

A quantitative ERP-driven framework for the circular economy: development and simulation-based validation for sustainable manufacturing

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Abstract

Purpose – To address the significant fragmentation in Circular Economy (CE) assessment models and the gap in their deployment within digital enterprise platforms. This research presents the Quantitative ERP-Driven CE (Q-EDCE) Framework to bridge the divide between sustainability theory and manufacturing Information Technology.

Design/methodology/approach – The study develops a multi-layered architecture that includes a Strategic Layer for establishing Value Retention Processes (VRPs), an Operational Layer that links these to functional ERP modules (such as Reverse Logistics and SCM), and a Measurement Layer that defines six specific Sustainability KPIs (S-KPIs). This conceptual model integrates Industry 4.0 technologies like IoT and Big Data, along with real-time MES data flows. The framework is validated through a Python-based numerical simulation using an industrial detergent manufacturing dataset.

Findings – The simulation demonstrates that the architecture effectively transforms a linear “As-Is” baseline into a circular model, resulting in a 69.7% increase in the Material Circulating Rate (MCR) and a 50% increase in the Waste Recovery Rate (WRR). Additionally, the conceptual integration enables a shift from retrospective, static reporting to dynamic, proactive decision-making and real-time resource optimization.

Originality/value – This work redefines ERP systems from simple transactional tools to powerful digital infrastructures that enable circularity. It provides a unique, systematic roadmap for integrating circular performance directly into organizational data flows, transforming sustainability from an abstract goal into a tangible corporate advantage.

Keywords Circular economy (CE), Sustainable ERP (S-ERP), Industry 4.0, Numerical simulation, Sustainability key performance indicators (S-KPIs), Framework validation, Data-driven decision making

Paper type Research article

1. Introduction

Traditional manufacturing follows a linear economic model characterized by the extraction of natural resources, the production and consumption of goods, and the final disposal of goods as waste. This approach, commonly described as the “take–make–use–dispose” paradigm

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(Rahman, 2025), has historically relied on the implicit assumption that natural resources are abundant, easily accessible, and inexpensive to manage (Saha and Saha, 2024). However, in the light of ecological pressures and resource limitations, the model has proven unsustainable over the long term, prompting a re-examination of this flawed assumption (Laba Nzuzi, 2025). This is evidenced by the dramatic increase in global raw material extraction, which has more than tripled since 1970, reaching nearly 100.6 billion tons annually and far exceeding the sustainable threshold of 50 billion tons (Quaker United Nations Office, 2021), while accounting for roughly half of global greenhouse gas emissions and over 90% of biodiversity loss and water stress (United Nations Environment Program, 2024). Scientific assessments in 2025 confirm that seven of the nine planetary boundaries have now been breached, including the ocean acidification boundary, indicating that Earth has moved outside its safe operating space and is jeopardizing the stability of life-supporting systems and future human well-being (Potsdam Institute for Climate Impact Research, 2025). Therefore, transitioning from a linear economy (in which resources are used once and discarded) to a regenerative, “closed-loop” economic system will be essential for reducing resource extraction, increasing resource reuse, and dramatically reducing waste. The closed-loop economy promotes responsible use of resources, replenishes natural capital, and enhances the resilience of the planet’s ecosystems. Its implementation represents one of the greatest challenges to creating an environmentally sustainable planet and enabling future generations to thrive (Huttmánová et al., 2024).

To address these systemic failures, the Circular Economy offers a regenerative alternative that treats resources as assets rather than waste. Central to this vision is the Butterfly Diagram (see Figure 1), which illustrates how materials can be preserved within continuous loops.

The Circular Economy (CE) is defined as a regenerative system that decouples economic growth from resource depletion by narrowing, closing, and slowing material and energy loops (Mandpe et al., 2023). Three primary pillars support this transition.

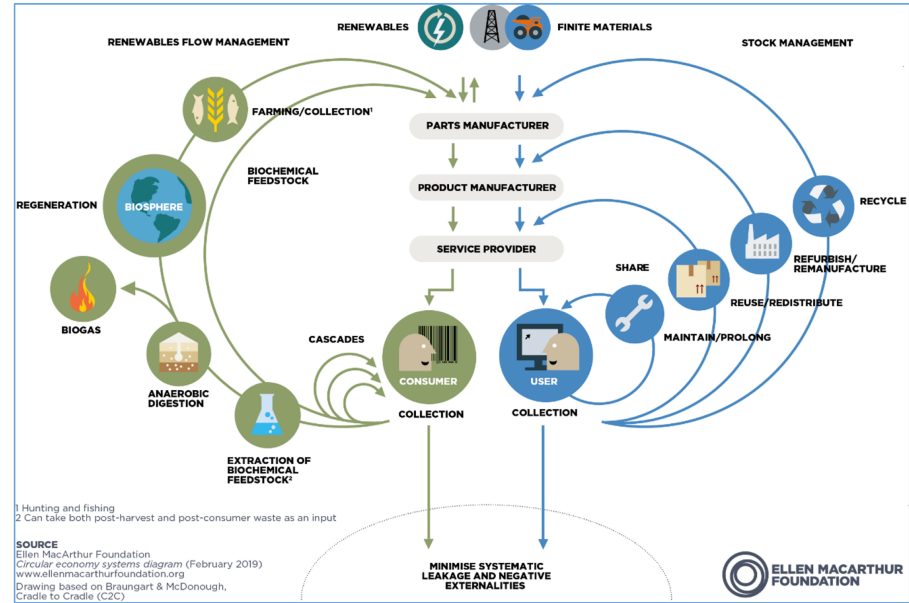


Figure 1. Butterfly diagram of circularity loops by the Ellen MacArthur Foundation. https://images.ctfassets.net/isq5xwjfoz2m/3v3SXApb5iKAFF4sSMClk/920fc7076d12cf6c2b4478c2d91dfbdc/Butterfly_Diagram.webp, Ellen MacArthur Foundation (2021)

- (1) **The Butterfly Diagram:** Developed by the Ellen MacArthur Foundation (Skene and Oarga-Mulec, 2024), it distinguishes between biological cycles (renewable materials returning to the biosphere) and technical cycles (finite materials like metals/plastics). It emphasizes that “inner loops,” such as maintenance and reuse, preserve more value and energy than “outer loops,” such as recycling.
- (2) **The 10R Framework (Figure 2):** This hierarchy ranks circular strategies from most circular (preventive measures like Refuse, Rethink, and Reduce) to least circular (last-resort solutions like Recycle and Recover). These are categorized into short, medium, and long loops based on their efficiency in retaining value.
- (3) **Business Model Innovation (PaaS):** Shifting from product ownership to Product-as-a-Service (PaaS) aligns producer incentives with sustainability, encouraging the design of durable, modular, and repairable goods (Golinska-Dawson et al., 2024), as illustrated by Figure 3.

To achieve this shift, Industry 4.0 technologies — particularly the internet of Things (IoT), Big Data, and Artificial Intelligence (AI) — are identified as essential drivers for transforming traditional industrial systems into sustainable ecosystems. These digital tools enable monitoring at every stage of the manufacturing process and support the “closing of the loop” for end-of-life products, thereby enabling their recovery and valorization. The IoT, in particular, enables real-time data collection, an essential condition for controlling emissions

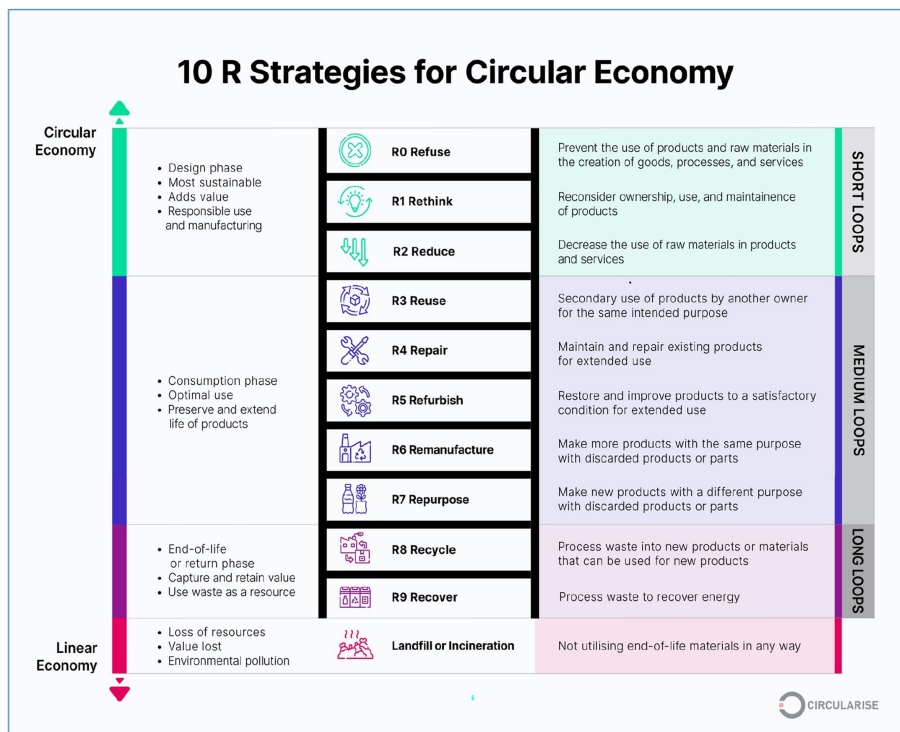


Figure 2. The 10R framework of the circular economy. <https://news.sustainability-directory.com/circularity/philips-pay-per-lux-model-advances-circular-lighting/>, Bouguern (2024)

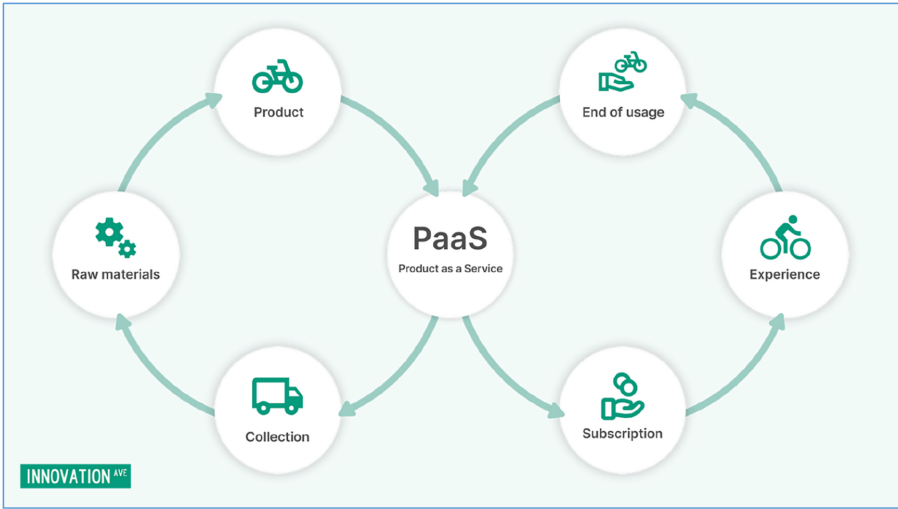


Figure 3. From ownership to Usership: Product as a Service (PaaS). [https://substackcdn.com/image/fetch/\\$s_!EQFD!,w_1456,c_limit,f_auto,q_auto:good,fl_progressive:steep/https%3A%2F%2Fsubstack-post-media.s3.amazonaws.com%2Fpublic%2Fimages%2F0cb5f24-9349-4553-956c-c6959df5d40b_1920x1080.png](https://substackcdn.com/image/fetch/$s_!EQFD!,w_1456,c_limit,f_auto,q_auto:good,fl_progressive:steep/https%3A%2F%2Fsubstack-post-media.s3.amazonaws.com%2Fpublic%2Fimages%2F0cb5f24-9349-4553-956c-c6959df5d40b_1920x1080.png)

and resource consumption throughout the value chain. Upstream simulations of environmental effects can be conducted using advanced digital modeling (e.g. digital twins). This offers an opportunity to reduce energy consumption while using minimal resources.

The use of Sustainable Enterprise Resource Planning (S-ERP) systems offers an opportunity to centralize the collection, management, and analysis of sustainability-related data across all organizational processes (Ferra *et al.*, 2021).

The concept of the Circular Economy is receiving considerable interest in both academic and policy circles, and it has also been identified as essential for rethinking economic growth and prosperity while ensuring the sustainability of the planet’s resources (Kirchherr *et al.*, 2023). To address industrial sustainability challenges, sustainable ERP (S-ERP) systems have become central to integrating environmental and social performance into operational processes, including resource planning, procurement management, production, and logistics, to optimize efficiency and achieve sustainability objectives (Mittal *et al.*, 2020). These systems also function as strategic tools that incorporate sustainability KPIs (S-KPIs) and enable continuous monitoring of operational performance, supporting responsible decision-making while strengthening organizational resilience and competitiveness (Yuzgenc and Aydemir, 2023; Yurtay, 2025; Yavuz *et al.*, 2023).

Despite their potential, S-ERP systems face a significant gap between conceptual frameworks and practical implementation in the Circular Economy. Most research remains theoretical, with few studies showing how raw ERP data can translate into measurable circular outcomes, such as longer product lifecycles or reduced resource extraction (Qureshi, 2022; Umut Yuzgenc and Aydemir, 2023). Existing work often overlooks the link between ERP structures and circularity indicators, and empirical validation is scarce. The existing literature does not consider the relationship between ERP structures and circularity indicators, and validation of this relationship remains limited (Enhancing Sustainability Integration in Sustainable ERP Systems, 2024). An effective, data-driven framework is still required to leverage ERP data for sustainability insights. Addressing this gap raises the following central question for this study:

How can a quantitative framework be developed to systematically map Sustainable ERP (S-ERP) modules and real-time data points to circular economy performance indicators, thereby generating measurable, data-driven outcomes for sustainable manufacturing?

To fill the gap between IT and sustainability, this research will officially launch the Q-EDCE Framework. This framework uses S-ERPs as tools for digital transformation and bridges the gap between Circular Economy theory and business practices. The framework creates transparency, traceability, and real-time exchange by integrating circularity into a central database across the entire value chain. The Q-EDCE Framework is structured in three separate layers.

- (1) Strategic Layer, which identifies and Aligns Core Circular Strategies (reuse, recycle, repair) (Radić *et al.*, 2026). Applies Cradle to Cradle (C2C) principles of “waste = food”, aiming to create regenerative systems and eliminate waste as a design concept. Adoption of these principles at a strategic level enables companies to achieve environmental legitimacy, meet stakeholder pressure and gain a sustainable competitive advantage through green differentiation.
- (2) Operational Layer where each functional S-ERP module has its own strategic goals, and therefore the respective functional elements of each S-ERP module (i.e. SCM, Reverse Logistics) are aligned with the overall strategic goals of transitioning to a closed-loop economy. These processes allow the reintegration of reclaimed/used materials into production through recovery, refurbishment, and redistribution, thereby supporting the goal of optimizing production batch quantities and efficiently using available resources to reduce reliance on virgin/raw materials and manufacturing costs.
- (3) Measurement Layer, which links real-time data from Industry 4.0 technologies (e.g. IoT-based monitoring) directly with Sustainability KPIs via ERP analytical tools that provide accurate, current metrics on energy usage/consumption; ecological footprint; and by-product generation. This shifts the focus from static reports to data-driven decisions, enabling evidence-based decisions that help justify the environmental and financial benefits of circular transitions.

The primary objective of this study is to bridge the gap between operational management and sustainability by establishing a systematic link between ERP system data and recognized circular-economy performance indicators. Specifically, it seeks to map ERP functionalities to quantitative metrics such as the Material Circulating Rate (MCR) and the Product Utilization Rate (PUR), which assess material recirculation and product lifecycle efficiency within circular systems (Yurtay, 2025). Based on this, the study aims to develop a data-driven roadmap to integrate Circular Economy concepts into sustainable manufacturing practices. Leveraging the integration capabilities of sustainable enterprise resource planning systems and Industry 4.0 technologies, such as the internet of Things for real-time monitoring and Artificial Intelligence for predictive analytics, this study aims to transform complex data into meaningful strategic insights to optimize resource utilization and reverse logistics efficiency. Finally, Section 5 provides an empirical validation of the framework through a numerical simulation, transitioning the study from theoretical constructs to a data-driven proof of concept.

2. The quantitative ERP-driven CE (Q-EDCE) framework

The Q-EDCE Framework addresses gaps in quantitative assessment and in the theoretical integration of Circular Economy principles within digital enterprise platforms.

It overcomes existing fragmentation in assessment models by providing a structured approach to operationalizing circularity through functional enterprise integration. Central to the Industry 4.0 paradigm, the framework uses real-time data from manufacturing processes

via MES integration to transform linear resource management into a closed-loop system. Organized into three layers (see Figure 4), it consists of: a Strategic Layer that identifies strategies such as reuse and recycling; an Operational Layer that maps these strategies to ERP modules, such as Reverse Logistics; and a Measurement Layer that defines S-KPIs linked to measurable ERP data. The framework ultimately aims to enhance resilience, sustainability, and data-driven approaches in manufacturing operations.

2.1 The strategic layer: visionary foundations and value retention

The Strategic Layer serves as the theoretical cornerstone of the Q-EDCE framework, establishing the conceptual “what” and “why” required for a successful transition from a linear to a Circular Economy (see Figure 5).

This transition is not merely an operational adjustment but a paradigm shift necessitated by the unsustainable human impact on the Earth—often characterized as the Anthropocene—in which the traditional linear framework of “take-make-use-dispose” has pushed the planet beyond its biophysical limits. In contrast to the unidirectional flow of raw materials into waste, the strategic vision of circularity seeks to decouple economic growth from resource depletion by converting production into a closed-loop system where resources are treated as assets to be preserved (see Figure 6).

2.1.1 Systems thinking and business model innovation (BMI). At its core, this layer is grounded in systems thinking, moving away from a “mechanistic” view of waste toward a holistic mindset in which everything is connected, and nothing is truly wasted. Consequently, achieving circularity requires Business Model Innovation (BMI), a fundamental reconfiguration of how an enterprise creates, delivers, and captures value. Strategic planning must shift the company’s value proposition from ownership to access—exemplified by Product-as-a-Service (PaaS) models—in which the producer retains responsibility for the product throughout its lifecycle.

2.1.2 The hierarchy of value retention processes (VRPs). To operationalize this vision, the framework adopts a new decision-making model guided by a hierarchy of action principles known as the “Rs”. These are better understood as Value Retention Processes (VRPs), in which the goal is to maintain products and materials at their highest utility and value for as long as possible.

These strategies are prioritized into three categories.

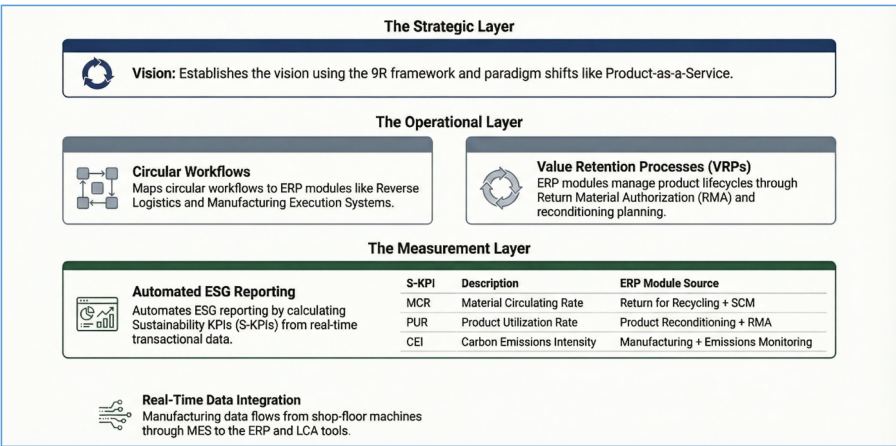


Figure 4. The Q-EDCE framework: integrating circular economy into ERP systems

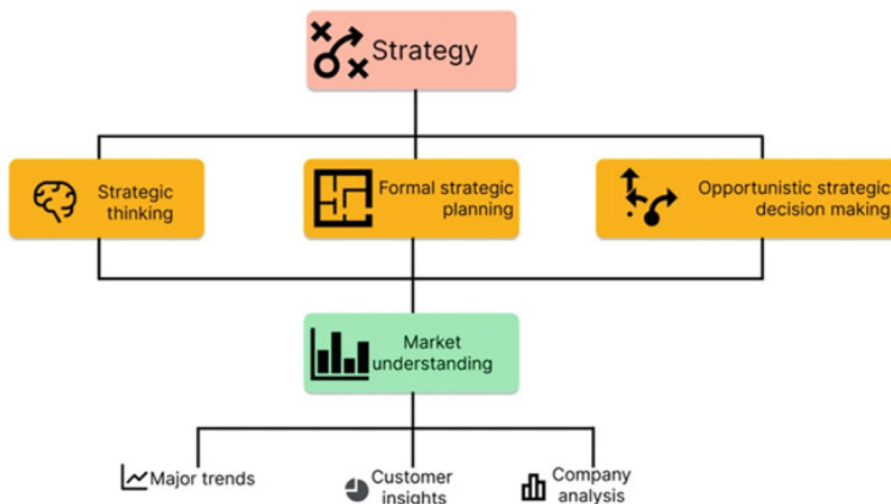


Figure 5. Three ways in which companies formulate strategy Erdiaw-Kwasie and Alam (2023)

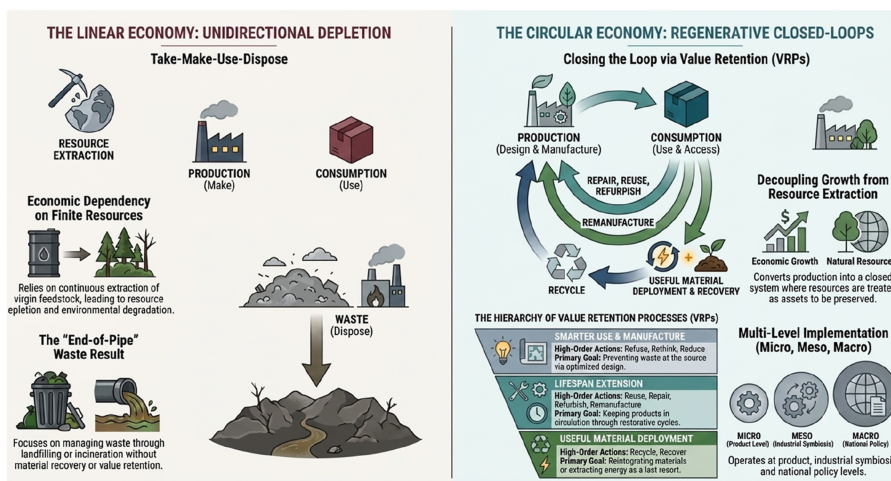


Figure 6. Linear economy versus circular economy process

- (1) Smarter Product Use and Manufacture: The highest-order strategies, such as Refuse, Rethink, and Reduce, focus on preventing waste at the source by optimizing product design and manufacturing efficiency.
- (2) Lifespan Extension: Strategies like Reuse, Repair, Refurbish, and Remanufacture aim to keep products and parts in circulation through restorative cycles, preserving the functional and economic value created during initial production.
- (3) Useful Material Deployment: As a last resort, Recycle and Recover are employed to reintegrate materials into the production cycle or extract energy from non-recyclable waste, minimizing the need for virgin feedstock (see Figure 7).

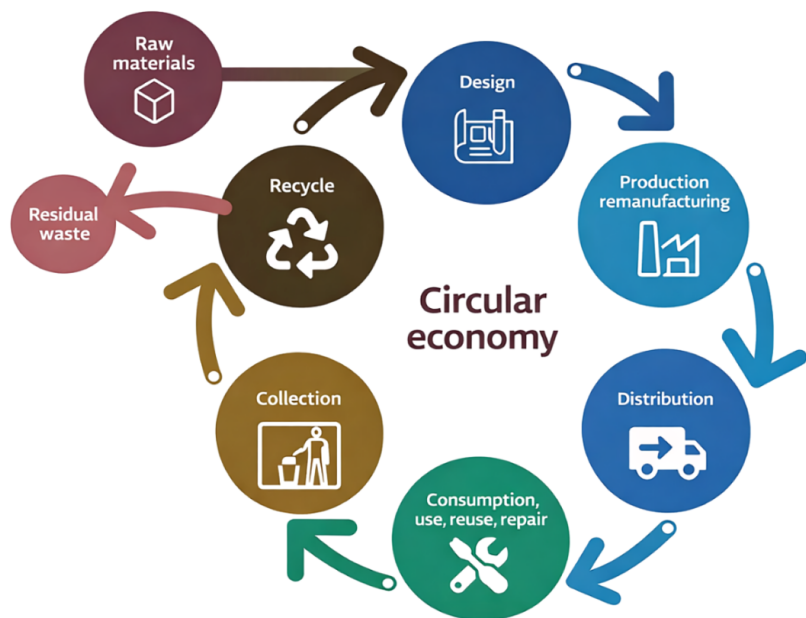


Figure 7. Process of a circular economy [Sustainability Directory \(2025b\)](#)

2.1.3 Strategic integration with Industry 4.0. The Strategic Layer provides the mandatory prerequisite for digital enterprise integration. By identifying the most viable circular pathway—such as deciding between remanufacturing and recycling based on real-time product condition—strategic planning guides the embedding of Industry 4.0 enablers into the S-ERP platform. Technologies such as the internet of Things (IoT) and Big Data Analytics serve as strategic interfaces, transforming static analysis into a dynamic, data-driven approach that enables firms to re-engineer operations and eliminate the need for vast inventories. Through this integration, circularity is transformed from an abstract goal into a measurable, manageable, and competitive corporate advantage.

2.2 Operational layer

The Operational Layer transforms strategic objectives into specific workflows executed via the ERP system, detailing the implementation of circular practices. It aligns circular goals with functional modules within the enterprise platform, including Reverse Logistics for handling returns and end-of-life products, Supply Chain Management (SCM) for overseeing the circular supply chain, and MES for real-time production monitoring. Additionally, it clarifies the necessary transactional data flows for processes such as Return Material Authorization (RMA) and material recovery tracking, thereby facilitating the integration of all circular operations for centralized inventory and product flow management (see [Figure 8](#)).

The selection of ERP modules within the operational layer of the Q-EDCE framework is guided by a comprehensive three-fold logic that integrates strategic goals, best practices from literature, and functional requirements for calculating circularity KPIs.

Initially, the framework emphasizes translating strategic objectives—such as reuse, refurbishment, and recycling—into actionable processes within the ERP system. This is exemplified by the selection of modules such as Reverse Logistics, Return Material

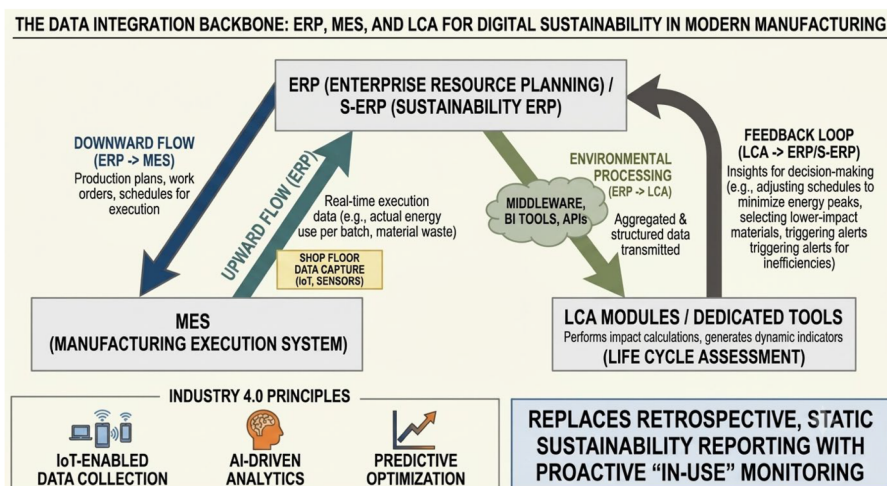


Figure 8. Real-time data flow ERP-MES-LCA for sustainability

Authorization (RMA), and Product Reconditioning, which are essential for managing these processes effectively.

Furthermore, the framework draws on established best practices and Circular Economy literature, highlighting the importance of logistics and flow management as critical success factors for implementing a Circular Economy.

Additionally, integrating an MES supports Industry 4.0 initiatives, while sustainability modules such as Energy and Emissions Monitoring align with recognized standards for resource intensity and carbon accounting.

Moreover, module selection is driven by their ability to provide the necessary measurable data fields for the framework’s Measurement Layer, ensuring that key performance indicators (KPIs) such as the MCR, WRR, and CEI can be accurately calculated. Lastly, the modules are strategically chosen to cover the entire closed-loop product lifecycle, incorporating Supplier Sustainability Tracking for the “Beginning of Life,” MES for “Middle of Life” monitoring, and Reverse Logistics for “End of Life” recovery, thereby ensuring a holistic approach to circularity.

The integration of ERP, Manufacturing Execution System (MES), and LCA (Life Cycle Assessment) forms a vital operational backbone for achieving digital sustainability within the Q-EDCE framework. By establishing a seamless, **real-time data pipeline**, this integration connects shop-floor execution with enterprise-level planning and lifecycle-wide environmental assessments, thereby facilitating proactive resource management aligned with sustainability goals. At the shop-floor level, the MES plays a crucial role by collecting granular data from machines, sensors, and IoT devices—including metrics on energy consumption, raw material usage, and production output—to bridge the gap between planned production and actual execution. From an ERP perspective, integrating LCA tools significantly enhances the ability to monitor and evaluate environmental impacts throughout the product lifecycle, translating operational metrics from MES into key indicators such as carbon footprint, energy intensity, and waste impact (ORIS Connect, 2025).

In this context, the ERP system evolves into an S-ERP (see Table 1), serving as the central hub that aggregates MES data with broader business information, such as procurement and finance, to transform raw production data into actionable insights. This backbone positions the ERP as the intelligent core of digital sustainability, transforming isolated data into comprehensive insights, as evidenced by S-ERP’s comparative advantages over conventional systems.

Table 1. Comparative overview of ERP and S-ERP

Criteria	Conventional ERP	S-ERP
Objective	Optimize operational and financial efficiency	Integrate sustainability into all business operations, balancing economic performance with ecological objectives (e.g. ceramic plants targeting both cost reduction and 20–30% lower CO ₂ per m ² of tiles)
Sustainability capabilities	Limited or absent; sustainability handled via separate/add-on tools	Embedded sustainability management: CO ₂ tracking, energy consumption monitoring, waste management, Circular Economy principles (e.g. SAP S/4HANA Sustainability Control Tower)
Environmental management	No active management of resources or emissions; retrospective focus	Proactive green practices: green supply chain, e-waste management, eco-design integration, alignment with ISO 14001 (e.g. real-time kiln emission control in ceramic firing lines)
Stakeholder integration	Minimal engagement on sustainability issues; limited transparency	Enhanced collaboration with employees, suppliers, customers; real-time sustainability reporting (e.g. shared supplier carbon dashboards in Bosch or Saint-Gobain ceramic supply chains)
Energy and resources efficiency	Not a primary concern; efficiency driven mainly by cost savings	Digitalized systems optimize energy use, reduce server load and waste, minimize resource consumption, and support renewable energy adoption (e.g. IoT sensors on tile drying and firing kilns automatically shifting to off-peak renewable tariffs)
Data handling	Retrospective and periodic (e.g. manual Excel uploads once per shift or day)	Real-time and dynamic; automated streaming from shop-floor sensors (e.g. MES captures energy kWh every 10 s during tile pressing and feeds directly into ERP)
Integration with MES and LCA	Basic or manual data exchange; often siloed (e.g. CSV export/import between systems)	Seamless automated bidirectional flow: MES → ERP → LCA via APIs and middleware (e.g. Siemens Opcenter MES + SAP S/4HANA + SimaPro/OpenLCA calculating live carbon footprint per batch of ceramic tiles)
Decision-making support	Primarily economic/financial-driven (e.g. production scheduling based only on cost and delivery date)	Balanced triple bottom line with predictive analytics (e.g. AI in ERP flags “high-emission batch” and suggests alternative raw materials or slower firing curve to cut CO ₂ by 12% without missing deadlines)
Technology enablers	Traditional on-premise databases, limited IoT/AI connectivity	Full Industry 4.0 stack: IoT sensors, edge computing, AI analytics, cloud platforms (e.g. Microsoft Azure IoT Hub + Power BI dashboards integrated with Dynamics 365 and LCA tools)
Advanced circularity support	Absent; no lifecycle simulation or immutable traceability	Digital Twins simulate EoL/remanufacturing scenarios; Blockchain ensures provenance, traceability, and trust in closed-loop chains (e.g. secured DT data for verifiable recycled content)
Regulatory compliance and reporting	Static annual reports (e.g. Excel-based CSR or basic carbon inventory)	Automated, real-time ESG and CSRD-compliant reporting (e.g. live Scope 1–3 emissions dashboard in SAP that feeds directly into EU CSRD filings or ISO 14064 certification)

In the operational layer of the Q-EDCE framework, the selected ERP modules are presented as functional enablers that translate high-level strategic circular goals into concrete, executable processes (see Figure 9).

The integration of the internet of Things (IoT) and Big Data Analytics (BDA) acts as the sensory and cognitive layers that feed real-time data into the framework's Operational Layer. IoT serves as the embedded sensory backbone, continuously collecting data on product conditions, locations, and usage patterns, enabling manufacturers to monitor asset performance remotely and to facilitate "closing the loop" for end-of-life items through automated reverse logistics. Consequently, this real-time visibility transforms traditional linear models into regenerative cycles. Meanwhile, BDA processes these massive amounts of data to deliver actionable insights that identify resource intensity and waste hotspots, creating a data-driven feedback loop that informs actions within the S-ERP. This synergy transforms the S-ERP into an intelligent platform that proactively integrates economic and ecological performance, allowing organizations to transition from reactive compliance to proactive circularity (see Figure 10).

These modules are categorized into four primary functional areas, each responsible for specific circular activities and data flows.

2.2.1 Logistics and flow management modules. These modules are essential for managing the movement of goods in a closed-loop system.

- (1) Reverse Logistics: This module must present functionalities for managing returns, end-of-life (EoL) products, and product reconditioning.
- (2) Supply Chain Management (SCM): Used for the continuous monitoring of the circular supply chain and its associated environmental impacts.
- (3) Transactional Flows: The ERP system should specifically handle three key circular transactions:
 - Return Material Authorization (RMA)/Return for Repair: Manages items requiring repair, including receipt verification and status updates for repaired inventory.
 - Return for Recycling: Tracks EoL items until they are fully recycled and reintegrated into the system as new production materials.
 - Product Reconditioning: Tracks items through the step-by-step refurbishing process, from registration to the final update of refurbished product inventory.

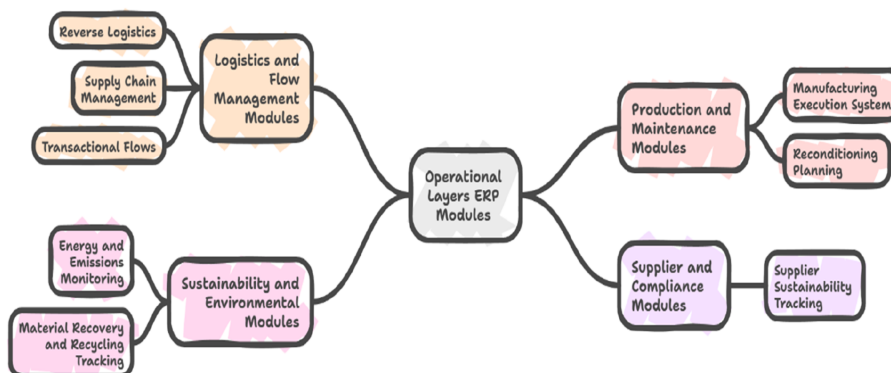


Figure 9. Operational layer erp modules for circular economy

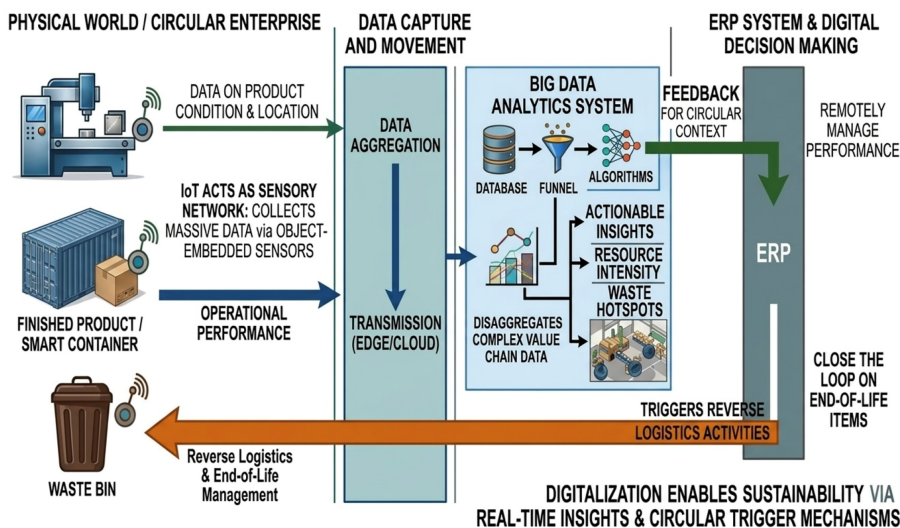


Figure 10. Smart enablers of ERP and digitalization for sustainability: IoT and big data analytics

2.2.2 Production and maintenance modules. These modules focus on the internal “Middle of Life” (MoL) and re-entry phases of products.

- (1) MES: Integrated with the ERP to provide real-time production monitoring, capturing data directly from shop-floor activities.
- (2) Reconditioning Planning: Coordinates the specific steps needed to optimize quality and resources during the refurbishment or remanufacturing of returned assets.

2.2.3 Sustainability and environmental modules. This area provides the specialized tracking needed for circularity assessments.

- (1) Energy and Emissions Monitoring: Functions for the control and reporting of energy consumption and greenhouse gas emissions.
- (2) Material Recovery and Recycling Tracking: Ensures the traceability and quantification of materials that are recovered and reintegrated into the production process.

2.2.4 Supplier and compliance modules. These focus on the “Beginning of Life” (BoL) and upstream circularity.

- (1) Supplier Sustainability Tracking: Presents tools to assess the ecological practices of vendors and quantify their use of recycled materials.

By presenting these specific modules and functionalities, the operational layer enables centralized management of inventories and product flows, ensuring that every circular action is recorded as a digital transaction for subsequent analysis in the Measurement Layer.

2.3 Measurement layer

The Measurement Layer operationalizes the quantitative assessment of circularity by establishing S-KPIs for measurable fields within Enterprise Resource Planning (ERP) systems. This layer facilitates data-driven sustainability management by linking strategic objectives to real-time monitoring, automating Environmental, Social, and Governance (ESG)

reporting, and ensuring supply chain traceability. Key metrics defined include MCR, PUR, and WRR, which align with functional ERP modules to enable a thorough evaluation of environmental and circular performance. The indicators are derived from established literature to guarantee robust, verifiable results that comply with international standards.

The Measurement Layer establishes the quantitative “how” of circularity through Sustainable Operations and Performance Measurement (SOPM) methodologies. Central to this approach is Life Cycle Assessment (LCA), which, following the ISO 14040/14,044 frameworks, evaluates environmental impacts from a cradle-to-cradle (C2C) perspective. This enables the framework to replace traditional disposal with closed-loop processes, transforming materials into nutrients for new cycles (see Figure 11).

Complementing LCA, Material Flow Cost Accounting (MFCA) (standardized under ISO 14051:2011) tracks and quantifies material flows and their associated costs throughout the production process. By categorizing outputs into positive products (revenue-generating) and negative products (wastes and losses), MFCA illuminates the often-overlooked economic burden of material leaks. Assigning monetary values to physical leaks, such as scrap or off-spec materials, identifies critical areas of value loss and directly supports the framework’s strategic goal of resource recovery (see Figure 12).

These methodologies provide the micro-level granularity required to define the following six S-KPIs, which transition the framework from static, retrospective reporting to dynamic, real-time monitoring.

The selected indicators are based on recognized frameworks for material circularity assessment, reverse logistics, waste management, and carbon accounting.

(1) **Material Circulating Rate (MCR)**

quantifies the proportion of materials entering a system (e.g. product, organization, region, or economy) that originate from circular sources, such as recycled or reused materials, relative to total material inputs. A higher MCR indicates a system that better closes material loops and reduces reliance on virgin resources, reflecting greater circularity in material flows (Sustainability Directory, 2025a).

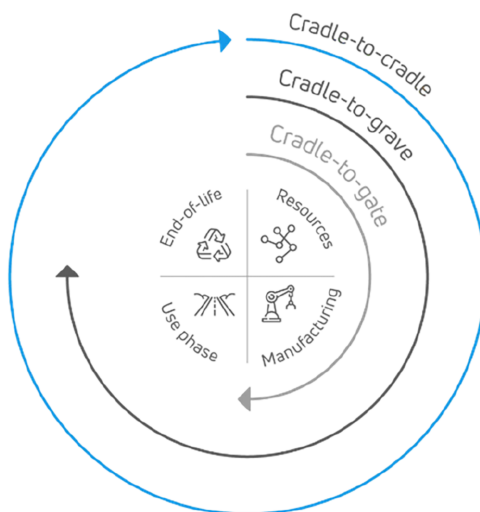


Figure 11. Production stages that different types of LCAs focus on <https://www.retyre.eco/an-introduction-to-life-cycle-assessments-from-cradle-to-cradle-and-beyond/>

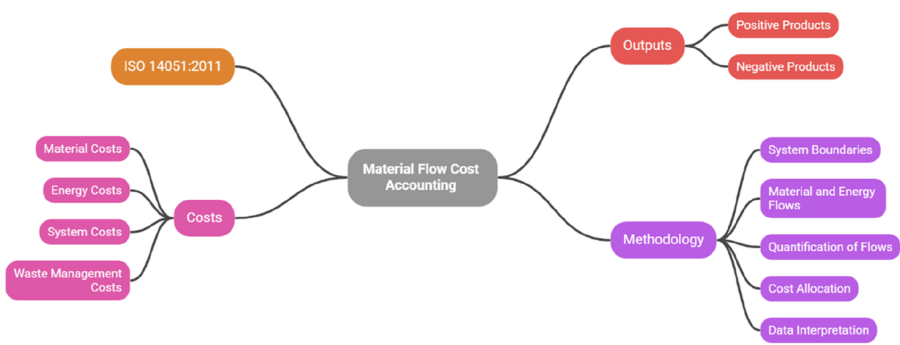


Figure 12. Material flow accounting (MFA) description, adapted from [Contini and Peruzzini \(2022a\)](#)

- (2) **Product Utilization Rate (PUR)**
Measures how effectively a product’s functional capacity is used over its lifespan. A higher PUR indicates greater efficiency in product use, supporting Circular Economy strategies such as reuse, refurbishment, and sharing models ([Sustainability Directory, 2025b](#)).
- (3) **Carbon Emissions Intensity (CEI)**
CEI measures the environmental impact of production activities by dividing carbon dioxide emissions by the total economic activity, such as GDP ([Chang et al., 2023](#)).
This metric follows international greenhouse gas accounting standards established by the International Organization for Standardization (ISO 14064).
- (4) **The Waste Recovery Rate (WRR)**
WRR assesses the proportion of generated waste that is recovered, recycled, or valorized ([Department of Climate Change, Energy, the Environment and Water, 2024](#)).
This indicator is commonly used in assessments of sustainable manufacturing and waste management performance, including studies published in the *Waste Management Journal*.
- (5) **The Water Intensity (WI)** measures the amount of water produced by an atmospheric water generator over a given period, allowing the assessment of water performance and efficiency ([Cattani et al., 2024](#)).
- (6) **Supplier Circularity Score (SCS)** measures a supplier’s level of circular performance, based on the weighted evaluation of its practices in sustainable sourcing, resource management, material recovery, and environmental compliance ([Bai et al., 2024](#)).

[Table 2](#) illustrates the operational core of the Measurement Layer within the Q-EDCE framework. It provides a blueprint for transforming raw enterprise data into actionable intelligence by linking six S-KPIs to specific functional modules and data points within an ERP system.

[Table 2](#) shows a significant evolution from traditional linear waste management to a closed-loop operational model, emphasizing the integration of sustainability into the core manufacturing processes rather than relegating it to public relations.

This transition is exemplified by the “Inner Loop” strategy, which prioritizes product integrity as measured by the PUR. By leveraging ERP modules such as Reconditioning

Table 2. Mapping of sustainability KPIs to ERP functional modules

KPI	Calculation method	ERP correspondence	Added value (circular economy)
Product Utilization Rate (PUR)	Reused or refurbished products are divided into returned or end-of-life products	Product Reconditioning, RMA, and Reconditioning Planning	<i>Lifespan Extension:</i> Keeps products in circulation through restorative cycles, preserving functional and economic value
Material Circulating Rate (MCR)	Recycled material divided by total material	Return for Recycling, Material Recovery, and SCM	<i>Closing Loops:</i> Reduces reliance on virgin resources by quantifying materials from circular sources
Supplier Circularity Score (SCS)	Recycled material from suppliers is divided by the total supplier material input	Supplier Sustainability Tracking and SCM	<i>Upstream Tracking:</i> Assesses vendors' ecological practices and their use of recycled materials
Waste Recovery Rate (WRR)	Recovered waste divided by total waste generated	Reverse Logistics and Material Recovery Tracking	<i>Material Deployment:</i> Measures the proportion of waste recovered, recycled, or valorized
Carbon Emissions Intensity (CEI)	Total CO ₂ emissions divided by Gross Domestic Product (GDP)	Manufacturing, Energy, and Emissions Monitoring	<i>Impact Measurement:</i> Tracks environmental impact and resource intensity to support data-driven decisions
Water Intensity (WI)	Total water consumed divided by production time	MES and Environmental Monitoring	<i>Efficiency:</i> Real-time assessment of resource performance within the manufacturing process

Planning, organizations can achieve higher profit margins while preserving the inherent value of finished products, compared with the more energy-intensive MCR.

Furthermore, the framework promotes decoupling growth from environmental impact by using Resource Intensity and Emissions metrics, enabling increased manufacturing output without a corresponding rise in ecological footprint. This strategic insight underscores the potential for absolute growth alongside reduced relative impact. Additionally, the focus on upstream accountability through the SCS enhances supply chain resilience by mitigating risks associated with the volatility of virgin raw materials.

Finally, the adoption of an S-ERP platform transforms sustainability metrics from mere historical indicators into proactive decision-making tools, embedding sustainability into daily operations and driving resource productivity. Overall, this comprehensive approach not only fosters environmental responsibility but also enhances operational efficiency and profitability.

3. Related works

The literature on Circular Economy performance measurement has evolved significantly, shifting from isolated metrics to more integrated frameworks (Panchal *et al.*, 2021). provides a comprehensive review of 120 papers, noting that while the technical cycle of CE relies on the R-framework (Reduce, Reuse, Recycle, etc.), recycling remains the most frequently used imperative (47%), followed by reuse (33%). However, this study identifies a critical gap: a lack of focus on inner loops, such as repair and remanufacturing, which retain more value than recycling. Similarly, Ratner *et al.* (2025a), highlights a “clear bias” in practical applications toward lower-value end-of-life (EoL) processes, such as recycling, leaving higher-impact strategies, such as “Refuse” or “Rethink,” underexplored.

A major contribution to the field is the development of systemic assessment tools (Vinante *et al.*, 2021). collected 365 firm-level metrics and organized them into a new Circular Value Chain framework, identifying that most current metrics are concentrated in Strategy and Vision or Operations. At the same time, fields such as HR management and training are

neglected. From a sustainability perspective (Contini and Peruzzini, 2022b), provides a database of over 270 leading sustainability indicators, categorized by the Triple Bottom Line (TBL), showing that while environmental indicators are abundant, social indicators are scarce.

The integration of Industry 4.0 (I4.0) technologies is widely regarded as a key enabler of CE (Javaid et al., 2024). Briefly explains how smart enablers such as AI, IoT, and big data can optimize manufacturing and close the loop for EoL items (Kerin, 2022). Specifically explores the synergy between Industry 4.0 Product Digital Twins and remanufacturing, noting that while research is increasing, no single review yet considers remanufacturing, I4.0, and CE in exhaustive detail.

Despite these advancements, several limitations or research gaps persist across the literature.

- (1) Lack of Standardization: There is no universally adopted monitoring framework or standardized metrics to evaluate CE impact robustly.
- (2) Data Availability: Measurement efforts are often inhibited by data differences, gaps, and a lack of information exchange between researchers and company managers.
- (3) Micro-Level Complexity: While macro and meso-level indicators are more established, it is notably more difficult to combine sustainable development and CE at the product or consumer level.
- (4) Static vs. Dynamic Metrics: Most current indicators are retrospective and static, failing to capture the temporal evolution and complex feedback loops of circular transitions.

Table 3 compares the Current Work (Q-EDCE) with prominent related frameworks from the literature, specifically highlighting the proposed KPIs.

The comparative table highlights several critical insights regarding the current state of Circular Economy performance measurement and positions the Quantitative ERP-Driven CE (Q-EDCE) Framework within this landscape. The following insights can be derived from the comparison.

- (1) Bridging the “Data-Driven” Gap
A primary insight is that, while existing literature offers an abundance of metrics—such as the 365 metrics identified in Vinante et al. (2021) and the 270+ indicators in Contini and Peruzzini (2022b)—there is a significant gap in how these metrics are operationalized in practice on digital enterprise platforms. The Current Work addresses this by specifically mapping KPIs such as MCR and PUR to concrete ERP modules (e.g. SCM, Reverse Logistics), moving beyond theoretical lists toward functional enterprise integration.
- (2) Addressing Metric Fragmentation
Table 3 underscores a “remarkable fragmentation” in CE assessment models. Frameworks such as those in Panchal et al. (2021) and Munonye (2025) show that researchers often struggle with a lack of standardization and divergent scopes. The Q-EDCE framework attempts to mitigate this by synthesizing a focused set of six S-KPIs designed for the manufacturing context, rather than overwhelming users with hundreds of uncoordinated metrics.
- (3) The Neglect of Social and Stakeholder Dimensions
The related works reveal a consistent bias toward environmental and technical indicators. Panchal et al. (2021) notes that social dimensions are the least explored, and Contini and Peruzzini (2022b) finds social indicators to be scarce. Even sophisticated models, such as the MCI in Brown and Bajada (2018), are criticized for overlooking the effects of multiple stakeholders. This identifies a future development

Table 3. Q-EDCE vs. Related Frameworks

Reference	Framework / Focus	Proposed KPIs / Indicators	Key limitations
Vinante et al. (2021)	Technical Nutrient Cycle Review	<i>MCI</i> (Material Circularity Indicator), <i>CEECI</i> (CE Efficiency Composite Index), <i>Longevity Indicator</i>	No standard metric; social dimensions are the least explored
Kerin (2022)	TBL Sustainability Screening	270+ <i>Leading Indicators</i> (e.g. Materials used in after-sales, Program to enhance community health)	Lack of indicators for environmental dimensions in business model development
Javaid et al. (2024)	Circular Value Chain Framework	365 <i>Metrics</i> (e.g. <i>M6</i> : CE incorporated in strategy; <i>M4</i> : leasing/renting BM implementation)	Remarkable fragmentation of assessment models and diverging scopes
Cayzer et al. (2017)	Product Performance Prototype	<i>CEIP</i> (Circular Economy Indicator Prototype score via spider diagram)	Opaque nature of a single metric; reliance on context-specific assumptions
Ratner et al. (2025b)	Circular Supply Network Dynamics	<i>VME</i> (Virgin Material Equivalence), <i>LVME</i> (Lifetime Virgin Material Equivalence), <i>Cycle Velocity</i>	Overlooks multiple stakeholder effects in simpler indicators like <i>MCI</i>
Munonye (2025)	Metric Synthesis Review	<i>CQAT</i> (Circularity-based Quantity Assessment Tool), <i>Circularity Score</i> , <i>MCI</i> , <i>CI</i>	Barriers in data interoperability and a lack of standardization
Current Work	Quantitative ERP-Driven CE (Q-EDCE) Framework	<i>MCR</i> (Material Circulating Rate), <i>PUR</i> (Product Utilization Rate), <i>CEI</i> (Carbon Emissions Intensity), <i>WRR</i> (Waste Recovery Rate), <i>WI</i> (Water Intensity), <i>SCS</i> (Supplier Circularity Score)	Focuses on ERP integration; needs further cross-industry empirical validation

opportunity for the Q-EDCE framework to enhance its SCS to better capture these missing social and stakeholder dynamics.

(4) Simplicity vs. Transparency

The comparison shows a trade-off between simplicity and depth. For example, [Cayzer et al. \(2017\)](#) proposes a single-score prototype (*CEIP*), which the literature describes as “opaque and potentially misleading” because it collapses complex data into one number. In contrast, the Current Work utilizes a multidimensional approach, tracking distinct areas such as *CEI* and *WRR* separately to ensure transparency in decision-making.

(5) Shift from Retrospective to Operational Metrics

Many existing indicators are “retrospective and static,” focusing on past performance. The Q-EDCE framework derives its insights from real-time ERP data and MES integration, allowing for more dynamic, “in-use” monitoring of resources. This shift is essential for Industry 4.0 applications, where real-time responsiveness is required to optimize product lifecycles and minimize waste.

(6) Focus on High-Value Loops

Related works such as [Panchal et al. \(2021\)](#) and [Ratner et al. \(2025b\)](#) highlight a “clear bias” toward recycling (a lower-value, end-of-life process). The Current Work specifically includes *PUR*, which encourages higher-value “inner loops” such as reuse and refurbishment, thereby aligning the framework with more advanced circular strategies.

4. Numerical simulation and quantitative framework validation

This section details the empirical validation of the Q-EDCE framework through a numerical simulation reflecting a detergent manufacturing environment. The simulation tests the framework’s robustness against varying production conditions, demonstrating how a Sustainable ERP (S-ERP) can yield measurable circular outcomes. It employs a state-transformation approach across three phases: establishing a Linear Baseline Scenario using existing datasets, simulating the Q-EDCE intervention, which incorporates Value Retention Process logic and real-time feedback, and finally recalculating the Sustainability Key Performance Indicators to assess improvements. Employing Python-driven analytics, the Q-EDCE framework is shown to enhance circular performance within organizational data flows, substantiating ERP systems as capable infrastructures for operationalizing circularity in manufacturing.

4.1 Simulation environment and baseline setup

The validation of the Q-EDCE framework begins with the creation of a numerical simulation environment that mimics a real-world industrial setting, specifically a detergent manufacturer within the chemical production sector. The primary objective of this setup is to evaluate the current effectiveness of resource utilization and identify opportunities to transition from a linear to a circular model through sustainable management practices. To define the scope and operational characteristics of this industrial system, the QQQQCP method is utilized, as shown in Table 4.

4.1.1 Dataset description and key variables. The simulation utilizes the Smart Manufacturing Resource Efficiency Dataset obtained from Kaggle [1], to provide the necessary operational data points. This dataset includes several critical variables required to calculate the framework’s S-KPIs.

- (1) Machine ID: A unique identifier for each production unit, allowing the system to monitor specific equipment performance and trigger localized maintenance or quality alerts.
- (2) Defect Rate (%): This variable measures the percentage of non-conforming products per cycle; in a linear baseline, these defects are treated as 100% waste sent to landfills.
- (3) Recycled Material (%): Reflects the proportion of circular materials used in the production process, serving as the primary indicator for material origin and circularity maturity.

4.1.2 The “as-is” state: the linear baseline scenario. The initial data analysis reveals a “Linear Baseline Scenario” (Dataset A), in which the ERP system functions merely as a loss recorder rather than an active optimizer. A preliminary investigation of this “As-Is” state highlights significant inefficiencies.

Table 4. QQQQCP analysis of the industrial context

Question	Answer
Who	Detergent manufacturing company
What	Production and resource management
Where	Chemical plant
When	Daily production
How	MES and ERP systems
Why	Improve circularity and reduce waste

- (1) Low Material Circularity: Recycled inputs comprise only 4.03%–4.06% of total material use, indicating an overwhelming dependence on virgin raw materials supplied by traditional, non-circular supply chains.
- (2) High Chemical and Packaging Waste: The system generates an average of 49.2 kg of waste per production cycle, primarily driven by an average defect rate of 2.53%.
- (3) Linear Logic Flow: The production process follows a strictly unidirectional path—Virgin Raw Material → Production → Defective Output → Waste—where no systematic process exists for reinjecting recovered materials back into the system.

This baseline assessment confirms that the current system is characterized by reduced material circularity, excessive reliance on external suppliers, and a high environmental footprint due to unrecovered material losses. These results provide the necessary justification for the subsequent circular intervention logic implemented in the framework's Strategic and Operational layers.

4.2 Simulation logic and circular intervention

The transition from a linear baseline to a circular enterprise is executed through the Strategic and Operational layers of the Q-EDCE framework. This section details the logical progression from identifying high-impact inefficiencies to implementing real-time digital interventions.

4.2.1 The strategic layer: prioritization and decision analysis. To operationalize the Strategic Layer, a Pareto analysis was conducted to classify and prioritize resource inefficiencies identified in the dataset. Based on the 80/20 principle, the analysis revealed that high levels of chemical and packaging waste and low material circularity account for the majority of operational problems (see Figure 13). These factors were selected as the primary strategic priorities for the circular transition.

Two quantitative methods guided the selection of specific circular strategies.

- (1) Design of Experiments (DOE): Evaluated defective material recovery scenarios (20%–70%). Although the 70% scenario offered the highest performance, the 50%

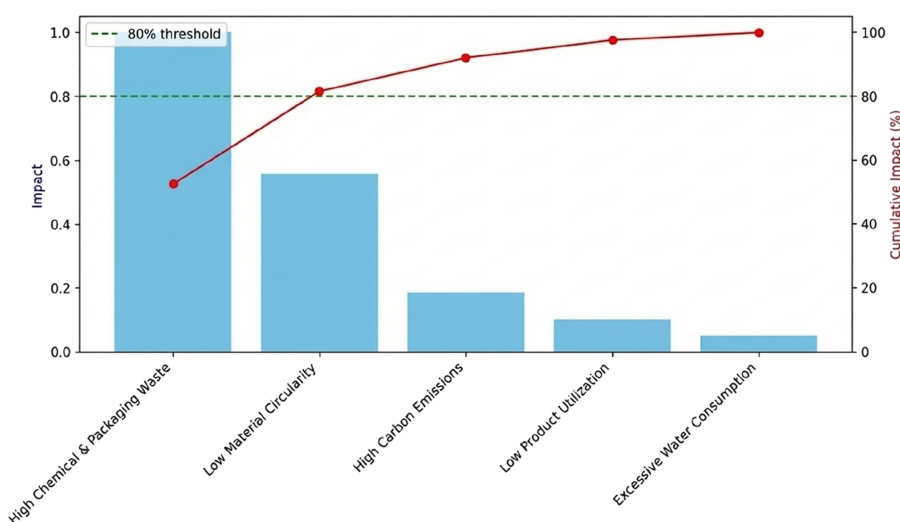


Figure 13. Pareto diagram of production inefficiencies

recovery rate was selected as the optimal solution because it provides a balanced improvement while remaining industrially feasible.

- (2) Multi-Criteria Decision Analysis (MCDA): Compared four scenarios for increasing recycled material usage (+10% to +40%). The 30% increase in recycled material usage achieved the highest decision score (7.70) based on cost, material availability, and environmental impact; thus, it was selected as the core strategy to improve the Material Circulating Rate (MCR).

These decisions effectively simulate the Value Retention Process (VRP) by converting defects into “virtual recycled inventory,” ensuring that waste from one batch becomes a circular input for the next.

4.2.2 The operational layer: simulating MES-ERP real-time feedback. The Operational Layer simulates an IoT-integrated S-ERP system that monitors production performance in real time. Shop-floor sensors capture data on waste and defects, which are synchronized with the ERP to trigger immediate corrective actions through a MES-ERP feedback loop (see Figure 14).

Two primary mechanisms govern the decision logic.

- (1) Waste Monitoring: Triggers an alert if waste exceeds the threshold (mean + 10% tolerance), leading to raw material dosage adjustments.
- (2) Defect Rate Monitoring: Activates a quality inspection alert and production load adjustment if the defect rate exceeds the 5% acceptable quality limit.

The following algorithm implements these “logic gates” to demonstrate how an ERP-driven system can proactively manage circularity.

Algorithm 1. Automated Waste and Quality Mitigation Logic

Input: Dataframe post_erp containing production cycle metrics.

Output: Updated post_erp with triggered alerts and adjusted operational parameters.

- 1. Calculate Waste Generation: For each production cycle, compute the total waste:
$$\text{Waste Generated (kg)} = [\text{Quantity Used (kg)} \times \text{Defect Rate (\%)}] / 100$$
- 2. Establish Threshold Limits: * Set Waste Threshold = Mean(Waste Generated) $\times$ 1.10
 - o Set Defect Threshold = 5%
- 3. Execute Waste Mitigation: * Identify: If Waste Generated > Waste Threshold, then set Waste_Alert = True.
 - o Adjust: For all active Waste Alerts, reduce Quantity Used by 5%.

===== OPERATIONAL LAYER RESULTS =====					
	Machine ID	Waste Generated (kg)	Waste_Alert	Defect Rate (%)	Quality_Alert
0	M002	2.931474	False	3.38	False
1	M009	1.385681	False	2.53	False
2	M001	1.731400	False	1.10	False
3	M010	2.784940	False	1.70	False
4	M003	2.769992	False	4.24	False

Figure 14. MES-ERP feedback loop schematic

4. Execute Quality Mitigation: * Identify: If Defect Rate > Defect Threshold, then set Quality_Alert = True.
 - o Adjust: For all active Quality Alerts, reduce Defect Rate by 15%.

4.3 Comparative S-KPI analysis

The final phase of the validation process involves a quantitative comparison between the Linear Baseline (Dataset A) and the Q-EDCE Scenario (Dataset B). This analysis demonstrates the effectiveness of the framework by measuring the “delta” or improvement across the six defined Sustainability Key Performance Indicators (S-KPIs). This section provides the empirical “Proof of Concept,” illustrating how transforming an ERP system into a sustainable management platform directly impacts circularity outcomes.

4.3.1 Performance results: before vs. after intervention. The implementation of the Strategic Layer (waste recovery and increased recycled content) and the Operational Layer (real-time MES feedback) led to measurable improvements in system performance. The average values for each dataset are summarized in [Table 5](#).

4.3.2 Analysis of circular gains. The data reveal that the most significant impact was observed in the circularity-specific metrics. The Material Circulating Rate (MCR) and Supplier Circularity Score (SCS) increased from approximately 4.06%–6.89%. This improvement is a direct result of the strategic decision to increase recycled material usage by 30% and the operational conversion of defects into “virtual recycled inventory”.

Furthermore, the Waste Recovery Rate (WRR) showed the most dramatic transformation, moving from 0.0 to 0.5. This confirms that the framework successfully transitioned the plant from a “100% waste” model to a “closed-loop” model, in which 50% of defective material is recovered for reuse in subsequent batches.

In contrast to the significant gains in material circularity, the Sustainability KPIs for Product Utilization Rate (PUR), Carbon Emissions Intensity (CEI), and Water Intensity (WI) remained stable between the Pre-ERP and Post-ERP scenarios. This stability is expected and demonstrates the framework’s precision in tracking specific operational changes. As established in the Strategic Layer, the primary interventions in this simulation were designed to optimize material loops—specifically, to increase recycled content by 30% and the recovery rate of defective materials by 50%.

Because the scope of this particular validation did not include energy-efficiency retrofits, water recycling systems, or product longevity extensions (such as remanufacturing or repair services), these indicators correctly reflect the baseline manufacturing conditions. This underscores a key finding: the Q-EDCE framework provides a transparent and modular assessment in which circular gains are strictly mapped to the specific strategic priorities selected by management, rather than presenting generalized or “hallucinated” improvements across unrelated dimensions. Consequently, CEI, PUR, and WI serve as control variables in

Table 5. S-KPI comparison between Pre-ERP and Post-ERP scenarios

S-KPI	Dataset A (Pre-ERP)	Dataset B (Post-ERP)	Improvement/Status
Material Circulating Rate (MCR)	0.0406	0.0689	+69.7%
Supplier Circularity Score (SCS)	0.0406	0.0689	+69.7%
Waste Recovery Rate (WRR)	0.0000	0.5000	Significant Gain
Product Utilization Rate (PUR)	0.9747	0.9747	Stable
Carbon Emissions Intensity (CEI)	0.2831	0.2831	Stable
Water Intensity (WI)	0.0000	0.0000	Stable (No intervention)

this simulation, confirming that the framework accurately distinguishes between material-centric circularity and broader resource-efficiency retrofits.

4.4 Sensitivity analysis and discussion

To evaluate the robustness of the proposed Q-EDCE framework, a sensitivity analysis was conducted by varying several key operational parameters. This analysis serves as a “stress test” to assess how changes in production conditions affect the system’s sustainability performance and to verify whether the framework remains effective under adverse scenarios.

4.4.1 Impact of defect rate variation. The defect rate is a critical variable as it directly influences the Product Utilization Rate (PUR), the volume of waste generated, and the material recovery potential. Three scenarios were tested: a 20% reduction in defects (Low), the current baseline (Normal), and a 20% increase in defects (High).

The sensitivity analysis (Figure 15) reveals that the Q-EDCE framework possesses intrinsic resilience. While traditional ERP systems merely record the negative financial impact of a 20% increase in defects, the integrated VRP logic ensures that 50% of that loss is immediately recaptured as a secondary raw material. This demonstrates that the framework not only tracks sustainability but also operationalizes the decoupling of production errors from environmental waste. The stability of the PUR (which varies by only ± 0.01) confirms that the MES-ERP feedback loop effectively contains quality fluctuations before they cascade into systemic circularity failures.

4.4.2 Discussion on framework robustness. The sensitivity analysis confirms that the proposed framework maintains stable performance even under fluctuating quality conditions. By using real-time data from the MES layer to trigger immediate re-entry of materials into the virtual inventory, the framework prevents inefficient production cycles from continuing. This dynamic feedback loop—mapping specific defect data to circular strategy selection—demonstrates a level of sustainability intelligence that traditional ERP systems lack.

This numerical simulation provides the empirical validation needed to bridge the gap between Information Technology and sustainability. It demonstrates that Sustainable ERP (S-ERP) platforms are not merely recording tools but are capable digital infrastructures that

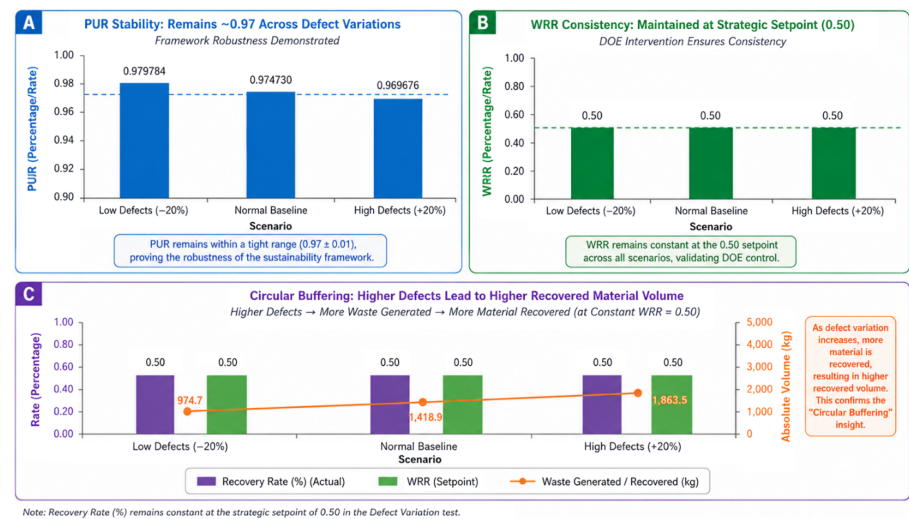


Figure 15. Sensitivity of sustainability KPIs to operational variability

can operationalize circularity and drive measurable outcomes in a real-world manufacturing environment.

5. Conclusion

The Q-EDCE framework addresses the critical gap between Circular Economy theory and digital industrial implementation by mapping functional ERP modules to quantitative sustainability indicators. The findings from the simulation-based validation are summarized as follows.

- (1) Integrated Framework Architecture: The multi-layered Q-EDCE architecture successfully operationalizes circularity by embedding strategic value retention processes into functional Sustainable ERP (S-ERP) workflows.
- (2) Measurable Circularity Gains: Validation results demonstrate a 69.7% increase in the Material Circulating Rate (MCR) and a 50% Waste Recovery Rate (WRR), effectively transforming a linear “take-make-dispose” baseline into a closed-loop system.
- (3) Analytical Precision: The stability of the PUR, CEI, and WI indicators confirms the framework’s analytical precision, accurately reflecting that specific interventions were targeted at material loops rather than energy or water efficiency.
- (4) Systemic Resilience: Stress testing via sensitivity analysis confirms the framework’s robustness, with the Product Utilization Rate (PUR) maintaining stability (varying only by ± 0.01) despite significant fluctuations in production quality.
- (5) Redefinition of ERP Roles: ERP systems are repositioned from passive transactional tools to active digital infrastructures for sustainability, enabling a transition from retrospective reporting to real-time, proactive resource optimization.

Future research should prioritize longitudinal field implementation in live ERP environments to validate automated data acquisition and to integrate broader social ESG indicators that are currently underrepresented in circular models.

Data availability statement

The data that support the findings of this study are available in the Public Domain. The primary dataset used for simulation, titled “Smart Manufacturing Resource Efficiency Dataset,” can be accessed via Kaggle at the following URL: <https://www.kaggle.com/datasets/ziya07/smart-manufacturing-resource-efficiency-dataset>.

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Notes

1. <https://www.kaggle.com/datasets/ziya07/smart-manufacturing-resource-efficiency-dataset>

References

- Bai, C., Zhu, Q. and Sarkis, J. (2024), “Circular economy and circularity supplier selection: a fuzzy group decision approach”, *International Journal of Production Research*, Vol. 62 No. 7, pp. 2307-2330, doi: [10.1080/00207543.2022.2037779](https://doi.org/10.1080/00207543.2022.2037779).

- Bouguern, S. (2024), "A framework for circular economy (CE) implementation to drive sustainable industrial growth in the Algerian manufacturing sector", *Journal of Economic Growth and Entrepreneurship JEGE*, Vol. 7 No. 1, pp. 57-66.
- Brown, P.J. and Bajada, C. (2018), "An economic model of circular supply network dynamics: Toward an understanding of performance measurement in the context of multiple stakeholders", *Business Strategy and the Environment*, Vol. 27 No. 5, pp. 643-655, doi: [10.1002/bse.2069](https://doi.org/10.1002/bse.2069).
- Cattani, L., Cattani, P., Figoni, R. and Magrini, A. (2024), "Performance Assessment of Atmospheric Water Generators: A Review of Evaluation Tools and Proposal for a Novel Advanced Global Evaluation Index for HVAC–AWG Hybrid Solutions", *Applied Sciences*, Vol. 14 No. 24, 11793, doi: [10.3390/app142411793](https://doi.org/10.3390/app142411793).
- Cayzer, S., Griffiths, P. and Beghetto, V. (2017), "Design of indicators for measuring product performance in the circular economy", *International Journal of Sustainable Engineering*, Vol. 10 Nos 4-5, pp. 289-298, doi: [10.1080/19397038.2017.1333543](https://doi.org/10.1080/19397038.2017.1333543).
- Chang, H., Ding, Q., Zhao, W., Hou, N. and Liu, W. (2023), "The digital economy, industrial structure upgrading, and carbon emission intensity—empirical evidence from China's provinces", *Energy Strategy Reviews*, Vol. 50, 101218, doi: [10.1016/j.esr.2023.101218](https://doi.org/10.1016/j.esr.2023.101218).
- Contini, G. and Peruzzini, M. (2022a), "Sustainability and Industry 4.0: Definition of a Set of Key Performance Indicators for Manufacturing Companies", *Sustainability*, Vol. 14 No. 17, 11004, doi: [10.3390/su141711004](https://doi.org/10.3390/su141711004).
- Contini, G. and Peruzzini, M. (2022b), "Sustainability and Industry 4.0: Definition of a Set of Key Performance Indicators for Manufacturing Companies", *Sustainability*, Vol. 14 No. 17, 11004, doi: [10.3390/su141711004](https://doi.org/10.3390/su141711004).
- Department of Climate Change, Energy, the Environment and Water (2024), *Resource recovery and waste materials analysis*, Australian Government, available at: <https://www.dcceew.gov.au/environment/protection/waste/publications-data/national-waste-resource-recovery-reporting/resource-recovery-waste-materials-analysis>
- Ellen MacArthur Foundation (2021), *The Butterfly Diagram: Visualizing The Circular Economy [Page web]*, Ellen MacArthur Foundation, available at: <https://www.ellenmacarthurfoundation.org/circular-economy-diagram>
- Enhancing Sustainability Integration in Sustainable ERP Systems (2024), *International Journal of Production Research*, Vol. 62 No. 5, pp. 1456-1475, doi: [10.1080/00207543.2023.2301234](https://doi.org/10.1080/00207543.2023.2301234).
- Erdiaw-Kwasie, M.O. and Alam, G.M.M. (Eds) (2023), *Circular Economy Strategies and the Un Sustainable Development Goals: Responsible Consumption and Production*, Springer, SDG 12.
- Ferrari, A.M., Volpi, L., Settembre-Blundo, D. and García-Muiña, F.E. (2021), "Dynamic life cycle assessment (LCA) integrating life cycle inventory (LCI) and Enterprise resource planning (ERP) in an Industry 4.0 environment", *Journal of Cleaner Production*, Vol. 286, 125314, doi: [10.1016/j.jclepro.2020.125314](https://doi.org/10.1016/j.jclepro.2020.125314).
- Golinska-Dawson, P., Zysnarska, Z. and Pender, A. (2024), "Assessment of the maturity of product-as-a-service business models for household appliances from the perspective of R strategies in the Circular Economy. Procedia CIRP", *31st CIRP Conference on Life Cycle Engineering (LCE 2024)*.
- Huttmanová, E., Chovancová, J., Petruška, I. and Sallaku, K. (2024), "Circular economy in action: Examining the decoupling of economic growth and material use across EU countries", *European Journal of Sustainable Development*, Vol. 13 No. 4, pp. 13-22, doi: [10.14207/ejsd.2024.v13n4p13](https://doi.org/10.14207/ejsd.2024.v13n4p13).
- Javaid, M., Haleem, A., Khan, I.H., Singh, R.P. and Khan, A.A. (2024), "Industry 4.0 and circular economy for bolstering the healthcare sector: A comprehensive view on challenges, implementation, and futuristic aspects", *Biomedical Analysis*, Vol. 1 No. 2, pp. 174-198, doi: [10.1016/j.bioana.2024.06.001](https://doi.org/10.1016/j.bioana.2024.06.001).
- Kerin, M.E. (2022), *Industry 4.0: Product Digital Twins for Remanufacturing Decision-Making*, Doctoral dissertation, University of Birmingham, available at: <http://etheses.bham.ac.uk/id/eprint/12540/7/Kerin2022PhD.pdf>

- Kirchherr, J., Yang, N.H.N., Schulze-Spüntrup, F., Heerink, M.J. and Hartley, K. (2023), "Conceptualizing the Circular Economy (Revisited): An analysis of 221 definitions", *Resources, Conservation and Recycling*, Vol. 194, 107001, doi: [10.1016/j.resconrec.2023.107001](https://doi.org/10.1016/j.resconrec.2023.107001).
- Laba Nzuzi, B. (2025), "L'économie circulaire : un défi pour une économie durable au RD Congo en 2025", *Revue Internationale de la Recherche Scientifique (Revue IRS)*, Vol. 3 No. 2, pp. 1842-1864, doi: [10.5281/zenodo.15275599](https://doi.org/10.5281/zenodo.15275599).
- Mandpe, A., Paliya, S., Gedam, V.V., Patel, S., Tyagi, L. and Kumar, S. (2023), "Circular-economy approach to sustainable solid waste management: A developing-economy perspective", *Waste Management and Research*, Vol. 41 No. 3, pp. 499-511, doi: [10.1177/0734242x221126718](https://doi.org/10.1177/0734242x221126718).
- Mittal, S., Khan, M. and Romero, D. (2020), "Twenty-five years of ERP implementation research: Trends, challenges, and future directions", *Computers in Industry*, Vol. 118, 103207, doi: [10.1016/j.compind.2020.103207](https://doi.org/10.1016/j.compind.2020.103207).
- Munonye, W.C. (2025), "Towards circular economy metrics: a systematic review", *Circular Economy and Sustainability*, Vol. 5 No. 5, pp. 4093-4135, doi: [10.1007/s43615-025-00604-5](https://doi.org/10.1007/s43615-025-00604-5).
- ORIS Connect (2025), *What is Life Cycle Assessment (LCA) in Linear Infrastructure?* ORIS Connect, available at: <https://www.oris-connect.com/en/blog/what-is-life-cycle-assessment-lca-in-linear-infrastructure>
- Panchal, R., Singh, A. and Diwan, H. (2021), "Does circular economy performance lead to sustainable development?—A systematic literature review", *Journal of Environmental Management*, Vol. 293, 112811, doi: [10.1016/j.jenvman.2021.112811](https://doi.org/10.1016/j.jenvman.2021.112811).
- Potsdam Institute for Climate Impact Research (2025), "Planetary Health Check 2025: Seven of nine planetary boundaries now breached – ocean acidification joins the danger zone", available at: <https://www.pik-potsdam.de/en/news/latest-news/seven-of-nine-planetary-boundaries-now-breached-2013-ocean-acidification-joins-the-danger-zone>
- Quaker United Nations Office (2021), "The circular economy and trade", (Working Paper No. 1 in TESSD Series), available at: https://quano.org/wp-content/uploads/2021/10/The-Circular-Economy-and-Trade_paper_A4_24_09.pdf
- Qureshi, A. (2022), "Sustainable ERP systems and their role in Circular Economy practices", *Journal of Cleaner Production*, Vol. 350, 131456, doi: [10.1016/j.jclepro.2022.131456](https://doi.org/10.1016/j.jclepro.2022.131456).
- Radić, A., Arsić, S., Plotnic, O. and Milošević, I. (2026), "The role of ERP systems in supporting the transition to a circular economy", *Proceedings of the 19th International Conference on Environmental Science and Technology (CEST2025)*.
- Rahman, S. (2025), *Linear economy: How it Fuels Resource Depletion & Waste*, Wellri, 24 24, available at: <https://wellri.com/linear-economy-how-it-drives-resource-depletion-waste>.
- Ratner, S.V., Lychev, A.V., Muravleva, E.D. and Muravlev, D.M. (2025a), "Measuring Circular Economy with Data Envelopment Analysis: A Systematic Literature Review", *Mathematical and Computational Applications*, Vol. 30 No. 5, p. 102, doi: [10.3390/mca30050102](https://doi.org/10.3390/mca30050102).
- Ratner, S.V., Lychev, A.V., Muravleva, E.D. and Muravlev, D.M. (2025b), "Measuring Circular Economy with Data Envelopment Analysis: A Systematic Literature Review", *Mathematical and Computational Applications*, Vol. 30 No. 5, p. 102, doi: [10.3390/mca30050102](https://doi.org/10.3390/mca30050102).
- Saha, S.K. and Saha, J. (2024), "The Transition in Economic Theory from Linear to Circular for Sustainability: A Case Study"
- Skene, K.R. and Oarga-Mulec, A. (2024), "The Circular Economy: The Butterfly Diagram, Systems Theory and the Economic Pluriverse", *Journal of Circular Economy*, Vol. 2 No. 3, doi: [10.55845/lxe9236](https://doi.org/10.55845/lxe9236).
- Sustainability Directory (2025a), "Material Circularity Rate", *Sustainability Directory*, available at: <https://lifestyle.sustainability-directory.com/term/material-circularity-rate/>
- Sustainability Directory (2025b), "Circularity performance metrics", *Sustainability Directory*, available at: <https://product.sustainability-directory.com/term/circularity-performance-metrics/>

- Umut Yuzgenc, I. and Aydemir, E. (2023), "Sustainable ERP systems: A green perspective", *In the 1st International Conference on Pioneer and Innovative Studies*, All Sciences Proceedings, pp. 533-540, available at: <https://as-proceeding.com/index.php/icpis>
- United Nations Environment Program (2024), "UNEP/EA.4/22: Environmental impacts of natural resource use [Report]", *United Nations Environment Program*, available at: https://digitallibrary.un.org/record/3978225/files/UNEP_EA.4_22-EN.pdf
- Vinante, C., Sacco, P., Orzes, G. and Borgianni, Y. (2021), "Circular Economy Metrics: Literature Review and Company-Level Classification Framework", *Journal of Cleaner Production*, Vol. 288, 125090, doi: [10.1016/j.jclepro.2020.125090](https://doi.org/10.1016/j.jclepro.2020.125090).
- Yavuz, O., Uner, M.M., Okumus, F. and Karatepe, O.M. (2023), "Industry 4.0 technologies, sustainable operations practices, and their impacts on sustainable performance", *Journal of Cleaner Production*, Vol. 387, 135951, doi: [10.1016/j.jclepro.2023.135951](https://doi.org/10.1016/j.jclepro.2023.135951).
- Yurtay, Y. (2025), "Carbon Footprint Management with Industry 4.0 Technologies and ERP Systems in Sustainable Manufacturing", *Applied Sciences*, Vol. 15 No. 1, p. 480, doi: [10.3390/app15010480](https://doi.org/10.3390/app15010480).
- Yuzgenc, I.U. and Aydemir, E. (2023), "Sustainable ERP Systems: A Green Perspective", *International Conference on Pioneer and Innovative Studies*, Vol. 1, pp. 533-538, doi: [10.59287/icpis.886](https://doi.org/10.59287/icpis.886).

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