range of indicators compared to those without a strategy or unaware of its existence. However, the application of indicators is not exclusive to companies with a formal strategy — 16% of respondents without a strategy also reported using selected indicators.

IV. Discussion

The findings of this study provide crucial insights into the current landscape of Cir-cular Economy (CE) strategy adoption and Key Performance Indicator (KPI) appli-cation within a diverse group of enterprises, predominantly Small and Medium-sized Enterprises (SMEs). This section will interpret these findings, connect them to existing literature and identified challenges in CE measurement and monitoring.

The survey revealed a notable gap in the formal adoption of CE/ESG strategies, with a significant 58.1% of responding companies reporting no such initiatives in place. This, coupled with the observation that 45% of companies do not utilize any of the literature-recognized CE indicators examined in this study, suggests that de-spite the growing academic and policy emphasis on circularity, its systematic opera-tionalization and measurement face considerable hurdles. This is particularly perti-nent given that SMEs, which often face greater resource constraints, constituted a substantial portion of our sample.

The limited uptake of CE indicators, especially the more complex sustainability or integrated indicators (both reportedly used by only 19% of respondents), can be di-rectly linked to the inherent challenges in KPI measurement. One of the most promi-nent barriers is the complexity of data collection across product lifecycles, especially in globalized supply chains. Circular KPIs often require data from various domains—including material sourcing, production, usage, and end-of-life handling—which may be managed by different departments or even external partners. As a result, data is frequently fragmented, inconsistently formatted, or siloed across incompatible sys-tems (Moraga et al., 2019), (Aljamal et al., 2024). This hampers the integration of datasets needed for accurate lifecycle-based indicators such as Material Flow Analy-sis (MFA), Exergy Analysis (EXA), or Circular Economic Value (CEV).

Another persistent issue is the lack of standardized methods and frequency for KPI reporting. Companies may define and calculate the same indicator (e.g., recy-cling rate or material intensity) differently depending on the scope, boundaries, or data availability. Infrequent updates or one-off assessments further reduce the relia-bility of the data for tracking progress over time. This inconsistency undermines benchmarking efforts and complicates alignment with industry or regulatory frame-works like the EU Circular Economy Monitoring Framework or ISO 14009 (Elia, Gnoni and Tornese, 2017), (De Pascale et al., 2021).

Furthermore, high-quality KPI measurement is often a time-consuming and re-source-intensive process. Gathering primary data from production lines, managing software tools for analysis (e.g., LCA software like SimaPro or OpenLCA), and align-ing the results with strategic goals requires significant investments in training, digital infrastructure, and cross-functional coordination. For small and medium-sized enter-prises (SMEs) in particular, these requirements can pose a major obstacle to adopting circular KPIs at scale (Cahyadi et al., 2024), (Keles, Cruz Rios and Hoque, 2025).

Moreover, the broad applicability of the circular economy across industries intro-duces additional complexity. While some KPIs are well-suited for material-intensive sectors such as manufacturing, they may be ill-fitted for service-based or digital busi-ness models. This sectoral variation results in a proliferation of KPI sets—each tai-lored to specific processes, materials, or product lifecycles—thus reducing the ability to compare performance across different organizations or industries (Elia, Gnoni and Tornese, 2017), (De Pascale et al., 2021).

Finally, the willingness of external stakeholders (e.g., suppliers, recyclers) to share sensitive operational or environmental data may be limited due to confidentiality concerns or competitive interests. This impedes the ability to assess full lifecycle im-pacts or incorporate externalities such as reuse potential, embodied carbon, or post-consumer recovery rates into internal KPIs (Jäger-Roschko and Petersen, 2022).

Addressing the identified challenges in KPI measurement and adoption is crucial. The literature suggests several potential strategies for KPI optimization, which merit further investigation. Due to the limited scope of this study, practical optimization strategies will be explored in future research, following broader and more comprehen-sive data collection efforts.

V. Conclusions

The transition to a circular economy requires a fundamental rethink of how organiza-tions measure, monitor and optimize their sustainability performance. In this context, Key Performance Indicators (KPIs) serve as indispensable tools - not only for track-ing progress, but also for identifying opportunities, guiding innovation and informing strategic decisions. This article has explored the taxonomy, measurement approach-es, optimization strategies and practical applications of circular KPIs, with a focus on their role in driving systemic change.

The study conducted in this article aimed to preliminarily verify the extent to which CE/ESG indicators proposed in the literature are being applied in the SME business environment. The findings revealed that formal strategies related to Circular Economy (CE) and Environmental, Social, and Governance (ESG) remain uncom-mon among micro and small enterprises, with over 58% of respondents reporting no such strategies or actions in place. Nevertheless, more than half of the surveyed com-panies use at least one CE/ESG indicator, most frequently in categories related to performance, materials, and energy use.

A key insight from this analysis is that no single KPI is sufficient to capture the full complexity of circular performance. Instead, a multi-dimensional approach that includes generic, performance-based, material, energy, sustainability and integrative indicators is essential. These different metrics provide complementary perspectives on resource use, economic viability and environmental impact, helping organizations to develop balanced and informed circular economy strategies.

Robust data infrastructure and digital technologies - including IoT, AI, blockchain and lifecycle analysis tools - are critical for collecting, analyzing and integrating the data needed to populate these indicators. However, as highlighted in Chapter 4, data fragmentation, methodological inconsistencies, and the resource intensity of KPI management remain persistent challenges, particularly for small and medium-sized enterprises.

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