CHALMERS
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The Role of Maintenance Towards Circular Economy

A Case Study of Maintenance Practices and Circularity Integration at An Automotive Manufacturer

Master's thesis in the master's program Quality and Operations Management

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025
www.chalmers.se

Master's thesis 2025

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Abstract

The manufacturing industry is a major contributor to global greenhouse gas emissions, yet it also holds vast potential for sustainability transitions. As circular economy (CE) principles gain traction, integrating them into established industrial frameworks presents a persistent challenge especially within Company-Specific Production Systems (XPS) and its core pillars such as Professional Maintenance (PM) which are traditionally cost-driven and exclude social and environmental perspectives of sustainability. This thesis investigates how PM can evolve into a strategic enabler of sustainability by embedding CE indicators.

Initially, a Systematic Literature Review (SLR) was conducted which identified 23 CE indicators at the micro and nano levels of manufacturing as well as common barriers and enablers to their deployment. These indicators were assessed for their measurability, data requirements, and strategic fit within PM through a structured questionnaire and semi-structured interviews with professionals across a Swedish manufacturing company.

The results showed that operational data was widely adopted at the sites, while energy, environmental and material data was significantly less adopted and more challenging for PM. Based on these insights, a parallel framework was developed that aligns the CE indicators with the existing PM maturity model. Together they capture both cost-efficiency and CE, by mapping indicators to maturity levels where data availability and implementation feasibility converge.

Having created the framework, key deployment considerations were identified in the literature and case study and then mapped against the appropriate levels in the framework. The study shows how management support and cultural readiness is important to consider initially, while more external perspectives, such as Environmental, Social, and Governance (ESG) reporting and supply chain collaborations are crucial towards higher maturity levels.

This thesis identifies CE Indicators suitable for PM, creates a CE-integrated maturity model and identifies deployment considerations. By doing so it provides an academically based, yet grounded in industry, way of integrating the CE perspective into PM.

Keywords: Circular Economy (CE), Professional Maintenance (PM), Company-Specific Production Systems (XPS), CE Indicators, Sustainability, Manufacturing, Maintenance Maturity Model, Automotive Industry, Maintenance and Sustainability framework

Acknowledgements

First, we want to express our gratitude towards our supervisors, Zeynab Allahkarami and Anderson Leal, who have guided us through what seemed like a daunting and complex task. Your availability, openness, feedback, and brainstorming were essential to this work.

Secondly, we want to highlight the contributions of the case study participants who took time out of their day to provide valuable input on maintenance contributions towards CE. This work would not be what it is without them.

Lastly, we want to spare a thought for all the friends we made, all the courses we have completed and all the long evenings we endured on our Chalmers journey.

- Måns Wikström, Axel Wreeby, May 2025

List Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

CE	Circular Economy
CE Indicator	Circular Economy Indicator
C2C	Cradle to Cradle
EoL	End Of Life
ESG	Environmental, Social, and Governance
MNE	Multinational Enterprise
PM	Professional Maintenance
SME	Small and Medium-Sized Enterprise
TQM	Total Quality Management
TPS	Toyota Production System
WCM	World Class Manufacturing
XPS	Company-Specific Production System

Contents

1 Introduction

This chapter begins by outlining the background of the study and highlighting the need for further research in the field. It then presents the aim and objectives of the study, along with the research questions guiding the investigation. Following this, the scope and limitations of the study are defined, establishing its boundaries.

1.1 Background

As global awareness of climate-related risks grows, the effects are becoming increasingly difficult to ignore. What was once a distant concern is now a defining issue of our time, with serious implications for ecosystems, economies, and societies. Rising global temperatures, more frequent extreme weather events, and long-term shifts in climate patterns have already begun disrupting essential systems like food and water supply (National Academies of et al., 2016). Without decisive action, global warming could exceed 1.5°C above pre-industrial levels, leading to significant environmental and social impacts (Allan et al., 2023).

The manufacturing industry stands out as a major contributor to climate change, accounting for 12.7% of global greenhouse gas emissions in 2021 (Ge et al., 2024). This sector consumes vast amounts of raw materials and energy, with emissions stemming from production processes, resource extraction, and global supply chains (Panagiotopoulou et al., 2022). However, the manufacturing industry also holds significant potential to drive sustainability through its global reach and influence. Research shows that Multinational Enterprises (MNEs) are responsible for nearly 30% of global CO_2-equivalent emissions (Mastrandrea et al., 2022), and given that 48% of economic activity among MNEs in EU countries stems from manufacturing (Eurostat, 2024), it is evident that industrial production plays a significant role in shaping global emission trends. Their extensive supply chains and scale make them both major contributors to environmental challenges and critical actors in sustainability transitions (Steenbergen & Saurav, 2023).

To address these challenges, the Circular Economy (CE) has emerged as a transformative framework. CE shifts from the traditional "take-make-dispose" model to systems that prioritize resource efficiency, waste reduction, and regeneration. By aligning economic activities with natural cycles, CE minimizes resource extraction, extends product lifecycles, and fosters innovation in reuse, remanufacturing, and recycling (Ellen MacArthur Foundation, 2013; Linder & Williander, 2017). Decision makers faced with this transition need to measure the outcome of the transition from linear and circular, this is done through CE Indicators (Jabbour et al., 2017). CE also has the potential to deliver social and economic benefits, including job creation in sectors like repair and recycling, and could result in a global net increase of 7 to 8 million jobs by 2030 (International Labour Organization, 2019).

Building on the critical role of manufacturing in climate change, as mentioned above, the CE provides a transformative framework to realign global production systems with sustainability goals. However, implementing CE principles (waste elimination, product circulation and nature regeneration) at scale is particularly challenging for multinational enterprises (MNEs), which must navigate diverse regulatory environments, resource disparities, and cultural differences (Anagnostakos, 2024). Frameworks like Lean manufacturing, World Class Manufacturing (WCM), and Six Sigma have historically pursued a "one-best-way" approach, focusing on improving efficiency and reducing waste, but while these universal principles have driven operational excellence, their application often falls short when addressing the unique complexities and sustainability challenges of modern global manufacturing (Netland, 2013).

To overcome these limitations, many companies began shifting in the 1990s to adopting tailored frameworks known as Company-Specific Production Systems (XPS). These systems are standardized yet adaptable, incorporating methodologies like Lean manufacturing, Total Quality Management (TQM), WCM, and Six Sigma to align operational practices with the unique strategic goals and cultural contexts of individual organizations. Unlike traditional improvement initiatives, which are often temporary and narrowly focused, XPS programs are deeply embedded within a company's culture and structure, enabling them to serve as long-term strategies for continuous improvement and operational excellence (Netland, 2013).

As Netland (2013) highlights, this shift from the "one-best-way" to an "own-best-way" approach marks a significant evolution in how MNEs address operational challenges. By focusing on tailored, holistic, and sustainable improvements, XPS frameworks provide the adaptability required to align global operations with diverse industrial needs.

Despite their adaptability, current XPS implementations often remain cost-driven, prioritizing operational efficiency and waste reduction over broader sustainability goals (Dennison et al., 2024). Barriers such as infrastructure limitations, high investment costs, and the complexity of global supply chains further hinder the widespread adoption of circular and sustainable practices (Rizos et al., 2021). While these barriers pose challenges, XPS provides a structured framework to integrate sustainability performance metrics within its key management processes. By systematically tracking resource efficiency, emissions, and lifecycle assessments, XPS can evolve beyond cost efficiency to also drive environmental and social sustainability (Brosnan, n.d). This would require expanding current XPS performance indicators beyond cost and production efficiency to include circularity metrics such as material reuse rates, energy recovery, and closed-loop supply chain integration. In the context of XPS, Professional Maintenance (PM) serves as an important tool for embedding sustainability into operational strategies. By focusing on equipment reliability, resource optimization, and lifecycle management, PM ensures that manufacturing systems operate efficiently while reducing waste and extending the lifespan of assets (Franciosi et al., 2023).

To ensure a systematic and efficient approach, PM is often implemented using structured frameworks. These frameworks provide structured methods and tools for prioritizing maintenance activities by, for instance, classifying machines based on breakdown losses, spare part costs, and criticality, ensuring that resources are allocated effectively (Leal et al., 2024). While existing approaches are effective in driving cost efficiency, their alignment with sustainability and circular principles remains limited. Despite the increasing emphasis on sustainable manufacturing, there is a lack of research on how PM can contribute to sustainability within XPS, leaving a gap in understanding its potential role in circular economy transitions. Additionally, since PM is a part of the broader XPS in place at many manufacturing companies, the cost centered design usually reflects practices within these sub areas as well, neglecting the integration of sustainability principles. Integrating CE principles into PM practices can bridge this gap, transforming maintenance strategies into key enablers of sustainability within XPS. By improving sustainability efforts through reactive, preventive, and proactive maintenance stages, PM not only supports operational excellence but also addresses the broader challenges of sustainability and circularity in manufacturing (Franciosi et al., 2023).

1.2 Aim and Objectives

The aim of this thesis is to suggest how Professional Maintenance within Company-Specific Production Systems can evolve from a cost-driven approach to one that integrates circular economy principles. Specifically, the objectives are to develop a refined framework that incorporates circular economy indicators into the existing PM maturity model at site level, collect and analyze data through a case study to assess and rank these indicators within the model, and propose practical deployment strategies for sustainability-driven maintenance practices. A case study on a Swedish automotive manufacturer will serve as a foundation for validating these approaches in a real-world setting.

The objectives of the study are three-fold:

1. **Identify** relevant circular economy indicators that align with PM by reviewing existing literature and current industry best practices.
2. **Develop** the existing PM maturity model by integrating environmental and social sustainability dimensions that can be adopted in real-world manufacturing settings.
3. **Evaluate** barriers and enablers for each level of maturity when deploying and implementing new CE initiatives within PM practices.

1.3 Research Questions

To reach the aim of this thesis, three research questions are formulated. The research questions that are to be answered in the thesis are the following:

RQ1: Which CE indicators are most widely recognized for assessing the sustainability and circularity of PM practices within XPS?

RQ2: How can CE indicators be integrated into the current maturity model for PM used at the company, and what attributes should be assessed to measure their maturity?

RQ3: What should be considered as key barriers and enablers during the deployment of sustainable and circular initiatives within PM practices?

1.4 Limitations

This study is limited by a one-semester timeframe, which influences the overall scope and restricts the generalizability of the findings. As a result, the research focuses on a single company and its multiple sites. With a longer timeframe, a cross-sectional study involving several companies could have been conducted, allowing for broader generalization and deeper insights through firmographic variation. Consequently, the findings of this thesis should not be interpreted as universally applicable but rather as an exploratory step, offering methods and strategies that can support deployment efforts and serve as a foundation for future research with a wider scope.

Another limitation of this study is the indirect connection to the case company. As external researchers, an internal contact person had to facilitate access and most communication to relevant stakeholders. While this support was very valuable for the study, it posed challenges in reaching a broader sample size and securing project participation, which may have limited the depth and breadth of data collection.

2 Theoretical Background

This chapter presents the theoretical foundation for the study by reviewing relevant concepts and frameworks from the literature on CE, CE indicators, XPS, and PM. CE is defined along with its core principles and key models for measuring the sustainability performance. For XPS, the chapter presents key concepts and relevant models that structure production systems and drive operational efficiency. In the section on PM, established frameworks and methodologies used at the company are explored to understand maintenance's role in production and sustainability. The chapter concludes by showcasing existing examples of how XPS and PM integrate CE principles to enhance sustainability in industrial contexts.

2.1 Circular Economy

The CE has gained significant attention as a sustainable economic model, offering an alternative to the traditional linear economy, which follows a take-make-dispose approach. Instead of relying on continuous resource extraction and waste generation, CE aims to close material loops by promoting reuse, remanufacturing, and recycling (Murray et al., 2017). The concept of CE has deep historical roots, tracing back to discussions in economic geography in the 1940s, where the efficient utilization of resources and waste minimization were early considerations. By the 1960s and 1970s, these ideas evolved into what became known as Industrial Ecology, integrating ecological principles into industrial systems (Ekins et al., 2020). This was highlighted by Spilhaus (1970), who emphasized the need for a planned industrial revolution that would eliminate waste by closing material loops. He argued that waste is merely a resource that has yet to be properly utilized and promoted designing products with reuse, remanufacturing, and circularity in mind, shifting responsibility from public waste management to industrial systems that mass-collect, disassemble, and repurpose materials.

The formalization of CE principles accelerated in the 1980s and 1990s, particularly with the ground breaking work of Frosch and Gallopoulos, who envisioned an industrial ecosystem where waste from one process becomes the raw material for another (Ekins et al., 2020). Their work laid the foundation for the modern understanding of industrial symbiosis (Ekins et al., 2020), a key component of CE, which refers to the collaboration between industries where by-products, waste materials, or energy from one company are used as inputs for another, reducing overall resource consumption and minimizing waste (Hossain et al., 2024).

More recently, Cradle-to-Cradle (C2C) and The Performance Economy have played a foundational role in shaping what is now recognized CE. These concepts emerged as early frameworks that challenged the traditional linear economy, laying the groundwork for many of the principles now central to CE (Ellen MacArthur Foundation, 2023). Circular systems in production were popularized through C2C concept developed by McDonough and Braungart (2010), which promotes a regenerative design philosophy, ensuring that products are created with biological and technical cycles in mind. In this model, materials are designed either to biodegrade safely (biological nutrients) or to be continuously reused in industrial systems without loss of quality (technical nutrients). Unlike conventional recycling, which often leads to downcycling and material degradation, C2C emphasizes upcycling, where waste is transformed into equal or higher-value products, minimizing resource depletion and environmental harm (Ellen MacArthur Foundation, 2023; McDonough & Braungart, 2010).

Similarly, The Performance Economy, proposed by Stahel (2010) shifts the focus from selling goods to providing services, encouraging product-life extension, remanufacturing, and shared ownership models. This approach prioritizes access over ownership, where companies retain control over products and recover them at the end of their lifecycle for reuse or refurbishment (Ellen MacArthur Foundation, 2023).

All of these former models have laid the foundation to what we today call CE. Both frameworks directly support CE's goal of closing material loops, reducing waste, and ensuring that resources remain in use for as long as possible. C2C's design philosophy aligns with CE's principles of regenerative cycles, while The Performance Economy's service-oriented approach complements CE's ambition to reduce material throughput and environmental impact. Over the last two decades, CE has evolved from a theoretical framework to a policy-driven approach, especially within China's Five-Year Plans and the European Union's Circular Economy Action Plan (European Commision, 2020; Murray et al., 2017). Often described as "*an industrial economy that is restorative and regenerative by intention and design*" CE seeks to align economic activities with nature's cycles by creating systems that reduce waste and focus on reusing and regenerating resources (Morseletto, 2020). It is now considered a key strategy for reducing resource dependency, mitigating climate change, and enhancing economic resilience (Murray et al., 2017).

The transition towards CE offers significant opportunities across all three dimensions of sustainability: economic, environmental, and social resilience. Economically, CE fosters innovation and new business models focusing on reuse, refurbishment, and remanufacturing, creating opportunities for cost savings and new revenue streams (Linder & Williander, 2017). Environmentally, CE prioritizes resource efficiency, reducing the need for raw material extraction and mitigating the impact of waste and pollution. Shifting to circular production systems in key industries, such as automotive, could lead to significant reductions in carbon emissions and resource consumption (Ellen MacArthur Foundation, 2013). Socially, CE creates opportunities for job growth in sectors such as recycling, repair, and remanufacturing. By fostering innovation in circular practices, CE not only reduces environmental degradation but also enhances community resilience by improving access to sustainable resources and goods. Transitioning to a circular model can result in a global net increase of 7 to 8 million jobs by 2030, as estimated by the International Labour Organization (2019) showcasing its potential to strengthen social and economic development.

The CE is built on three core principles that provide a foundation for sustainable production and consumption (Ellen MacArthur Foundation, 2024):

1. **Eliminate waste and pollution**
   CE aims to prevent waste and pollution by intentionally designing products and systems to be durable, reusable, and recyclable. Materials are categorized as biological nutrients, which can safely return to the environment, or technical nutrients, which are retained in production cycles.
2. **Circulate products and materials**
   This principle focuses on extending the life cycle of resources through reuse, repair, remanufacture, and recycling. By maintaining the value of materials and products, CE reduces the need for new raw material extraction and minimizes waste.
3. **Regenerate Nature**
   CE not only aims to minimize harm but also actively works to restore ecosystems. It achieves this by returning biological materials to the environment as nutrients, supporting regeneration, while using renewable energy sources to power production processes, ensuring that natural systems are enhanced rather than depleted.

These three principles are visualized through the Ellen MacArthur Foundation's butterfly diagram shown in Figure 1, which illustrates the flow of materials through two interconnected cycles: the biological cycle (left side)) and the technical cycle (right side) (Ellen MacArthur Foundation, 2019).

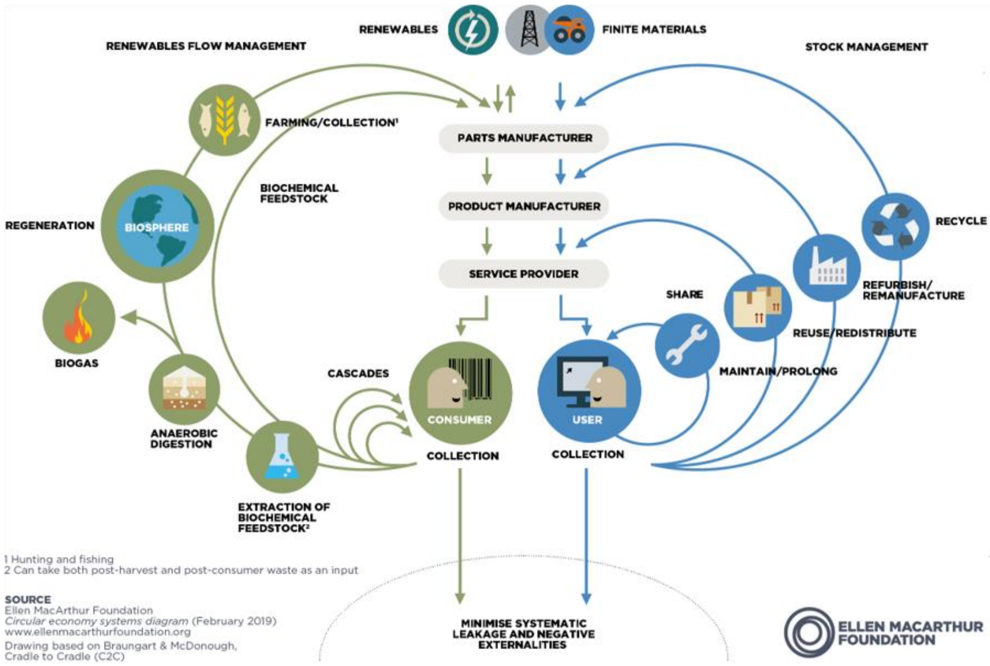

Figure 1: The butterfly diagram (Ellen MacArthur Foundation, 2019)

The technical cycle focuses on extending the life of durable goods through repair, reuse, remanufacturing, and recycling. This ensures that technical nutrients, such as metals and plastics, are preserved within the economy rather than discarded. The biological cycle addresses consumable materials, such as food and natural fibres, which are designed to safely decompose and return as nutrients to the environment, regenerating natural systems (Ellen MacArthur Foundation, 2019). The biological cycle addresses consumable materials, such as food and natural fibres, which are designed to safely decompose and return as nutrients to the environment, regenerating natural systems (Ellen MacArthur Foundation, 2019).

The technical cycle is particularly relevant in industrial and manufacturing contexts, where durable materials such as metals, plastics, and synthetic materials play a crucial role in economic and environmental sustainability. Unlike the biological cycle, which relies on natural decomposition processes, the technical cycle requires intentional strategies to maintain material value, reduce resource extraction, and limit waste (McDonough & Braungart, 2010). The technical cycle emphasizes keeping resources in use for as long as possible through four key strategies (Ellen MacArthur Foundation, 2013), where the focus for this thesis will be on the first one *(Maintenance & Repair)* (Figure 2).

Maintenance & Repair	Extends the lifespan of products by fixing or maintaining components, reducing the need for new materials. This is particularly effective in industries such as electronics, machinery, and industrial equipment, where small repairs can prevent entire systems from becoming obsolete.
Reuse & Redistribution	Involves redistributing products still in usable condition through resale, leasing, or second-hand markets. Common in sectors like furniture, electronics, and tools, this strategy minimizes waste and reduces demand for virgin resources.
Refurbishment & Remanufacturing	Refurbishment restores used products to working condition, while remanufacturing rebuilds them to an as-new state, often with updated features. These processes, widely used in industries like automotive and electronics, significantly reduce material and energy consumption.
Recycling	Processes end-of-life products to recover valuable materials like metals and plastics. Recycling reduces waste and dependence on raw material extraction while maintaining material quality through circular strategies that avoid downcycling.

Figure 2: The four key strategies of the technical cycle (Ellen MacArthur Foundation, 2019)

2.1.2 Circular Economy Indicators

As CE continues to gain traction as a sustainable alternative to the linear economic model, the challenge lies in effectively measuring its implementation and impact (Kulakovskaya et al., 2023). To integrate CE principles into business operations, it is essential to establish measurable performance indicators that assess circularity and sustainability (Mayer et al., 2019; Moraga et al., 2019). CE indicators serve as tools for evaluating how well materials, products, and resources are kept in circulation while minimizing waste and resource depletion. Similar to commonly used KPI's in businesses, they provide a structured approach for tracking the effectiveness of circular strategies, helping businesses, policymakers, and researchers align operations with sustainability objectives (Rossi et al., 2020).

CE indicators are typically assessed using quantitative and qualitative methods, depending on the type of data they rely on and the specific aspect of circularity they measure (Valls-Val et al., 2022). Quantitative indicators use numerical data to provide measurable insights, such as resource efficiency rates, waste reduction percentages, or the proportion of recycled materials in a product. These indicators allow for precise tracking of circular performance over time and facilitate comparisons across industries and sectors. Qualitative indicators, on the other hand, assess more subjective aspects of circularity, such as stakeholder engagement, policy effectiveness, decision making, or consumer behaviour (Kowalski et al., 2023). While harder to standardize and measure, qualitative indicators provide essential context for understanding the broader systemic effects of circular economy initiatives (Waas et al., 2014).

Beyond their classification as quantitative or qualitative, CE indicators can be applied in different scales, including guidelines, tools, indicators, and metrics. Guidelines provide overarching frameworks and principles for implementing circular economy strategies, offering recommendations for best practices rather than specific measurement criteria. Tools serve as structured methodologies, such as lifecycle assessment (LCA) models or circularity calculators, that help businesses and policymakers apply circular principles in decision-making (Valls-Val et al., 2022). At the core of CE measurement are indicators themselves, representing high-level measurement points, signalling a specific trend or performance in circularity (Saidani et al., 2019). At the lowest level are metrics, which as described by Vinante et al. (2021), are measurable quantities and data points used to track the CE indicators over time. However, according to Rocchi et al. (2021), there is a lack of consensus when assessing CE strategies, specifically at the product or company level, due to the large number of metrics/indicators/tools that exist and there is a great need for standardised procedures to achieve it.

CE indicators are commonly categorized into three dimensions: environmental, economic, and social, which align with the three pillars of sustainability (Mesa et al., 2018). Environmental indicators measure resource efficiency, waste reduction, and energy consumption, highlighting the ecological impact of circular strategies. Economic indicators focus on financial performance, including cost savings, revenue generation from circular business models, and improvements in resource productivity. Social indicators assess the broader societal effects of CE practices, such as job creation, stakeholder engagement, and consumer acceptance of circular products (Mesa et al., 2018).

CE indicators can be assessed at different levels, reflecting the scale at which circularity is measured and the actors involved. Understanding these levels is crucial for selecting appropriate indicators that align with specific sustainability goals and business strategies (WBCSD, 2018). Each level provides distinctive insights, ranging from material properties to national-level circular performance. Indicators can be assessed at four levels which is illustrated in Figure 3. (Saidani et al., 2017), each offering insights at different scales (WBCSD, 2018).

Nano-level indicators assess individual materials, components, and processes, focusing on recyclability, biodegradability, and energy intensity. Micro-level indicators evaluate circularity at the product, company, or consumer level, measuring product longevity, repairability, and resource efficiency. Meso-level indicators examine circularity within industrial networks, assessing waste exchange and resource loops. Macro-level indicators track national and global circular performance, including recycling rates, material consumption, and policy impact (Kulakovskaya et al., 2023; WBCSD, 2018).

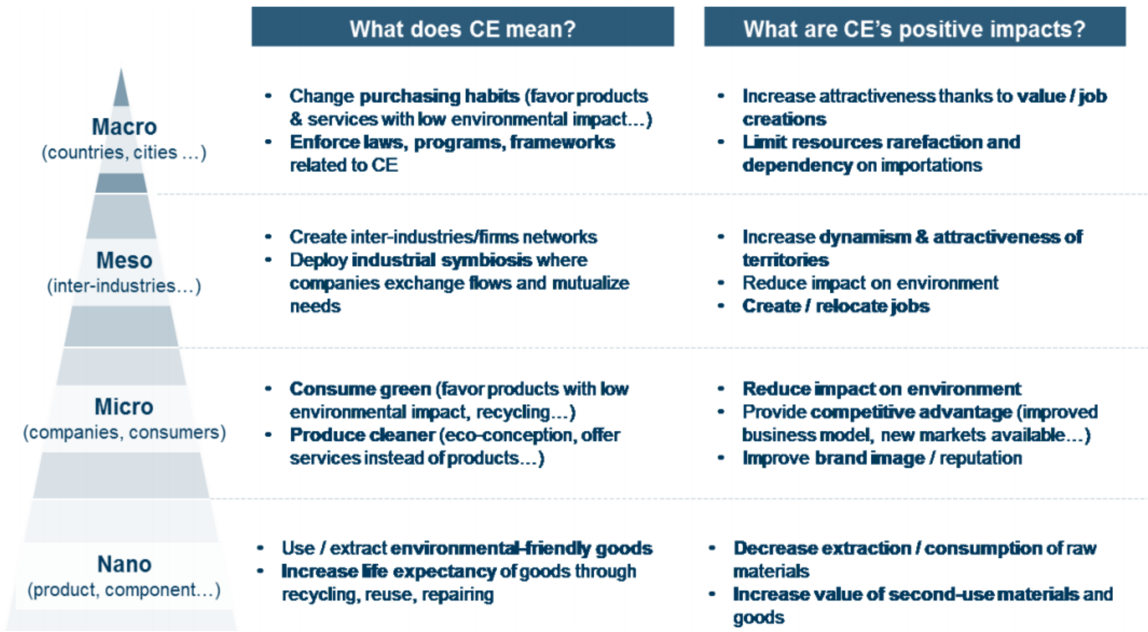

Figure 3: The four levels of CE indicators (WBCSD, 2018)

Given their focus on material efficiency and product longevity, the nano and micro levels are particularly relevant in industrial settings where PM plays an important role in extending the lifespan of components and optimizing resource use.

The implementation of CE indicators faces challenges related to data availability, standardization, and practical application. Many indicators and tools require detailed LCA and material flow analysis (MFA), but research show that companies often lack consistent and precise data about resources, products, and processes (Bianchini et al., 2019). Additionally, the absence of standardized methodologies makes cross-sector comparisons difficult, limiting the ability to track progress at an industry-wide scale (WEF, 2024). While these challenges present barriers, they also highlight the need for continued refinement and standardization of CE indicators. As businesses and policymakers increasingly prioritize circular strategies, improving data collection, aligning methodologies, and developing more actionable metrics will be crucial in ensuring CE indicators drive meaningful change (Muradin & Foltynowicz, 2019).

2.2 Company Specific Production Systems

The continuous effort of production companies to improve their operations in a systematic and cohesive way is nothing new. Taylor (1911) introduced the concept of scientific management, and among it, the idea of shop management and the scientific and systematic way for the pursuit of best practice on the shop floor. Yin et al. (2018) describe these concepts as being fundamental in Henry Ford’s creation of the assembly line and Taiichi Ohno’s development of the Toyota Production System (TPS). Taylor’s scientific management, Henry Ford’s innovative assembly line and the development of the TPS, showed a fundamental change in conviction, now there was a singular best way of organizing production practices (Netland, 2013) and those best practices should be shared throughout the company by the creation of a company specific production system (XPS) (Voss, 1995).

The success of the TPS created ripples across the worlds manufacturing companies and academics flooded to study the phenomena that would later coin the concepts of lean manufacturing and World Class Manufacturing (WCM) which became central for XPS (Flynn et al., 1997; Schonberger, 2008).

The ten interconnected pillars of the WCM can be seen in Figure 4, Pałucha (2012) presents how these pillars together build WCM and company specific production systems.

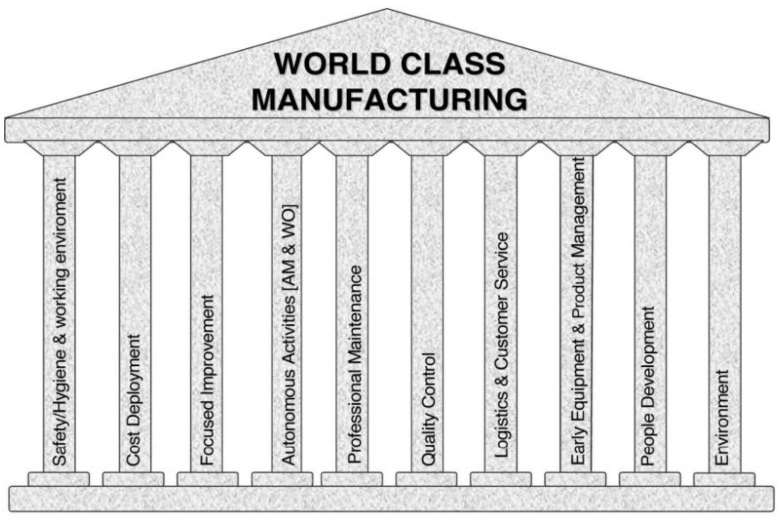

Figure 4: The ten pillars of WCM (Pałucha, 2012)

2.3 Professional Maintenance

A well-designed production system is only as effective as the reliability of the equipment it depends on (Lee & Ebrahimpour, 1984). As manufacturing methodologies have evolved and companies adopted lean and WCM practices, maintenance strategies have also had to develop in parallel to meet rising efficiency demands (Leal et al., 2024). In this context, PM has emerged as a structured approach for ensuring equipment longevity and reliability, progressing from reactive to preventive, predictive, and ultimately proactive practices. At the case company, PM is implemented through two interconnected layers: a seven-step model that guides technical development at the machine level, and a five-level maturity model that assesses site-level progress based on how broadly and deeply PM has been deployed across operations (Leal et al., 2024). At the machine level, the seven-step approach provides a clear path from reactive to proactive maintenance (see Figure 5):

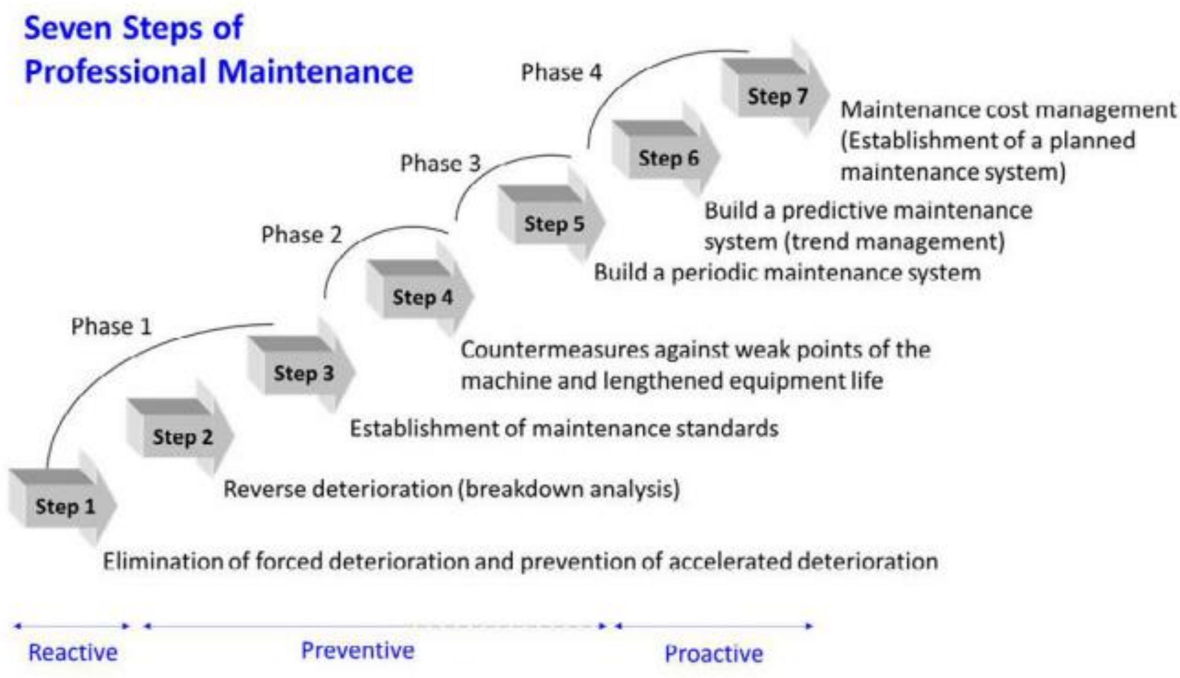

Figure 5: The seven-step approach to PM (Leal et al., 2024)

Steps 1–3 focus on restoring equipment to its original condition, eliminating forced deterioration, and establishing preventive maintenance standards.

Steps 4–5 introduce structured corrective measures and time-based maintenance routines to extend machine life.

Steps 6–7 shift to predictive and cost-controlled maintenance, supported by tools like trend analysis and computerized systems.

To guide implementation, machines are classified by criticality (AA, A, B, C), and a model machine is typically selected to apply and refine the seven-step method before scaling it to other areas.

At the site level, PM maturity is assessed across five levels, ranging from Level 0 (no implementation) to Level 5 (full deployment and integration). These levels reflect how widely and effectively the 7 steps have been applied across machines and areas. The levels are determined by factors such as the percentage of machines covered, the progression of those machines through the steps, and integration with supporting systems like spare parts management, visual control, and preventive planning (Leal et al., 2024).

3 Methodology

This chapter outlines the methodology used to assess the applicability of CE Indicators within PM at the case company. The chapter begins by identifying relevant CE indicators using a literature review, it then introduces the case study and the concurrent mixed method approach. It proceeds to describe how the results from the case study are used to; evaluate CE indicator relevance for PM, create the framework model for PM and identify key enablers and barriers to deploying the framework at the case company. Lastly, research quality and ethical consideration in this thesis are discussed.

3.1 Project Method Overview

This thesis combines a systematic literature review (SLR) with a case study conducted at the company, utilizing a mixed methods research design. The methodology is designed to explore how CE indicators can be integrated into PM. The SLR forms the theoretical foundation of the study, applying a structured search in Scopus to identify relevant CE indicators, barriers, enablers, trends, and the current state of CE implementation in manufacturing. These insights provide a replicable and transparent knowledge base, which later guide the design of the case study. The overall thesis methodology is visually represented in Figure 6, which illustrates how the SLR and case study work in parallel to address the study's three research questions (RQ1–RQ3).

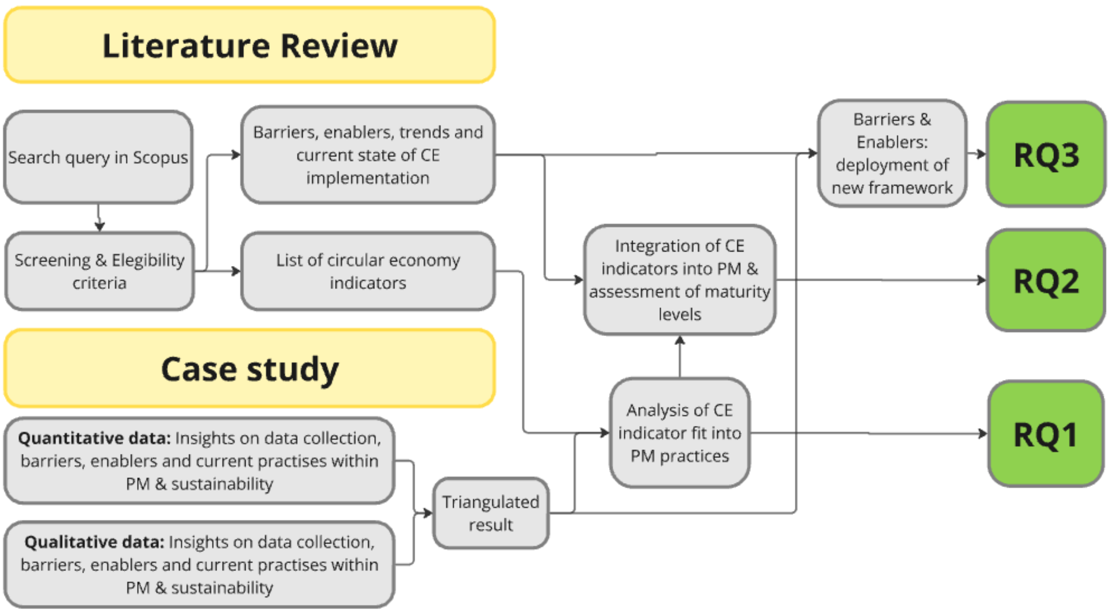

Figure 6: Overview of thesis methodology

The SLR forms the theoretical basis and selection of CE indicators, while the case study provides empirical insights and operationalizes these indicators in the context of PM within XPS. The case study applies a concurrent mixed-method approach, combining qualitative data from interviews and quantitative data from a structured questionnaire. The case study is conducted in collaboration with a major Swedish automotive company, where the company-established seven-step (machine classification), and five-level (site or hall classification) maturity model for PM is used as a foundation for analysis and further development. By aligning selected CE indicators with this model, the study aims to propose an extended maturity framework that brings a sustainability and circularity perspective into current cost-driven PM practices (Figure 7).

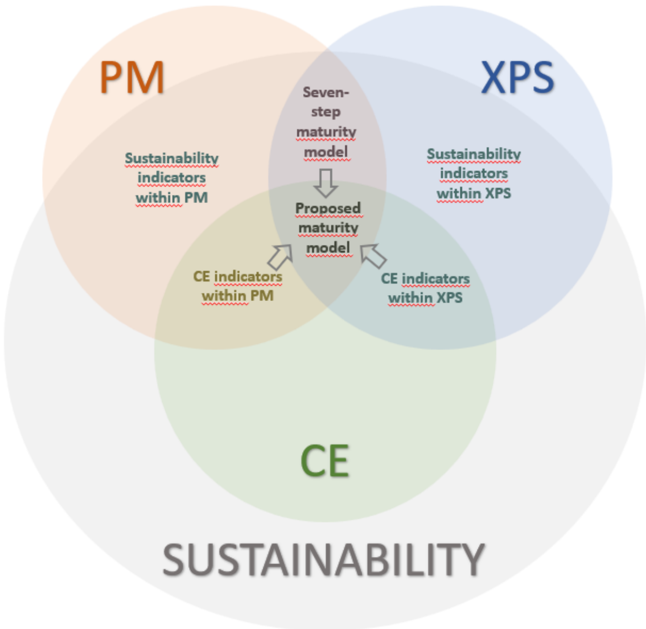

Figure 7: Conceptual model linking sustainability and circular economy indicators within PM and XPS to the proposed maturity model.

3.2 Literature Review

Since the literature serves as the foundation upon which new concepts are developed, a Systematic Literature Review (SLR) is the chosen methodological approach. As described by Bell et al. (2022), an SLR emphasizes thoroughness, reproducibility, and transparency by systematically documenting the review process, ensuring that each step, from literature identification to data synthesis, is clearly defined and replicable. A key advantage of the systematic review approach is its emphasis on clear and repeatable procedures, which strengthens the reliability of the conclusions drawn. The structured nature of SLRs ensures that relevant studies are identified using explicit inclusion and exclusion criteria, thereby reducing the risk of selection bias. Additionally, SLRs allow for a more comprehensive representation of research areas, as they ensure that all relevant keywords and subject domains are covered in the search process. This approach not only facilitates a holistic understanding of the field but also enhances the credibility of the findings by making the entire review process transparent and replicable (Lamé, 2019). To achieve methodological rigor, this thesis follows the step-by-step procedure outlined in Figure 8 by Bell et al. (2022). Additionally, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework is applied to document the article selection process, providing a clear overview of how studies were identified, screened, and included in the final dataset.

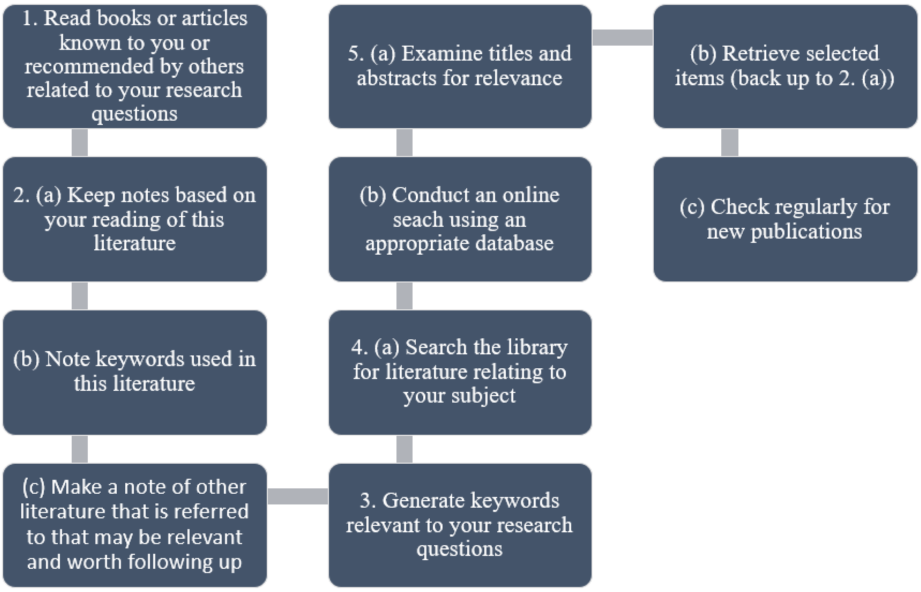

Figure 8: Systematic literature review methodology (Bell et al., 2022)

3.2.1 Identification of Articles

The first step in the literature review was to develop a set of keywords for the database search. To create a precise and thorough search strategy, an initial list of keywords was compiled by reviewing earlier collected literature from the Theoretical Background chapter on CE indicators. This involved analyzing research to identify commonly used terms related to CE performance measurement. By examining the language used in this literature, a carefully selected list of search terms was created to ensure the Scopus search would retrieve a broad yet relevant set of articles. Scopus was chosen as the academic database for this literature review, as it is the largest indexer of global research content (Lee et al., 2021).

The process of identifying keywords was iterative, starting with terms found in key articles that focused on CE indicators, specifically those related to performance measurement at the micro or nano level. The selection of terms was guided by the study's focus on measurable indicators rather than general conceptual discussions. To ensure no relevant studies were overlooked, the search string included variations of terms, synonyms, and alternative phrasings beyond the standard terminology used in the field. This approach helped capture a wider range of relevant literature while maintaining the precision needed for a systematic review. The search queries are presented in Table 1.

Table 1: Search query for the SLR

Search term	Language	Publication year	Data base
("circular economy" OR "circular") AND ("indicator*" OR "performance" OR "metric*" OR "c-indicator*" OR "circularity indicator*") AND ("micro level" OR "nano level" OR "micro-level" OR "nano-level")*	English	All years	Scopus

The result from the search gave 96 articles in Scopus. The search was performed on the 19th of February 2025.

3.2.2 Screening of Articles

To ensure that only the most relevant and high-quality studies were included in the systematic review, a screening process was applied to the 96 initially retrieved articles. The screening criteria were designed to refine the dataset by focusing on recent publications and studies explicitly addressing the micro or nano level of CE performance measurement. The first filtering step was conducted directly in Scopus, where the publication year was restricted to 2019 and later to ensure that only recent literature reflecting the latest developments in the field was considered.

Following this, a keyword-based filtering process was applied to assess whether each article focused on micro or nano indicators. Instead of relying solely on mentions in the title or abstract, only articles that explicitly included "micro" or "nano" in their list of keywords were retained. This ensured that the studies were primarily concerned with these levels of analysis rather than only making brief references. The result of this process was a refined set of 28 articles, and the screening criteria for article inclusion in this stage is shown in Table 2.

Table 2: Screening criteria for inclusion in SLR

Screening criteria	Motivation
Publication year between 2019 - 2025	In order to get the most recent literature on the topic area
Literature must have "micro" or "nano" as defined keyword	Macro and meso indicators not relevant for thesis

3.2.3 Eligibility of Articles

After the initial screening process, a set of eligibility criteria was applied to further refine the selection of articles included in the SLR. These criteria ensured that the final dataset contained only studies that were directly relevant to the thesis research and that they were academically rigorous. The eligibility criteria were developed to maintain consistency in data collection and analysis, ensuring that only high-quality sources contributed to the identification of CE indicators at the micro and nano levels.

A key requirement for inclusion was that articles had to explicitly mention specific CE indicators rather than broadly discussing CE principles. The goal of the systematic review was to compile a structured list of indicators, making it essential that each selected study provided measurable or methodological insights into indicator application. Additionally, articles had to be situated within a relevant field of research or industrial operation, ensuring that the collected indicators were applicable to the manufacturing sector. Studies that focused on unrelated sectors like health care, universities, municipalities, or provided only theoretical overviews without practical applications were excluded.

To ensure consistency in language and accessibility, only articles written in English were considered. This criterion was necessary to standardize data collection, preventing potential misinterpretations due to language barriers. Furthermore, to maintain academic rigor, only journal articles and conference papers that were peer-reviewed were included in the final dataset. Industry reports and non-peer-reviewed articles were excluded to ensure that the research was based on well-established and critically evaluated studies. The eligibility criteria applied in this stage were inspired by the systematic review methodology outlined by Shaheen et al. (2023). However, the criteria were adapted to fit the specific requirements of this research field, ensuring relevance to the manufacturing sector and CE performance measurement. After applying these eligibility criteria, a final list of 20 articles remained for data collection and analysis. The full eligibility criteria can be found in Table 3.

Table 3: Eligibility criteria for literature inclusion in SLR

Eligibility criteria	Motivation
The literature has to mention specific CE indicators	The goal of the SLR is to have a list of CE indicators
The literature has to be in a relevant field of research or operation	CE indicators collected has to be relevant within manufacturing
The literature has to be written in English	To ensure consistency in data extraction and analysis
Journal articles or conference papers has to be peer-reviewed	To ensure consistency and academic rigor

The literature inclusion process for this systematic literature review followed the PRISMA framework to ensure transparency and reproducibility. The PRISMA flowchart is represented in Figure 9, and it outlines the different stages of the review, including identification, screening, eligibility assessment, and final inclusion. The chart provides a structured overview of how the initial articles retrieved were systematically filtered based on predefined criteria, resulting in a final dataset of studies used for analysis (Page et al., 2021).

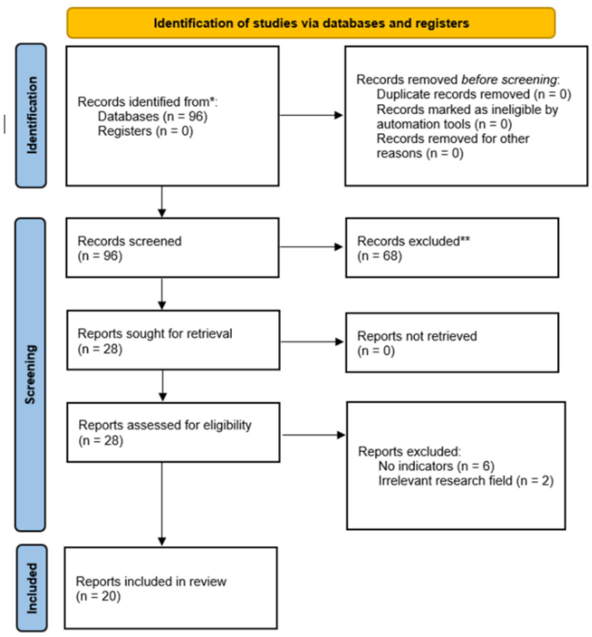

Figure 9: PRISMA procedure of literature review

3.2.4 Screening of CE Indicators

After extracting a long list totalling 488 CE indicators from the 20 documents in the literature review, a structured analysis was conducted to group and refine the indicators to later be able to identify the most relevant ones for further use in this thesis. Given the large number of indicators, a text-matching analysis was performed using the built in Excel Power Query tool, which allowed for identification of duplicates and systematic grouping of indicators with similar wording and meaning. All 488 extracted CE indicators and their corresponding literature can be found in Appendix C.

To ensure accurate grouping, a matching parameter was empirically tested to determine the most effective similarity threshold. Through iterative adjustments, a threshold of 75% (0.75) was found to provide the best balance between grouping similar indicators and avoiding incorrect matches. This automated grouping process helped merge closely related indicators, reducing the complexity of the dataset. However, as automated text-matching can introduce errors, a manual review was conducted afterward to improve the accuracy of the grouping. By applying the text matching in Excel Power Query tool, the initial 488 CE indicators from the Excel long list were sorted in a total of 268 specific groups.

To further refine the dataset, an academic validation screening criterion was applied to ensure that only indicators with strong support in the literature were kept. Each of the 268 grouped indicators was assessed based on the number of mapped occurrences in the reviewed studies. A minimum threshold of three occurrences per group was set, meaning that only indicators appearing in at least three instances were considered valid (Table 4). If an indicator group met this requirement, it was approved for further analysis.

Table 4: CE Indicator screening criteria

Screening criteria	Description	Motivation
Academic Validation (N>=3)	*The indicator must be documented a minimum of 3 times in the reviewed literature.*	*Enhances credibility and reliability of the indicator.*

Applying these criteria filtered the dataset from 268 to 37 distinct indicator groups, significantly reducing the total number of indicators while preserving those with strong academic backing. These 37 indicators accounted for a total of 194 mapped occurrences in the literature, showing their strong presence in the reviewed literature. This step ensured that only well-documented and widely recognized indicators progressed to the next phase of the study, improving the reliability and relevance of the final CE indicator selection.

3.2.5 Eligibility of CE Indicators

Inspiration for the development of eligibility criteria was drawn from Syu et al. (2022), who established a set of structured selection criteria for assessing the usability and usefulness of circularity indicators in manufacturing. Their approach relied on a predefined set of screening parameters to ensure that the indicators were both relevant and applicable in an industrial context. These criteria, as outlined in Table 5, focused on factors such as measurability, ease of use, data availability, and strategic relevance.

Table 5: List of usability and usefulness criteria used to assess the micro-level indicators (superscript annotation: [1] usability; [2] usefulness) (Syu et al., 2022).

Criterion	Description
Measurability[1,2]	Can be measured or quantified
Ease of use[1]	Without high costs and time-consuming procedures
Ease of understanding[1,2]	No or little prior knowledge required to calculate and use the indicator
Data availability[1]	Data required readily available or prepared easily
Strategic relevance[2]	In accordance with the company's mission
Validity[2]	Correctly represents the system being assessed
Reliability[2]	Gives accurate and consistent values
Transparency[1,2]	Possibility of third-party verification
Generalisability[2]	Interpretation independent of industry and product
Simplicity[1,2]	Low dimensionality, few indicators or single index
Compatibility[1,2]	Standardised, compatible with other methods
Information sharing[1,2]	Non-sensitive information to enable open exchange with stakeholders
Evolvability[1,2]	Possible to update and meet evolving requirements

This approach provided a solid criteria foundation, but to streamline the selection process, the criteria were adjusted to better align with the specific objectives of this study. The modifications aimed to make the process more efficient by focusing primarily on measurable CE indicators, ensuring their direct applicability to the manufacturing sector, and reducing the reliance on highly detailed usability and usefulness assessments. The final set of eligibility criteria applied in this study is summarized in Table 6.

Table 6: Eligibility criteria used for final screening of CE indicators

Screening criteria	Rank	Description
Measurability	*1*	The indicator must be based on quantifiable data.
Data Consistency & Quality	*2*	The mapped indicator group must have uniform naming and structured data.
Integration Feasibility	*3*	Must not be too complicated or advanced to fit into industrial workflows.
Decision-Making Support	*4*	The indicator must provide actionable insights for decision-making.
Cross-Industry Consistency	*5*	The indicator must be applicable across different manufacturing sectors.
Practical Applicability	*6*	The indicator must be relevant for real-world industrial use.
Clear Definition & Calculation	*7*	The indicator must have a defined calculation method and definition.

To enhance methodological consistency and accuracy, backward snowballing was employed to trace each indicator's original source, which ensured the inclusion of its foundational definition, data requirements, and application context. The set of 37 indicator groups were in this last stage screened down to a final list of 23 remaining different indicators to be further analysed in the thesis project.

3.3 Case Study

Following the identification of academically recognized and relevant CE indicators through the literature review, this study applied a concurrent mixed-method case study in collaboration with the company. The aim of the case study was twofold: first, to operationalize and align selected CE indicators with PM practices, and the existing maintenance maturity model used within XPS; and second, to contrast or validate the current trends, barriers, and enablers of CE implementation identified in the literature. The case study bridged the academic world of CE with qualitative and quantitative insights gathered from the real-world industrial settings. The outcome of this case study is a set of practical considerations for integrating CE perspectives into PM practices within an actual manufacturing environment.

With the purpose of bridging the gap between research and industry as well as CE and PM, a mixed-method approach enabled this thesis to combine quantitative and qualitative methodologies into a single analysis in order to take advantage of the strengths of each while offsetting their respective weaknesses (Johnson & Onwuegbuzie, 2004). This study employed a closed-end questionnaire as the quantitative data method which provided breadth and generalizability, while semi-structured interviews enabled the capture of qualitative data to bring depth and context, see Figure 10. Due to their complementary nature, using both types of data brings greater certainty and a wider context to the findings (Dawadi et al., 2021).

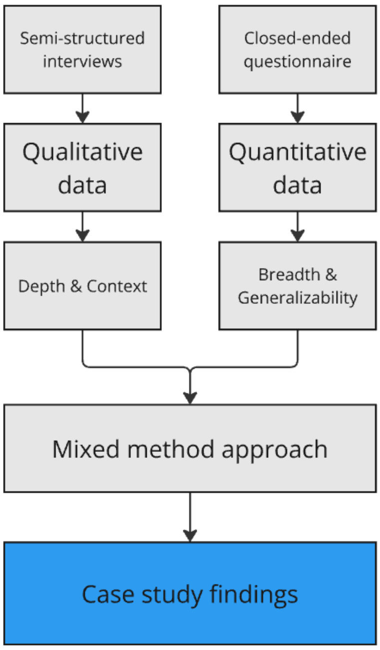

Figure 10: Visual representation of case study methodology

The wider findings were achieved by the quantitative findings capturing patterns and variable relationships, while the qualitative findings helped interpret the findings and put them in meaningful context (Creswell, 2003). The complementary nature of a mixed method approach is not the only advantage. The incorporation of both methods enabled this study to take advantage of triangulation, the usage of multiple sources in order to verify the results and thus create stronger conclusions (Carter et al., 2014). A consequence of triangulation is that the credibility of the result gets enhanced as the results of one method confirming, contradicting, explaining the results of the other and wise versa. The mixed method approach enabled this study to better capture a complex information that neither method would have captured entirely on its own (Poth & Munce, 2020).

While the mixed-method approach enabled a comprehensive understanding through both quantitative and qualitative insights, its success depended on a well-considered sampling strategy. As noted by Onwuegbuzie and Collins (2007), the choice of sampling in mixed-method research depends on the intended type of inference. Since this study aims to explore and understand a specific phenomenon, rather than generalize to a larger population, participants were purposefully selected to provide relevant and meaningful insights.

Following the parallel design described by Collins et al. (2006), this study employed different samples from the same population for the qualitative and quantitative components. This allowed the qualitative interviews to explore depth, while the quantitative questionnaire reached a broader range of respondents. Furthermore, to support this parallel design, the study used stratified purposeful sampling as proposed by Collins et al. (2006). This approach divided the population into professional subgroups and purposefully selected participants from each, ensuring consistency across data sources. This method also facilitated triangulation and comparability between datasets, strengthening the study's overall validity.

3.3.1 Interview Methodology

Semi-structured interviews were used as the qualitative component in the concurrent mixed methods approach applied in this study and a total of five were carried out. The purpose was to provide contextual depth and support the interpretation of the quantitative findings. The interviews were designed to explore how CE indicators align with PM practices, to inform the development of the maturity-based CE framework, and to complement the deployment consideration themes in terms of barriers and enablers identified in the literature review.

A semi-structured interview was chosen because it enabled this study to have a distinct list of questions to be addressed, however, while still enabling the researchers to be alert and flexible enough to switch the order around. Semi-structured interviews stress open-ended questions with the interviewee elaborating when needed (Denscombe, 2017). The full open-ended interview questions guide can be found in Appendix B. The interview questions were primarily informed by insights from the systematic literature review, allowing for exploration of current academic perspectives on CE indicators, implementation trends, and contextual challenges.

The interviews were be carried out through Microsoft Teams and was be recorded by video, enabling the generation of automatic transcripts which later gone over by the researchers with the video in parallel. The recording of the videos went hand in hand with (Bell et al., 2022) who stress that open questions require the capturing of as much detail and nuance as possible for future analysis due to the lack of standardisation.

The transcripts of the interviews in this part was be subject to a thematic analysis, according to the six step method by Kiger and Varpio (2020) which is a method for qualitative data analysis with the practical meaning of scanning cross the collected data sets to identify, analyse and collect repeated patterns. It is a method which is described as an excellent method for the understanding of experiences, thoughts and behaviours over entire data sets (Kiger & Varpio, 2020).

3.3.2 Questionnaire Methodology

To collect quantitative data in the concurrent mixed-method design, this study developed a self-administered questionnaire in Microsoft Forms and received a total of 27 responses. The primary objective was to gain structured insights into how CE–related data is collected and managed at the site level, and to identify perceived barriers and enablers to implementing CE indicators within current PM practices. The questionnaire was designed using primarily closed-ended questions with 5-point Likert scale items that are used to measure opinions or attitudes and offer standardization, enabling efficient and consistent data analysis (Bell et al., 2022; Joshi et al., 2015; Santos et al., 1999). One open-ended question was included at the end to enable the respondents to describe freely, to gain some qualitative insights and let respondents add new perspectives and information that else could have been missed by a closed-ended question.

The response alternatives in the questionnaire were largely based on findings from the systematic literature review, ensuring alignment with current academic knowledge on CE indicators, implementation trends, and contextual challenges. In the questionnaire, both "Other (please specify)" and "Don't know/Prefer not to answer" response options were included where appropriate to improve response accuracy and reflect the range of respondent knowledge and perspectives. These options can help reduce forced or invalid answers and are recommended in survey design to capture non-attitudes and unanticipated views (Krosnick, 2018).

To support depth and data accuracy in the analysis, a series of control questions were included, covering their professional role, years of experience, and self-assessed familiarity with CE and PM. These control variables allowed the responses to be segmented, making it possible to observe how views on data availability or implementation challenges differ across organizational functions, for example, between maintenance personnel and sustainability managers.

The assessment of barriers and enablers was a central component of the questionnaire. Respondents were asked to rate their agreement with statements derived from literature on common obstacles (e.g., lack of data access, resource constraints, lack of knowledge) and potential enablers (e.g., management support, digital infrastructure, training availability). This helped identify where gaps or strengths exist in the organization's readiness to adopt circular practices. To ensure neutrality and avoid response bias, all questions were phrased using balanced and non-leading language, following guidance from Bhandari (2023, June 22). For example, evaluative statements were framed using neutral formulations such as "Indicate your level of agreement with the following statement," avoiding assumptions or persuasive wording.

The questionnaire was distributed digitally via Microsoft Forms to a stratified purposeful sample of professionals within the company, including technicians, engineers, managers, and directors. This strategy follows the sampling principles outlined by Collins et al. (2006), enabling consistency across subgroups and supporting data triangulation with qualitative results. The full questionnaire is provided in Appendix C.

The questionnaire responses were exported to Microsoft Excel, where descriptive comparisons and analysis were conducted based on the control variables (e.g., role, experience, CE/PM knowledge). Results were visualized through charts and diagrams to support interpretation and identify patterns related to process and product data collection, barriers, enablers, and perceived maintenance maturity. These findings collected from the questionnaire formed the basis to the later synthesis and framework development in the thesis project.

3.3.3 Framework Construction and Deployment Mapping

All CE indicators identified through the structured literature review had already been screened using the eligibility criteria described in Chapter 3. From this filtered set, each indicator was reviewed and discussed in relation to its usefulness within PM, drawing on insights from the case study. The evaluation focused on how well each indicator aligned with current PM practices, challenges, and priorities. Special attention was given to whether the indicators could support decision-making, be automated, and be clearly understood by the organization. Based on this assessment, 16 CE indicators were considered relevant and practically applicable within a PM context. These indicators formed the basis for the continued analysis in the framework.

The core developed framework was built using a quantitative analysis of two variables collected for each type of data: how widely the data is currently used (adoption rate) and how difficult it is perceived to be to collect and analyze (difficulty rating). This analysis provided the foundation for the framework. Each data type was plotted on a two-axis graph, with adoption rate on the x-axis and perceived difficulty on the y-axis. This created a visual pattern where the data points tended to follow a gradient, from data that is easy to work with and already widely used, to data that is more complex and less commonly used. The logic behind this is that easier and more accessible data is usually found in organizations with lower maintenance maturity, while more advanced data typically appears in more mature environments.

To make sense of this pattern, a trendline was added to the plot. The trendline was meant to help guide how the data could be divided into five levels that reflect increasing maturity in PM. Thresholds were then drawn along this trendline to group the data into five categories. Each category represents one maturity level, from foundational to strategic levels. The placement of these boundaries was done with two main goals:

Clustered grouping: Data points within each level should be close to each other and along the trendline to form a natural cluster.

Logical content: Similar types of data types (like reuse rates and recycling rates) should belong to the same maturity level as much as possible, to keep each group meaningful and clear.

After the data was grouped into five maturity levels, CE indicators were linked to each level based on their data requirements. The CE indicators identified through the structured literature review are listed in Appendix D, where each one includes a definition, required input data, and, in some cases, a calculation method. Using this information, each CE indicator was mapped to the maturity level where the necessary data was available. This mapping ensured that the recommended CE indicators were realistically achievable based on a company's current data capabilities.

To capture deployment-related barriers and enablers, a dedicated section was included in the questionnaire using a mix of Likert scale and open-ended questions. These were designed to explore which factors were perceived as most important for enabling or hindering the implementation of CE-related practices. Similar questions were also addressed during the interviews to provide further context and depth.

After collecting all responses, interview insights were used to identify qualitative factors that could indicate maturity beyond data availability or PM practices. Two factors stood out as particularly relevant: familiarity with circular economy concepts and the degree of cross functional collaboration. Based on this, deployment considerations were segmented along four perspectives: data readiness, PM maturity, CE familiarity, and cross functional collaboration. These four perspectives formed the basis for the analysis presented in Chapter 6.3. For integration into the framework, the segmentation based on PM maturity was used to assign each barrier and enabler to either low, mid, or high maturity. This allowed deployment-related factors to be connected to different stages of maturity in the final framework in Chapter 6.4.

3.4 Research Quality

When describing the quality criteria in business research, Bell et al. (2022) provides three important criteria for evaluation, reliability, replicability, and validity. Reliability, being concerned with the repeatability of the results, are the measurement systems consistent throughout the research. Reliability concerns are expressed by Bell et al. (2022) regarding characteristics of the interviewers and respondents behaving differently depending on the person, and to mitigate this both researchers will be present at the same time. Another reliability concern is brought up by Bell et al. (2022) when it comes to literature reviews and how the structured literature review with its stress on transparency, came about as a result of a long history of limited visibility, choosing to do a structured literature review is how this thesis aims to address this concern. The structured literature review also helps with replicability which is concerned with how replicable the results are by other researchers. The chosen method for research question one and three, the structured literature review, provides good replicability whilst the case study nature of the third question leaves more to be desired as a case study examines a particular phenomenon, context in a singular point in time (Bell et al., 2022). Last of the quality criteria is validity, validity regards the degree of integrity of the statements and conclusions drawn in the research. A difference between internal, concerns of causality between variables, and external validity, generalizability of the findings, is introduced by Bell et al. (2022) which has a divided impact on this thesis as research questions one and three utilize a literature review and thus cross-sectional in nature whilst it is combined with a case study in the second and third.

3.5 Research Ethics

When planning to conduct research, ethical aspects have an important role right from the start. Bell et al. (2022) describes four ethical principles in business research which include: (1) Harm to participants, (2) Lack of informed consent, (3) Invasion of privacy, (4) Involvement of deception. Regarding harm to participants, researchers must ensure that respondents are not in any way affected because of their participation in the research. On informed consent, it is described as informing the participants sufficiently such as they can make an informed decision about participating in the research or not. Invasion of privacy is described as the intrusion into participant's personal space and gathering too much information. Lastly, the prevention of deception is described as moral and not pursuing self-interest in the conduction of the research (Bell et al., 2022). These considerations have been included in the planning, carrying out and analysis of the data collection throughout the whole thesis by creation of a data consent form.

4 Literature Review

This chapter presents the findings from the literature review on CE Indicators. The chapter first details the results and characteristics of the literature review and the selection process that led to the identification of the final indicators chosen for further development in this thesis. It then explores the current usage and trends regarding CE Indicators in the literature, followed by an analysis of the key barriers and challenges hindering their implementation. This chapter also identifies potential enablers that could support the adoption of CE indicators. Lastly, the remaining CE indicators, their description, their type and original article, if applicable, is presented.

4.1 Literature Review Characteristics

The literature review procedure presented in Chapter 3 rendered a series of 20 articles to be included in the study. The articles reviewed were published across a range of eight different journals, see Table 7, the most prominent being "*Journal of Cleaner Production*" followed by "*Sustainable Production and Consumption*", tightly followed by "*Resources, Conservation & Recycling*". The remaining journals are included to a lesser extent and the journal of 'Computers and chemical engineering' being the only outlier. The journals are mainly focused on sustainability and production engineering which may suggest that CE indicators are spread across various multi-disciplinary fields however it is clear that it stays within its domain.

Table 7: Range and count of publishing journals

Publishing Journal	Count
Journal of Cleaner Production	6
Sustainable Production and Consumption	5
Resources, Conservation & Recycling	4
Computers and Chemical Engineering	1
Journal of Industrial and Production Engineering	1
MDPI	1
International Journal of Life Cycle Assessment	1
Proceedings of the Design Society	1
Total	**20**

Leaving the journals behind and analysing the countries of origin of the articles by gathering the country of origin for the institution each author is present at, the results point towards a predominantly European perspective, see Table 8. A strong presence from Brazil and USA and a minor presence from Australia which together make up the only non-European literature included in this literature review. The fact that most articles originated from within Europe leads to an interesting question whether CE indicator is more of a European focus. This geographical concentration raises questions about the broader global engagement with CE indicator and whether similar research efforts are being undertaken elsewhere. Studying the key contributions of these European studies may shed light on why this regional focus exists.

Table 8 Countries of researchers in articles

Countries	Count
Spain	14
Brazil	9
Italy	7
USA	6
Sweden	4
Denmark	4
France	4
Netherlands	3
Portugal	2
Slovenia	2
Switzerland	1
Australia	1
Total	57
European	41
Non-european	16

4.2 Literature Review Findings

This section presents findings from the literature on CE indicators, including the most widely recognized in the studied literature, CE indicators current main usage and trends, key challenges, and enablers for future implementation in industrial settings. It explores issues such as standardization, assessment complexity, and the emphasis on end-of-life (EoL) strategies while also highlighting opportunities for improved integration and policy support.

4.2.1 Screening and Selection of Circular Economy Indicators

The literature review initially identified 488 occurrences of CE Indicators across 20 selected articles. To refine this extensive dataset a structured screening process, described in detail in the Methodology chapter (section 3.2.4 and 3.2.5), was applied consisting of both screening and eligibility criteria to ensure relevance and applicability to this study.

Following the first stage of screening, which excluded all indicators with less than 3 occurrences in the literature, the number of indicators was reduced to 37, representing a total of 194 occurrences out of the 488 in the literature. The final step in the selection process applied an additional layer of evaluation, further narrowing the indicators to a final list of 16. Table 9 below presents the last stage of the indicator selection process, highlighting the 16 CE indicators that passed screening.

Table 9:Indicators identified from SLR with 3 or more occurrences in the literature

Indicator	Academic Validation (N>=5)	Measurability	Data Consistency & Quality	Integration Feasibility	Decision-Making Support	Cross-Industry Consistency	Practical Applicability	Clear Definition & Calculation	Mark
Material Circularity Indicator	14	✓	✓	✓	✓	✓	✓	✓	✓
Renewable material used	14	✓	✓	✓	✓	✓	✓	✓	✓
% of Hazardous waste over Total waste generated	7	✓	✗	✓	✓	✓	✓	✗	✗
Circular Economy Toolkit	7	✗	✗	✓	✓	✗	✓	✗	✗
Environmental fines over Number of products sold	7	✓	✗	✓	✗	✗	✓	✗	✗
NOx, SOx, and other significant air emissions over Products sold	7	✓	✓	✓	✓	✗	✓	✓	✗
Diverted waste from disposal	6	✓	✗	✓	✓	✓	✓	✗	✗
Circular Economy Indicator Prototype	6	✓	✓	✗	✓	✓	✓	✓	✗
Product-level Circularity Metric	6	✓	✓	✓	✓	✓	✓	✓	✓
Total energy consumed	6	✓	✓	✓	✓	✓	✓	✓	✓
Longevity Indicator	6	✓	✓	✓	✓	✓	✓	✓	✓
Product Recovery Multi-Criteria Decision Tool	6	✓	✓	✓	✓	✓	✓	✓	✓
Reuse Potential Indicator	6	✓	✓	✓	✓	✓	✓	✓	✓
Sustainable Circular Index	6	✓	✗	✗	✓	✓	✗	✗	✗
Circular Economy Index	5	✓	✓	✓	✓	✓	✓	✓	✓
Renewable energy consumed	5	✓	✓	✓	✓	✓	✓	✓	✓
Circulytics	5	✓	✓	✓	✓	✓	✓	✗	✗
Expended Zero Waste Practice Model	5	✗	✓	✗	✓	✓	✗	✗	✗
Circularity Calculator	5	✓	✓	✓	✓	✓	✗	✓	✗
Material Reutilization Score	5	✓	✓	✓	✓	✓	✓	✓	✓
% of Material to be reclaimed/recovered	4	✓	✓	✓	✓	✓	✓	✗	✗
Other water discharge	4	✓	✓	✓	✓	✓	✓	✗	✗
Full time employees	4	✓	✓	✓	✓	✓	✓	✓	✓
Circularity Measurement Toolkit	4	✗	✗	✓	✓	✓	✓	✗	✗
Building Circularity Indicator	4	✓	✗	✓	✓	✗	✓	✓	✗
Circularity Index	4	✓	✓	✓	✓	✓	✓	✗	✗
Recycling DesirabilityIndex	4	✗	✗	✗	✓	✗	✗	✗	✗
Value-based ResourceEfficiency	4	✓	✓	✓	✓	✓	✓	✓	✓
Recoverability rate	4	✓	✓	✓	✓	✓	✓	✓	✓
% of Recycled input material used	4	✓	✓	✓	✓	✓	✓	✗	✗
% of Water consumed over Total water withdrawa	3	✓	✓	✓	✓	✓	✓	✗	✗
Water withdrawal	3	✓	✓	✓	✓	✓	✓	✓	✓
Circular Economy Measurement Scale	3	✗	✗	✗	✓	✗	✗	✗	✗
Circular Economy Performance Indicator	3	✓	✗	✗	✓	✓	✓	✗	✗
Ease of Disassembly Metric	3	✓	✓	✓	✓	✓	✓	✓	✓
Recycling Indices	3	✓	✓	✓	✓	✓	✗	✓	✗
Product take-back	3	✓	✓	✓	✓	✓	✓	✓	✓

4.2.2 CE Indicators Usage Today and Trends

In the literature there is evidence for which CE indicators are used and for what purposes they have been implemented or created. A common theme among the literature is that CE indicators are used for decision-making and for monitoring the progress towards CE. CE indicators enables companies and policymakers to track the circularity progress by making informed decisions and advise investments into circularity. Lindgreen et al. (2020) and S. G. Baratsas et al. (2022) describe how implemented CE indicators enable informational communication, progress monitoring, informed decision making and investments. Furthermore, Drofenik et al. (2025), Franco et al. (2021), Rincón-Moreno et al. (2021), and Matos et al. (2023) describe how CE indicators are used to inform on sustainability strategies and enable the alignment between companies and global reporting frameworks.

Despite multiple reports of current uses of CE indicators, there is evidence supporting the notion that the adoption of CE indicators remains fragmented and limited. Lindgreen et al. (2020) notes that within the context of fast-moving consumer goods sector, CE indicators has been implemented in a very limited degree which is reinforced by Kristensen and Mosgaard (2020) who share that micro-level adoption of CE indicators is low throughout industry and by Khadim et al. (2022) who states that CE indicators are used in policy discussions but it is in its infancy when it comes to implementation in industry.

The uses of CE indicators seem clear, but the implementation is still fragmented as of today. Various articles comment on the types of tools, methods, metrics, or indicators that are applied today and how they relate to sustainability. If CE indicators are related to the three pillars of sustainability, many of them cover economic and environmental factors but are significantly lacking in the social factor (de Oliveira et al., 2021; Franco et al., 2021; Kristensen & Mosgaard, 2020; Matos et al., 2023; Vural Gursel et al., 2023). Kristensen and Mosgaard (2020) describes how CE indicators lean heavily towards the economic and environmental factors while neglecting the social. Franco et al. (2021) has a similar view and goes one step further to describe them as not only underrepresented by also lacking in terms of concrete measurement frameworks, making it hard for implementation. Matos et al. (2023) agrees with the lack of focus on social aspects and focuses in on the lack of consideration for social equity and labour conditions. Vural Gursel et al. (2023) presents how only 3 out of 24 metrics used in their study covers the social perspective and de Oliveira et al. (2021) point out how CE indicators often ignore worker well-being, social equity and community impact. Based on the included literature in this study, there is overwhelming evidence for the social aspect of the three pillars of sustainability being under considered in CE indicators.

In the literature, several trends can be decerned, both Khadim et al. (2022) and Drofenik et al. (2025) comment on how CE indicators are integrated with digital tools at an increasing rate. Furthermore, Drofenik et al. (2025) state how digitalization is improving the measurability of CE indicators and how blockchain, IoT and data analytics leads to transparency and accountability, necessities for CE initiatives.
Increased digitalization leads to increased measurability, transparency and accountability but it is not the only trend which can be decerned. In the literature there is evidence policy-makers pushing for increased corporate adoption of CE indicators. Drofenik et al. (2025) presents how regulatory bodies such as the EU are working for greater adoption of CE indicators and Baumer-Cardoso et al. (2023) is in agreement with Lindgreen et al. (2020) stating that larger companies have started to integrate CE indicators into their sustainability reports and investor disclosures.

4.2.3 Lack of Standardization and Comparability of CE Indicators

One of the most widely reported challenges in the literature is the lack of standardization among CE indicators, particularly at the micro and nano levels, where companies struggle to assess and compare their circularity performance. Several studies emphasize that CE indicators vary significantly in focus, methodology, and data requirements, leading to inconsistent results even when applied to the same organization (Matos et al., 2023; Roos Lindgreen et al., 2021; Valls-Val et al., 2022). This makes it difficult for companies to navigate the available methods and tools and select appropriate indicators for measuring circularity in a meaningful way.

Valls-Val et al. (2022) highlight that most CE indicators differ in data accuracy and calculation methods, making benchmarking and comparability between industries very difficult. Similarly, Matos et al. (2023) argue that micro-level indicators are highly fragmented, with some focusing on recycling rates while others emphasize material efficiency or EoL strategies, leading to contradictory interpretations of circularity performance. The lack of alignment across indicators means that companies operating across different sectors often find it challenging to adopt a single, reliable framework for assessing their circularity progress (Kristensen & Mosgaard, 2020).

This inconsistency is particularly problematic for businesses attempting to integrate CE indicators into their decision-making processes. Without a standardized framework that effectively connects national-level circular economy strategies with company-level implementation, companies are left to interpret circularity on their own terms, leading to high variability in CE assessments and can hinder companies from translating CE goals into actionable strategies (Kristensen & Mosgaard, 2020). Kristensen and Mosgaard (2020) further note that due to this lack of standardization, companies often prioritize economic aspects of circularity over environmental and social dimensions, which can lead to a narrower approach to sustainability rather than a truly holistic CE strategy.

As a result of these challenges, many companies have opted to develop their own internal CE measurement frameworks rather than relying on existing, yet inconsistent, assessment tools at the micro level. Roos Lindgreen et al. (2021) report that, in a study of 39 interviewed companies, 74% relied on their own self-developed frameworks for measuring circularity, while only 24% utilized the Ellen MacArthur Foundation's Butterfly Diagram. While this approach allows businesses to tailor indicators to their specific needs, it further exacerbates the problem of industry-wide standardization.

Another layer of complexity arises from the conceptual ambiguity surrounding CE itself, which contributes to the fragmentation of CE indicators. Due to varied interpretations of circularity across industries and policy frameworks, companies often struggle to align their CE assessments with broader sustainability objectives (Vural Gursel et al., 2023). Saidani et al. (2020) further note that many CE indicators prioritize material recirculation while neglecting circular business models, reverse logistics, and design-based circularity approaches, which could otherwise provide a more comprehensive measure of circularity performance. The lack of a unified conceptual basis for CE measurement results in businesses emphasizing easier-to-quantify material flows rather than addressing more complex, systemic circular economy strategies (Lindgreen et al., 2020).

4.2.4 Complexity and Resource Demands of CE Assessments

Another widely reported barrier for implementing CE performance measurement for companies in the literature is the complexity and resource-intensive nature of CE assessment tools, particularly for businesses at the micro level. Many CE indicators require detailed data collection, extensive manual input, and technical expertise, making their adoption difficult, especially for small and medium-sized enterprises (SMEs) (Franco et al., 2021; Valls-Val et al., 2022). Valls-Val et al. (2022) highlight that many existing qualitative CE tools contain an overwhelming number of questions and require lengthy assessment procedures, discouraging businesses from using them regularly.

Similarly, Baumer-Cardoso et al. (2021) found that companies often face internal coordination challenges when collecting data for CE assessments, as multiple departments such as procurement, production, and sustainability teams need to be involved. Furthermore, Roos Lindgreen et al. (2021) argue that businesses often struggle with quantitative CE indicators, as many of them rely on external data sources, such as recycling rates, material recovery percentages, or supply chain-wide tracking, which are not always accessible for companies.

4.2.5 Overemphasis on EoL management in CE Indicators

A significant barrier to the effective implementation of CE indicators is, according to literature, their predominant focus on material recycling and EoL strategies, often at the expense of higher-value circular approaches such as reuse, remanufacturing, and eco-design. While recycling plays an important role in circularity, its overrepresentation in CE assessments turn away attention from more impactful upstream interventions that could lead to greater sustainability outcomes (de Oliveira & Oliveira, 2023; Kristensen & Mosgaard, 2020; Matos et al., 2023).

Several studies reveal that CE indicators predominantly measure circularity through recycling and remanufacturing rates, rather than emphasizing waste prevention and resource optimization. de Oliveira and Oliveira (2023) highlight that many CE assessments focus on material recirculation, even though recycling is the least sustainable option in CE and contributes less to sustainability than reuse, repair, and design-based innovations. Similarly, Matos et al. (2023) find that micro-level CE indicators are largely centred on recycling and remanufacturing, with minimal attention to reuse, disassembly, or product life extension.

Khadim et al. (2022) further emphasize that most CE indicators, still in early development, overemphasize recycling and reuse while neglecting critical factors such as energy efficiency, emissions reduction, and water conservation, limiting businesses' ability to adopt holistic sustainability strategies. Likewise, Franco et al. (2021) argue that CE assessments tend to prioritize material flows at the end of a product's life cycle, overlooking product longevity, smarter resource use, and circular design innovations that could prevent waste generation from the outset. This imbalance hinders the adoption of long-term resource retention strategies, reinforcing a narrower, material-centric approach to circularity.

Kristensen and Mosgaard (2020) further emphasize that most CE measurement frameworks focus on EoL processes, such as remanufacturing and waste recovery, rather than design-based strategies that could reduce material consumption from the outset. This skewed approach to circularity risks misleading businesses into prioritizing recycling improvements rather than investing in systemic changes that could yield greater environmental and economic benefits. This strong emphasis on recycling also influences how companies structure their sustainability initiatives. Without a broader set of assessment tools that account for reuse, remanufacturing, and product longevity, organizations may continue to rely on recycling-centric strategies that do not maximize material value retention. de Oliveira and Oliveira (2023) caution that the current CE measurement landscape reinforces the perception that recycling alone is a sufficient circular strategy, even though higher-level interventions could contribute more effectively to long-term sustainability goals.

4.2.6 Integration with Corporate Reporting Systems and Assessment Frameworks

One of the most significant enablers for implementing CE indicators is their integration with existing sustainability assessment frameworks and corporate reporting systems. Several studies emphasize that aligning CE measurement tools with established methodologies, such as Life Cycle Assessment (LCA), Material Flow Analysis (MFA), and Environmental, Social, and Governance (ESG) frameworks, can improve their usability and adoption by businesses (Baumer-Cardoso et al., 2023; Jerome et al., 2022; Valls-Val et al., 2022).

Jerome et al. (2022) highlight that combining CE indicators with LCA-based assessments allows for a more comprehensive evaluation of environmental sustainability, ensuring that circularity efforts do not create unintended trade-offs. Similarly, Valls-Val et al. (2022) and Baumer-Cardoso et al. (2023) find that businesses that already track sustainability metrics in their reports can embed CE indicators into their existing data collection processes, reducing the burden of additional assessments. This approach enables companies to leverage existing reporting structures to enhance circularity measurement, facilitating more transparent and comparable assessments across industries.

Furthermore, Roos Lindgreen et al. (2021) emphasize that CE indicators should be designed to complement well-established sustainability evaluation methods, enabling companies to assess circularity within broader environmental and social impact frameworks. This integration not only improves measurement accuracy but also ensures that CE strategies contribute meaningfully to corporate sustainability goals.

4.2.7 Stakeholder Collaboration and Organizational Learning

Another significant enabler for implementing CE indicators is organizational learning, which plays a critical role in the progressive adoption of CE. Aranda-Usón et al. (2020) emphasize that the transition from a linear to a circular model is not immediate but develops gradually, allowing firms to grow internal capabilities over time. This stepwise progression supports experimentation and reduces resistance to change, particularly in areas like CE measurement, which often require new competencies and routines. As companies engage in more CE-related activities, they accumulate experience that improves their ability to adopt and work with indicators (Aranda-Usón et al., 2020).

Stakeholder collaboration also helps CE indicator implementation by enabling knowledge sharing, resource pooling, and alignment of expectations. Aranda-Usón et al. (2020) underscore the importance of engaging a broad set of actors including local government, suppliers, and industry partners to strengthen the institutional and technical foundations for CE adoption. Similar findings are repeated in other studies, where industrial symbiosis and shared data infrastructures are shown to reduce the cost and complexity of CE indicator implementation (Jerome et al., 2022; Roos Lindgreen et al., 2021).

4.3 Remaining CE Indicators

16 CE indicators were selected for further investigation in this thesis, as they met the screening and eligibility criteria outlined in the Methodology chapter (Sections 3.2.4 and 3.2.5). These indicators are listed in Table 10. The CE indicators have a short description of their intended use and way of assessment, a four key strategies categorization to associate each indicator with which of the four key strategies of the technical circle by Ellen MacArthur Foundation (2013), and lastly the reference to the source article if applicable. If no source or CE Categorization is given then there is non and not possible to place in the four key strategies. For a more detailed description and the data requirements of each CE indicator, see Appendix D.

Table 10: Selected CE Indicators from literature review

CE Indicator	Description	CE Categorization	Source
Material Circularity Indicator (MCI)	The MCI is a metric that quantifies how circular a product's material flows are, ranging from 0 (linear) to 1 (circular), by assessing virgin material use, unrecoverable waste, product utility, and alignment with technical and biological cycles.	Maintenance & Repair, Recycling	Ellen MacArthur Foundation and Design (2015)
Renewable material used (RMU)	The RMU indicator measures how effectively a company replaces non-renewable materials with renewable, sustainably sourced ones in its production or packaging.	Refurbishment & Remanufacturing, Recycling	Stefanos G. Baratsas et al. (2022)
Product-level Circularity Metric (PLCM)	The PLCM measures a product's circularity based on the economic value of components sourced from previously used products, allowing aggregation across diverse parts and supply chains.	Refurbishment & Remanufacturing, Recycling	Linder et al. (2017)
Total energy consumed (TEC)	Total energy consumed of a site/department/line	Maintenance & Repair	N/A
Longevity Indicator (LI)	The LI is a value-based metric that quantifies how long materials contribute value within a product system, through initial use, reuse, and recycling, to support Circular Economy goals and help organizations assess and improve resource circularity.	Maintenance & Repair	Franklin-Johnson et al. (2016)
Product Recovery Multi-Criteria Decision Tool (PRMCD)	The PR-MCDT is a flexible evaluation method that helps companies select the most suitable EoL circular economy strategy by comparing options like repair, reuse, remanufacturing, and recycling against traditional models using adjustable criteria that balance circularity benefits and business feasibility.	Reuse & Redistribution, Refurbishment & Remanufacturing	Alamerew et al. (2020)

Reuse Potential Indicator (RPI)	RPI is a dynamic, quantitative tool that measures the technical feasibility of reusing waste materials, independent of market factors, by assessing how resource-like they are based on current commercial technologies.	Reuse & Redistribution, Recycling	Park and Chertow (2014)
Circular Economy Index (CEI)	CEI is a simple, value-based metric that evaluates recycling effectiveness by comparing the economic worth of recovered materials to that of original inputs, promoting innovation and aligning with policy and industry goals.	Recycling, Refurbishment & Remanufacturing	Di Maio and Rem (2015)
Renewable energy consumed (REC)	Total renewable energy consumed of a site/department/line	Maintenance & Repair	N/A
Material Reutilization Score (MRS)	MRS, part of the Cradle to Cradle Certified™ Product Standard, measures how effectively a product’s materials can be recovered and reused in circular biological or technical cycles, supporting waste minimization and continuous material use.	Refurbishment & Remanufacturing, Recycling	Institute. (2016)
Full time employees (FTE)	How many of operational personnel which is considered full-time employed		N/A
Value-based Resource Efficiency (VRE)	The VRE indicator is a circular economy metric that uses the market value, rather than mass, of stressed resources to assess how efficiently economic actors generate added value, offering a simple, policy-aligned approach based on national statistics.	Refurbishment & Remanufacturing, Recycling	Di Maio et al. (2017)
Recoverability rate (RR)	The Recoverability Rate measures how much of a product’s mass or environmental impact can be recovered at EoL for reuse, recycling, or energy recovery, helping identify design improvements through both material and environmental benefit analysis.	Refurbishment & Remanufacturing, Recycling	Ardente and Mathieux (2014)
Water withdrawal (WW)	How much water is withdrawn	Recycling	N/A
Ease of Disassembly Metric (EDM)	The Ease of Disassembly Metric (eDiM) is a circular economy indicator that estimates disassembly time using MOST-based calculations to help designers, regulators, and recyclers improve product disassemblability for repair, reuse, remanufacturing, and recycling.	Refurbishment & Remanufacturing, Recycling	Vanegas et al. (2018)
Product take-back (PTB)	How many products are sent back to their suppliers for handling	Refurbishment & Remanufacturing, Recycling	N/A

5 Case Study Results

This chapter presents the combined questionnaire and interview results from the case study at the company. It begins with an overview of the respondents' roles, experience levels, geographic distribution, and their familiarity with CE and the XPS maintenance maturity model. The chapter then explores key areas relevant to the thesis, including current practices within PM and CE at the case study company, as well as barriers and enablers for CE indicator implementation. Within these areas, key identified themes are addressed and analysed. For visual results and full questionnaire data, see Appendix E - Complete Questionnaire Results, presented below are the key results used in the thesis.

5.1 Participant Overview

In the case study, questionnaires and interviews were conducted in parallel. A total of 27 individuals responded to the questionnaire: 23 were based in Sweden, one in France, and three in Brazil. The respondents represented a focused group of professionals closely involved in maintenance operations across the company. When asked about their fields of involvement (multiple choices possible), 79% indicated they were engaged in maintenance functions, 11% in production or manufacturing, and 10% in sustainability or environmental management. In terms of experience, 56% reported having more than 10 years of professional experience. The interview part of the case study included five participants: a Sustainability Manager, a Technology Manager within maintenance, a Director of XPS and two Maintenance Engineers tasked with operational maintenance and improvement. Of these, three were based in Sweden, one in France, and one in Brazil. All interviewees had roles directly or indirectly related to the maintenance function.

When asked to indicate their familiarity with the concept of CE, 15% of respondents reported being unfamiliar, 30% stated they were somewhat familiar, 33% said they were moderately familiar, and 22% indicated they were very familiar with the concept.

Similarly, regarding familiarity with the seven-step model for PM, 4% of respondents reported being unfamiliar, 22% said they had heard of it but were unsure of the details, 15% were somewhat familiar, 26% were moderately familiar, and 33% stated they were very familiar with the model.

5.2 Current Practices in PM and CE

When asked how maintenance at their site was currently planned in terms of reactive, preventive, predictive, or proactive, 19% of respondents indicated that their site was primarily reactive, focusing on fixing equipment after failure. Around half (52%) reported that their site followed a mostly preventive approach, involving scheduled maintenance to reduce breakdowns. Meanwhile, 11% stated that their site employed predictive maintenance, using data and monitoring to anticipate failures, and another 11% reported a proactive approach, which involves extending equipment life through design changes and upgrades. Lastly, 7% of respondents said they were unsure.

After providing input on how PM is planned at their site, respondents were asked to assess their site's position within the five levels of the seven-step model for PM. 4% of respondents placed their site at Level 1, indicating a largely reactive approach with occasional preventive work. 26% identified their site as Level 2, characterized by a well-established base of preventive maintenance with some condition-based practices. 33% selected Level 3, meaning their site incorporates cost analysis and supports equipment design alongside developed condition-based maintenance routines. 22% chose Level 4, where maintenance is fully integrated with design, benchmarking, and high-reliability systems. 8% stated that their site operates at Level 5, the highest level, where maintenance is fully predictive, optimized, integrated, and data-driven. Finally, 7% of respondents indicated they were unsure of their site's maturity level.

After reflecting on their site's position within the seven-step model for PM, respondents were asked to describe the current state of PM and CE practices, and whether maintenance activities have been used to improve CE performance in production. Among the respondents, 7% stated that CE is not considered in maintenance. Most respondents, 63%, believed that maintenance contributed to CE occasionally, but not in a structured way. Meanwhile, 15% reported that CE-related KPIs are tracked as part of maintenance reporting, and 4% indicated that CE and maintenance data are fully integrated into sustainability tracking. Lastly, 11% of respondents said they were unaware of how CE relates to maintenance at their site. However, in the interviews there was overwhelming support for the role of maintenance in CE, the Sustainability Manager noted: "*Maintenance has huge impact... extending machine life, reducing waste, being able to renovate instead of throwing things away.*"

And the Technology Manager in maintenance stated: “*If a machine breaks, you get downtime, more energy use, scrap – maybe even product scrap. That’s the opposite of circular economy.*”
While most respondents believed that maintenance currently contributes to CE only occasionally, they were also asked to reflect on the collaboration between maintenance and sustainability functions within their organizations. In response, 11% indicated that maintenance and sustainability teams are not aligned, while another 11% said the alignment is *somewhat* present and that the sustainability teams set targets, but maintenance is not actively involved in the process. A larger portion, 41%, described the relationship as *moderate*, with occasional collaboration between the two functions. Meanwhile, 18% characterized the collaboration as *strong*, where maintenance plays an active role in sustainability and CE initiatives. Lastly, 19% of respondents said they were unsure about the relationship.

After providing input on the planning, maturity, CE contribution of PM, and collaboration with sustainability functions at their site, respondents were asked about the current state of data collection related to operational performance, energy and environmental factors, and material and resource efficiency within maintenance activities in terms of adaption and perceived difficulty in collection. Table 11 provide an overview of the results across different data categories and their respective ratings by the respondents as well as averages for each category.

Table 11: Data adoption and perceived difficulty [1-5] at site level

Type of data	**Description**	**Adoption**	**Average Difficulty [1-5]**
Operational Performance Data		**AVG. 76%**	**AVG. 2**
Machine Downtime	Unplanned stoppages and lost production time	89%	1,5
Failure Frequency	How often breakdowns occur	89%	1,6
Repair Speed	Measuring how quickly maintenance teams restore equipment	85%	1,8
Maintenance Task Completion Rate	Percentage of scheduled maintenance tasks completed on time	81%	2
Maintenance Quality	Repairs that require additional intervention due to initial fix failure	33%	3
Energy & Environmental Impact Data		**AVG. 22%**	**AVG. 3,5**
Machine Energy Use	Monitoring the energy consumption of equipment and processes	33%	3,2

Energy Efficiency	Energy savings resulting from maintenance activities	26%	3,8
Maintenance Process Emissions	Environmental impact of lubrication, cleaning, and repairs	19%	3,6
Water Use in Maintenance	Water consumed during maintenance tasks	7%	3,7
Chemical Usage	Use of lubricants, degreasers, and other hazardous materials	37%	2,9
Component Lifecycle Impact	Emissions of spare parts and materials	11%	3,8
Material & Resource Efficiency Data		**AVG. 29%**	**AVG. 3**
Spare Parts and Equipment Consumption	Usage rates, inventory levels, and procurement needs	52%	1,8
Component Reuse & Refurbishment	Assessing how often parts are repaired or reused	30%	2,7
Component Recycling and Remanufacturing Rate	How frequently parts are recycled or remanufactured	22%	2,9
Waste Generation	Scrap rates, disposal, and material losses	22%	3,3
Lifecycle Tracking of Components Usage	Wear, longevity, and replacement cycles	41%	3,2
Procurement Sustainability	The recycled content of sourced spare parts and equipment	8%	3,8

The results show that the *Operational Performance Data* was considered easy when it comes to collection, receiving an average data collection difficulty rating of 2 out of 5. In this category, *Machine downtime* was considered the easiest and *Maintenance quality* the hardest to collect. In the interviews, the Director of XPS noted that it is with the operational performance data maintenance automatically track their contribution towards CE by tracking the prolonging of the use phase, stating: "*We have a wide spectrum of machines… with many inputs influencing the performance… the more we can capture of the inputs, the better the performance*". The argument concludes by the explanation of how an optimally performing machine uses less energy and due to optimal performance conditions, the components last longer.

Energy & Environmental impact data on the other hand was associated with considerable data collection difficulty by the respondents, receiving an average data collection rating of 3,5 out of 5. *Chemical usage* was seen as the easiest to track, while *Component lifecycle impact* was considered the most difficult.
In the interviews, the Sustainability Manager provided additional context on the energy data in maintenance:
"*A large problem for us has been the lack of energy-data from each machine individually. At the moment we know the energy usage from an entire hall containing hundreds of machines... it makes it challenging to work systematically.*".

On the topic of energy data of machines, the XPS Director noted how:
"*We would like to have the data from every machine. Or from everything that is using energy, but it's not practical, possible and quite expensive to take that decision*".
Because it isn't practical to track everything, there is prioritization and the collection of new data is driven on a need basis in terms of a project or improvement, stating:
"*You can add and start measuring when you work in a continuous improvement project. You then find what data you have and you find what data you don't have*"

Concludingly, *Material & Resource efficiency* data was considered among the more challenging categories to collect, with an overall average difficulty rating of 3 out of 5. *Spare Part and Equipment Consumption* was perceived as the easiest to track, while *Procurement Sustainability* was considered the most difficult.

5.3 Barriers and Enablers

When respondents were asked about the future maturity of their site within the 5-level maturity model, there was a strong sense of optimism regarding progress toward higher levels. While a few anticipate maintaining their current level, the majority foresee advancement along the maturity scale. When asked about their site's future maturity, 26% of respondents indicated that their site would reach Level 3, 33% predicted Level 4, and another 30% believed their site would achieve Level 5. Meanwhile, 7% stated that they were unsure, and one outlier (4%) anticipated that their site would remain at Level 1. On the topic of increased maintenance maturity, the XPS Director described how data collection and usage becomes increasingly comprehensive as you move higher in the maturity framework, stating:
"*…we are gathering more data, the more mature you are, yes. And you also learn what data is good to have... Over time, you are also trying a lot and trying to gather data, but what you see is that was not valuable to do also... that is also in the maturity journey"*

With the expectation that site maturity will increase over the next three years, respondents in the questionnaire were asked in free-text responses what factors might influence this development. Many emphasized the critical role of stronger leadership and clearer prioritization from plant or top-level management. A lack of attention, resources, or consistent follow-through from leadership was frequently identified as a major bottleneck. The questionnaire results align closely with findings from the interviews. The Technology Manager in maintenance noted during the interviews:

"Where I've seen the most growth is when the director or the site management team is dedicated, asking for it daily, weekly, monthly."

Where management support is strong, improvements are expected to follow. While management commitment and organizational focus were commonly stressed, another recurring theme was the need to improve the way data is collected and analyzed. Respondents highlighted the importance of structured data from sensors and systems (such as CMMS), noting that much of the current data is manually entered and potentially unreliable. The Technology Manager in maintenance added some context by describing how more and more data are extracted by adding sensors, stating:

"*We do try to extract more and more data by putting in sensors or extracting from Product Lifecycle Support (PLS) or similar. We have projects ongoing today also to extract new data and energy consumption of the machine*."

And then described the need for automatic measurements and visual communication:

"*It needs really to be maybe automated or something about using our digital toolbox here to create this easygoing way of how to visualize.*".

The Sustainability Manager had a similar view as the Technology Manager, stating:

"*We want a number, a graph, something management can understand and track progress with*"

and adds:

"*If it can come automatically, not extra paperwork or manual input, then there is big interest to follow up.*"

Better training and awareness around the use of data were also emphasized. A Maintenance Engineer expressed this view in the interviews:

"In PM, if we improve data collection, we can have a better approach to improvements."

While data quality and usage were frequently mentioned, another important factor influencing maturity levels was the need to develop internal competence, both through training new staff and preserving the knowledge of experienced personnel approaching retirement. Sharing best practices and building a consistent understanding across teams was seen as critical, particularly when shifting towards predictive or condition-based maintenance strategies. In the interviews, a Maintenance Engineer emphasized the need for training and described how it was holding back the maturity of the site, stating:

"*There isn't a lot of PM understanding which is really holding us back in terms of maturity*"

On the topic of increased awareness of the use of data, the XPS Director described how there may be different levels of data maturity in the same organization and proceeded to describe how the maintenance function at the site in question was particularly mature, stating:
"*It's easy for the maintenance team because they are already ahead of other functions in the plant. They understand why they are gathering data, they understand the need of a deep logic and so on... If you look at another organization that maybe is not that mature, then you need to like start on a completely different level and maybe also take this good discussion, why is it good to gather data".*
And even when data is widely available it is an art to create meaningful insights, the XPS Director added:
"*To be able to make a stratification is like an art… you can have tons of data, but it's hard to know how to categorize or analyze it… It is an art to start with the data and say OK here it looks like a trend. Here is something that we will focus on. Should we look at the data from this perspective or this perspective*".
Additionally, respondents in the questionnaire highlighted the resource constraints in PM. Since operational work is their main priority, improvement work often suffers due to reprioritization, a respondent in the questionnaire noted on the topic of what will influence maintenance maturity:
"*Resource constraints, we have a vast amount of equipment which to raise the level of maintenance maturity requires extensive efforts, which is often digested by other prioritized activities*."
The resource constraints and prioritisation slow down progress even though maintenance is often aware of what needs to be done. And the fact that maintenance priorities operations means that sustainability initiatives has historically suffered the same fate as improvement work. A Maintenance Technician who had sustainability responsibilities added:
"…to be honest it is only about 5% of my work. I can sometimes work a complete day on it but only once a month".
The XPS Director provided insights which provide additional context on the prioritization of operations:

"*The big problem is prioritising, because sustainability & circular economy is not the only KPI or targets we have. It is always in competition with safety, quality, delivery and all the other KPIs*".

Furthermore, respondents stressed the need for standardized ways of working and closer integration with the XPS are highlighted as important. Respondents note that maintenance sometimes feels disconnected from broader XPS goals, making it harder to set direction and track progress. On the topic of PM being disconnected from the XPS, there was a comment in the questionnaire describing how the pillars of WCM and XPS create organizational silos, stating: "*The silos which the pillar thinking tends to create, risks suboptimization. We need enhanced flow thinking and responsiveness to meet standard of CE soon*"

Standardization and alignment with the XPS are needed, but so is technological development according to the questionnaire. Increased use of digital tools, especially AI, sensors, and smart data systems, is expected to be a major driver of progress. Some comments reflected optimism about the role of AI and condition-based maintenance, while others note the current gap between new technologies and traditional ways of working. The Technology Maintenance Manager noted during the interview when describing their current maintenance maturity efforts:

"*We are trying to push for condition-based monitoring, but first we really need to have the basics in place to avoid current breakdowns."*

Which agreed with the fact that technological and digital tools can enable maturity to increase, but questionnaire respondents also underlined the value of working across functions, especially with roles in Early Equipment Management (EEM), Product Development (PD), and IT, to align efforts and share responsibility for improvements. The Technology Manager in maintenance shared a similar view on cross-functional collaboration, stating: "*All of our focus areas are connected, and the higher the maturity level, the more the different focus areas, like maintenance, environmental, and others, are integrated into one system*."

After providing input on the development of their sites and the enablers and barriers expected to influence that development, respondents were similarly asked to assess the development of CE practices within PM. They were presented with the eight barriers that were identified mainly in the systematic literature review (see Section 4.2). The overwhelming sentiment was that all barriers were considered significant (see Figure 11), though *Complex Implementation* stood out as particularly challenging, receiving an average difficulty rating of 3,9 out of 5. This was followed by *Lack of Knowledge* and *Lack of Standardization*, 3,6 and 3,5 out of 5 respectively.

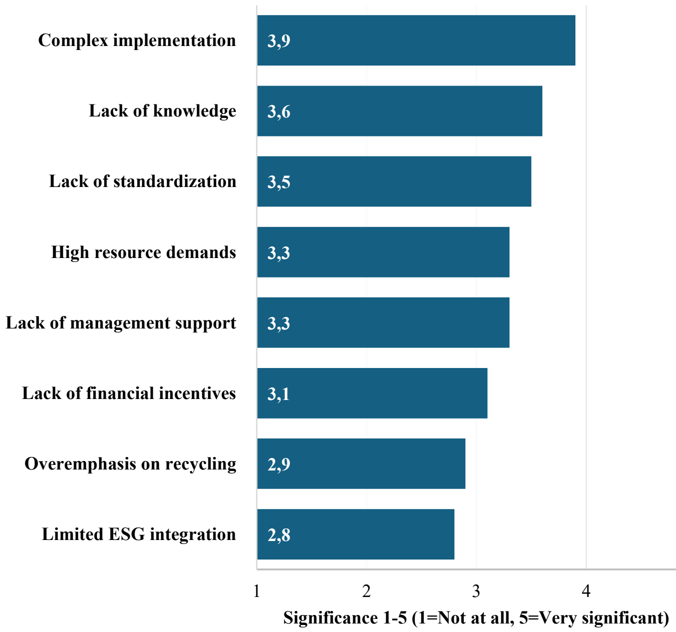

Figure 11: CE in PM barrier rating

Similarly, the perceived significance of CE Indicator implementation enablers is presented in Figure 12 below. The enablers are mainly identified from the systematic literature review (see Section 4.2). Respondents likewise regarded many enablers as significant. *Greater Support from Top Management* and *More Training and Awareness* were seen as the most critical, each receiving the highest significance rating of 4.3 out of 5.

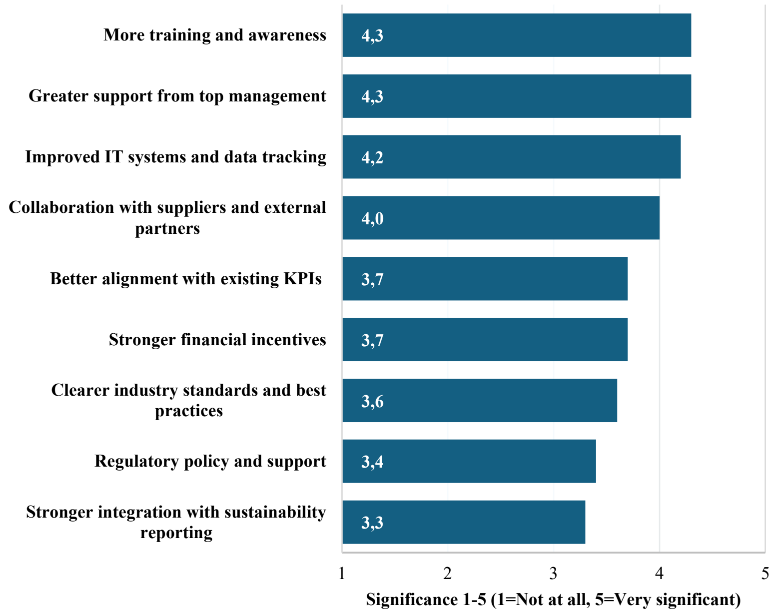

Figure 12: CE in PM enabler rating

The questionnaire results regarding the significance of enablers and barriers were reflected in the interviews. A technology manager in maintenance provided input that aligned with *Lack of Knowledge* being seen as a significant barrier, while also highlighting *More Training and Awareness* as critical, describing competence as "*one of the most critical things*." Similarly, the Sustainability Manager echoed this view, stating:

"We need to measure circular economy, but we have to get awareness up, we must start there.".

Starting with awareness and knowledge is the exact thing that the XPS Director described had recently been done at one of the sites, stating:

"*We have rolled out a big training in circularity and at the moment it has almost reached all employees*".

When reflecting on the results of the training, there was no resistance when it came to working and thinking in the new way and they noticed that a lot of projects already align with the mission of circularity:

"*There's no actual resistance in maintenance to work with this and follow it up. And then we can also see that a lot of actions is already taken in the area*"

Lack of Standardization was seen as a highly significant barrier, while *Clearer Industry Standards and Practices* were also regarded as important enablers, though slightly less critical. In the interviews, the uncertainty observed in the questionnaire responses was reflected across all organizational levels. The Sustainability Manager expressed this uncertainty, stating:

"*We want to measure circularity on site level… but we don't know how yet*"

while the technology manager in maintenance commented on the measurement of CE, saying: "*We don't have it today… we are working on how to calculate it*.".

The Sustainability Manager provided some context on what is being worked on in terms of measurements: "*We know we want an R index, a circulation index, a number to determine how circular we are*"

The lack of standardization was noted not only in measurements but also in processes. One Maintenance Engineer described the difficulties associated with repairs and remanufacturing:

"*To repair, the problem in my site is that if we have to send a spare part to an external company it is done by a maintenance engineer; if we don't have time or knowledge it sits at someone's desk.*"

This sentiment was echoed by the Technology Manager in maintenance, who, regarding the process for repair and refurbishment, described the ongoing uncertainty:

"*What should be the parameters if we go for refurbished or buy a new part?*" and stressed the need for a standardised determination process when deciding to send a part to a supplier for repair or refurbishment:

"*We need a simple internal model that could be the one deciding whether we should send the Request for Quotation or not.*".

A Maintenance Engineer described how the economic value of repair must be evident, stating: *"… it isn't enough to track which parts are repairable, we need how much we spend to repair vs. buy new*."

The questionnaire respondents deemed *Complex implementation* as the biggest barrier and the Technology Manager in maintenance shared a similar view, adding the following comment on implementation: "*It must be easy. If it takes a lot of effort to measure, it won't happen.*". The

Sustainability Manager added that “*If it’s integrated in our existing system… and automated, then people will use it. If it’s an extra step, it won’t happen*”.

Lack of Management Support was identified as a moderately significant barrier but considered one of the most important enablers by questionnaire respondents, a notion that was strongly reflected in the interviews as well. The Technology Manager in maintenance emphasized the role of leadership, stating: *"The most critical one… is the management commitment."* Similarly, the Sustainability Manager stressed the need to begin with leadership when raising awareness and driving change, adding: *"We need to educate management and raise awareness… it’s hard to navigate all the EU and emission rights otherwise."*

On the topic of leadership and CE the interviews further suggested that the path forward remains uncertain. The Sustainability Manager remarked: *"We want to measure circularity at a site level in order to, by 2030, be 100% circular, but today we don’t know entirely how to do that."*

An important enabler for CE was *Collaboration with suppliers and external partners* and this notion was found in the interviews as well. The XPS Director stated that sustainability parameters need to be more established in the purchasing decision: “*The sustainability parameters affecting the performance the machines will challenge the project teams to take the best decisions in terms of costs and environment at the when choosing between options*”

Lastly, the interviews addressed the cultural aspect of CE within PM, a perspective not covered in the questionnaire. When reflecting on barriers when it comes to CE implementation in PM, the Technology Manager stated:

"The challenge is to get the conservative maintenance organization to understand they impact sustainability," and on the transition from reactive to preventive maintenance there needs to be change of culture: *"We still celebrate the ‘firefighters’ who fix things quickly. But that breakdown might happen again in five months. We need a culture change to think long-term."*. and added:

“*The earlier the start, more we can talk about the long-term consequences of the decisions, what environmental and sustainability effect it will have*.”

One of the Maintenance Engineers shared a sentiment, expressing: *"If we don’t build a culture for sustainability, we won’t have actions."* The technician went on to describe how safety was once a major issue within the maintenance organization, but through a cultural shift, a "*safety culture*" was successfully established and proposing that a similar cultural transformation would be necessary to drive sustainability initiatives forward.

6 Analysis and Discussion

This chapter presents the integration of the CE perspective into the PM function at the case study company in terms of indicators, framework and deployment considerations. Drawing on both questionnaire responses and interview insights, the chapter begins by analyzing how CE indicators from the literature align with the current practices, preferences, and challenges in the PM organization. It then introduces a structured maturity framework which links CE indicators to data complexity and availability, enabling implementation approach across different levels of the PM maturity framework. Finally, the chapter explores practical considerations for CE indicator deployment, including key enablers and barriers, segmented by data adoption, PM maturity, CE familiarity, and cross-functional collaboration and relates them to the levels in the framework

6.1 Identification of CE Indicators Suitable for PM

The questionnaire indicated that CE is seldom integrated into PM at the case company. However, the interviews painted a somewhat more hopeful picture. The interviewees expressed enthusiasm about the potential for closer collaboration moving forward and recognized the distinct value PM could bring to advancing circularity. For instance, the Sustainability Manager highlighted PM's potential contribution to CE, and stated:

"*Maintenance has huge impact... extending machine life, reducing waste, being able to renovate instead of throwing things away.*".

This reflected a shared understanding of PM's essential role in driving CE efforts, indicating that the case company is aligned with the view that PM directly supports the technical cycle of the Butterfly Diagram by the Ellen MacArthur Foundation (2019) through actions like maintain/prolong, reuse/redistribute, and refurbish/remanufacture. It is therefore clear that PM can have a direct impact on CE outcomes. Still, the questionnaire results reveal a concerning disconnect between current PM practices and CE integration. As with any transformation, it is important to measure the transition de Mast and Lokkerbol (2012). Accordingly, the aim of this chapter is to examine how the CE indicators presented in section 4.3 can be applied within PM.

Regarding indicators and data collection, the case study provided several insights into the preferences of the PM organization. The questionnaire revealed that a lack of standardization posed a significant barrier, while clearer industry standards and practices were seen as key enablers. This suggests a strong preference within the PM organization for standardized indicators over those open to interpretation. Additionally, the case study showed a preference for quantitative indicators, i.e., those that produce measurable and trackable data. As such, indicators suited to the PM organization should be both standardized and quantitative. However, this has minimal impact on the selection of CE indicators, as both criteria were already incorporated into the eligibility framework outlined in section 3.2.5 of the literature review. At this stage of the screening, both comprehensive indicators like the *Circularity Index* and more specific metrics such as the *% of hazardous waste over total waste generated* were excluded due to insufficient standardization. Consequently, the 16 CE indicators that remain are all well-defined in terms of implementation and are highly quantitative in nature.

Another major barrier identified in the case study was the complexity of implementation, a concern echoed in the interviews. Both the Technology Manager in maintenance and the Sustainability Manager noted that high complexity could obstruct both adoption and follow-up. While the need for ease of implementation is clear, it is also important to recognize that the case company is still in the early stages of its CE journey. The questionnaire indicated that while most respondents acknowledged maintenance occasionally contributes to CE, the interviews provided evidence that there is currently no clear method for measuring that contribution. This uncertainty, combined with the fact that sustainability initiatives are often deprioritized in PM due to limited resources, could explain why most indicators are initially perceived as complex by the PM organization.

The perceived complexity highlighted in the case study likely stems from limited resources and a need for deeper knowledge, both identified in the findings. However, CE indicators differ in their implementation demands. Some, like *EDM WW*, and *FTE*, are relatively straightforward conceptually. Others, such as *VRE* or *MCI*, are more complex, requiring the integration of both environmental/energy and material/resource data. While each indicator presents its own challenges, the organization's early stage in integrating CE into PM means that many indicators may initially seem complex. The fact that most data types in the case study were viewed as difficult to collect supports this view. Still, this should not lead to the outright dismissal of specific indicators based solely on perceived implementation difficulty at this early stage. Instead, such complexity should be factored into the design of the framework presented in section 6.2 by placing more complex indicators at higher levels in the framework.

When discussing complex implementation, both the Sustainability Manager and the Technology Manager for PM emphasized that automated data capture and calculation would significantly support implementation, usage, and follow-up. In examining the CE indicators and their automation potential, some, such as *WW*, *REC*, and *PTB,* could, once implemented, deliver real-time automated data that can be integrated into operational performance reports. Other indicators, like *RPI* or *PRMCD*, which inform EoL decisions for products and materials, or *LI*, which assesses product/material longevity, initially require manual input but demand no further input beyond periodic recalculation. These recalculations can occur on a scheduled, revisional basis. With the right data infrastructure in place, many of these indicators, most of which are quantitative, could feasibly be automated.

Finally, the case study revealed a clear need for a standardized process in decision-making related to refurbishment, remanufacturing, and recycling. Both the Technology Manager and a Maintenance Engineer described situations where parts are left on a technician's desk awaiting a decision, with the process being unstandardized and, on a case-by-case basis, and the economic value of each decision unclear. Among the CE indicators, several, such as *PRMCD*, *EDM*, and *PTB*, offer either structured decision-making frameworks or ways to track EoL decisions. Additionally, value-based indicators at the product level, like *CEI* and *VRE*, can help demonstrate the economic benefits derived from refurbishment, remanufacturing, and recycling.

In conclusion, to determine which indicators are most recognized for measuring circularity and sustainability within PM and XPS, a literature review was conducted to identify relevant articles featuring CE indicators. These articles were subsequently screened and assessed against eligibility criteria, resulting in a final selection of 16 indicators. These 16 CE indicators were then analyzed in conjunction with the findings from the case study to evaluate their applicability to PM. The case study revealed a preference for CE indicators that are quantitative, standardized, communicative, automated, and that support decision-making related to refurbishment, remanufacturing, and recycling. While some of these preferences, such as being quantitative, based on standardized methodology, and aiding decision-making, were already part of the eligibility criteria, others, including communicative, automation, and specific alignment with refurbishment, remanufacturing, and recycling, emerged as new insights. When these additional criteria were applied to the selected indicators, all 16 were found to be applicable to PM. The final list of indicators is presented in Table 12, and more detail are available in Appendix D. Thereby addressing the first research question of this thesis.

Table 12: CE indicators suitable for PM

CE Indicator	CE Categorization	Source
Material Circularity Indicator (MCI)	Maintenance & Repair, Recycling	Ellen MacArthur Foundation and Design (2015)
Renewable material used (RMU)	Refurbishment & Remanufacturing, Recycling	Stefanos G. Baratsas et al. (2022)
Product-level Circularity Metric (PLCM)	Refurbishment & Remanufacturing, Recycling	Linder et al. (2017)
Total energy consumed (TEC)	Maintenance & Repair	N/A
Longevity Indicator (LI)	Maintenance & Repair	Franklin-Johnson et al. (2016)
Product Recovery Multi-Criteria Decision Tool (PRMCD)	Reuse & Redistribution, Refurbishment & Remanufacturing	Alamerew et al. (2020)
Reuse Potential Indicator (RPI)	Reuse & Redistribution, Recycling	Park and Chertow (2014)
Circular Economy Index (CEI)	Recycling, Refurbishment & Remanufacturing	Di Maio and Rem (2015)
Renewable energy consumed (REC)	Maintenance & Repair	N/A
Material Reutilization Score (MRS)	Refurbishment & Remanufacturing, Recycling	Institute. (2016)
Full time employees (FTE)		N/A
Value-based Resource Efficiency (VRE)	Refurbishment & Remanufacturing, Recycling	Di Maio et al. (2017)
Recoverability rate (RR)	Refurbishment & Remanufacturing, Recycling	Ardente and Mathieux (2014)
Water withdrawal (WW)	Recycling	N/A
Ease of Disassembly Metric (EDM)	Refurbishment & Remanufacturing, Recycling	Vanegas et al. (2018)
Product take-back (PTB)	Refurbishment & Remanufacturing, Recycling	N/A

6.2 Structuring Data and CE Indicators by Maintenance Maturity

This section presents the quantitative foundation for extending the XPS maintenance maturity model to include CE initiatives that expand the model from a cost driven approach to one that includes social and environmental dimensions. While Chapter 6.1 outlined CE indicators from literature and discussed their relevance for PM, the focus here shifts toward linking those indicators to practical data collection realities in industry. The goal is to use different types of maintenance related data in order to assess maturity levels in PM, and from there, connect and recommend CE indicators that match the required data types for each level.

To understand how data availability and complexity relate to maintenance maturity, a scatter plot was constructed using responses from the questionnaire (see Figure 13). Each of the 17 data types is positioned based on two variables: adoption rate and perceived difficulty of collection and analysis. The horizontal axis represents the proportion of respondents who reported that a specific data type is currently collected at their site. This reflects how widely established the metric is in practice. The vertical axis shows the average difficulty score, reported on a scale from 1 (very easy) to 5 (very difficult), indicating the perceived effort required to collect, process, and analyze the data.

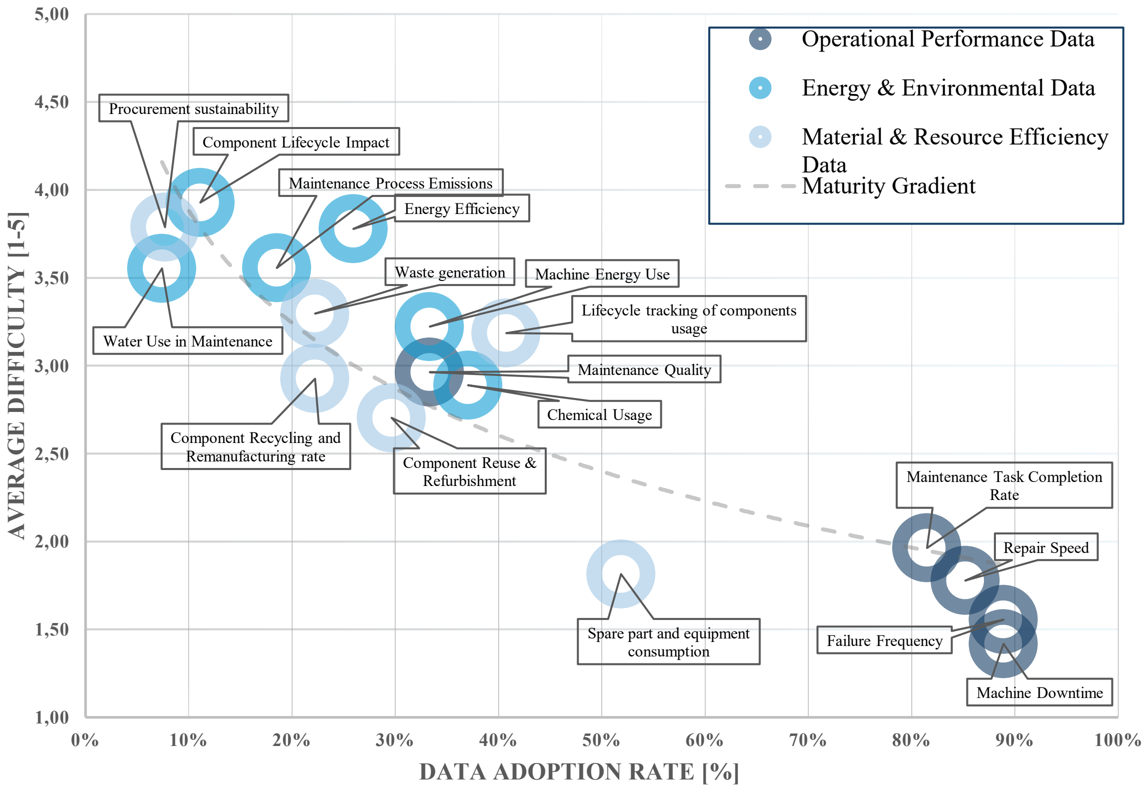

Figure 13: Data adoption rate against perceived difficulty of collection and analysis derived from questionnaire data.

The resulting distribution of data points reveals a clear diagonal pattern. Metrics with high adoption and low difficulty tend to cluster in the lower right corner, while those with low adoption and higher difficulty appear toward the upper left. This diagonal spread is interpreted as a maturity gradient, where metrics closer to the lower right are more foundational and integrated into standard PM practices, and those in the upper left represent more advanced or strategic skills that require greater organizational effort or system maturity to implement. This interpretation is supported by interview insights, where the XPS Director emphasized that as organizations advance in maintenance maturity, they tend to collect and stratify more data to guide improvement efforts.

To translate the maturity gradient into a format that supports practical use, the data points were grouped into five maturity levels based on adoption rate and perceived difficulty of collection and analysis. The thresholds between levels were guided by the visual distribution of the data, where natural groupings could be observed along the diagonal trend. These thresholds were then fine-tuned to reflect clusters of metrics with similar characteristics, as shown in Table 12. While not derived through statistical clustering, the objective was to create a structure that aligns with the way data practices could evolve in industrial maintenance settings.

Table 12: Thresholds for mapping data types into maintenance maturity levels

Maturity Level	Adoption rate	Average Difficulty
Level 1	$X \geq 80\%$	$Y \leq 2.0$
Level 2	$20\% \leq X \leq 80\%$	$1.80 \geq Y \leq 2.95$
Level 3	$20\% \leq X \leq 50\%$	$2.95 \geq Y \leq 3.50$
Level 4	$5\% \leq X \leq 30\%$	$3.50 \geq Y \leq 3.78$
Level 5	$X \leq 15\%$	$3.79 \geq Y$

Rather than being viewed as a rigid classification, this grouping should be interpreted as a roadmap or decision-support tool**.** By positioning each of the 17 data types within one of the five maturity levels, the structure helps practitioners assess their current data capabilities and reflect on which CE indicators are realistic and meaningful to apply. Figure 14 presents the final mapping, where each data point is color-coded by maturity level. The plot serves as a self-assessment reference that distinguishes between foundational, transitional, and advanced stages of data maturity in maintenance practices.

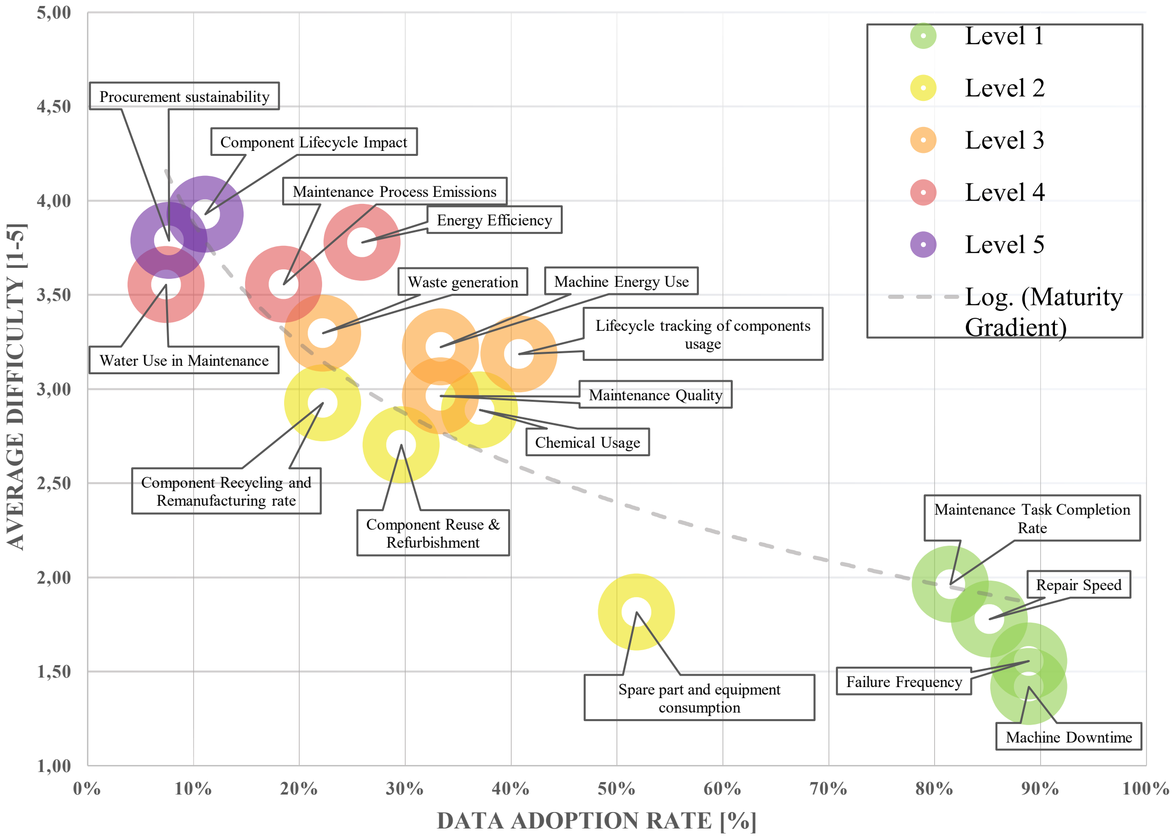

Figure 14: Mapped maturity levels for data types based on threshold criteria

6.2.1 Assessing Data Types and CE Indicators Across Maturity Levels

Building on the maturity segmentation shown in Figure 14, this section addresses Research Question 2 by exploring how widely recognized CE indicators can be integrated into the maturity model for PM within XPS. The discussion focuses on identifying which indicators are most appropriate for each maturity level, based on the availability and complexity of relevant data types. By doing so, the analysis provides a practical structure for supporting the implementation of sustainable and circular initiatives within maintenance, tailored to the capabilities present at each stage of maturity.

Level 1 - Foundational Metrics and Entry-Level Indicators

Level 1 includes data types that according to the case study result are widely adopted and considered easy to collect and use. Metrics such as *Machine Downtime*, *Failure Frequency*, *Repair Speed*, and *Maintenance Task Completion Rate* are typically system-generated, integrated into standard maintenance systems, and used on a daily basis. Their high adoption and low perceived difficulty suggest that they are well understood and require minimal additional effort. These metrics form the foundation of most maintenance reporting structures and are often the first to be standardized across sites. Given the simplicity and availability of data at this level, only a limited number of CE indicators can realistically be introduced. Rather than complex lifecycle or value-based metrics, suitable indicators at this stage focus on laying the groundwork for energy and resource monitoring. Although no CE indicators from the literature were directly mapped to Level 1, this stage still plays an important role in preparing the environment for CE measurement by establishing a reliable base of operational data practices.

This need for a solid foundation before more advanced strategies is also reflected in the interviews. The Technology Manager emphasized that the current focus is still on preventing breakdowns and stabilizing basic routines before moving toward condition-based approaches or sustainability tracking. This insight reflects the broader principle that circular and sustainable practices can only be built on top of reliable and stable core processes. In this context, Level 1 can be seen as enabling readiness rather than direct indicator implementation.

Level 2 - Progressive Metrics and Early CE Tracking

Level 2 contains metrics that are still accessible but involve slightly more effort to manage, according to our case study. This level includes *Spare Part and Equipment Consumption*, *Chemical Usage*, *Component Recycling and Remanufacturing Rate*, and *Component Reuse & Refurbishment*. These data types may require manual inputs and cross-referencing with material or procurement systems. While not as widely adopted as Level 1 metrics, they are still practical to work with and reflect an early stage of development from basic operational tracking toward resource and material consumption.

At this level, the PM organization is typically able to introduce simple CE indicators that rely on relatively straightforward data inputs. Two such indicators identified from the literature are the *Longevity Indicator* and the *Material Reutilization Score*. Both indicators are suitable for machines and spare parts, are relatively easy to calculate, and produce results that are straightforward to interpret. The *Longevity Indicator* uses initial product lifetime, and reuse and refurbishment lifetime contribution, which can be approximated through maintenance records and refurbishment logs. *The Material Reutilization Score* requires basic data on recyclable or reusable components, which aligns with efforts to track reuse and recycling in maintenance workflows, especially for spare parts. While both indicators may require estimation or partial data at this stage, they represent accessible entry points for measuring CE performance and can be scaled as data maturity improves.

Level 3 - Transitional Metrics and CE Integration

Level 3 includes data types that are moderately adopted and considered more difficult to collect or manage. This group includes *Maintenance Quality*, *Machine Energy Use*, *Lifecycle Tracking of Components*, and *Waste Generation*. These metrics often require input from multiple systems or involve some manual tracking. They are not always standardized across sites, and data availability may vary depending on the scope of local systems and routines. At this stage, maintenance teams typically begin to use data not only for technical follow-up, but also to support circular strategies through more structured and focused improvement projects.

At this level, several CE indicators become feasible to implement, particularly those that assess recoverability, disassembly, and the circular performance of materials and processes. Indicators such as the *Recoverability Rate*, *Total Energy Consumed*, *Full Time Employees*, *Ease of Disassembly Metric*, and *Circular Economy Index* can all be supported using the available data types in this maturity stage. The *Recoverability Rate*, for example, can be used to assess how much of a component or spare part can be recovered at EoL through recycling, reuse, or energy recovery. In a PM context, this indicator helps evaluate the downstream impact of maintenance choices, such as the selection of spare parts or chemicals and lubricants that are more easily recoverable after use. Similarly, the *Ease of Disassembly Metric* becomes relevant when evaluating maintenance-intensive products or subassemblies that require part replacement often. Tracking disassembly attributes can support decisions that reduce labour intensity from a social sustainability perspective and promote the reuse of components.

The *Circular Economy Index* is another relevant indicator at this level. It compares the economic value of recovered materials to the value of the original materials used. In a maintenance setting, this can help assess whether component recovery strategies (such as reclaiming high-value parts, chemicals, or lubricants) deliver actual economic and environmental value. Although adoption at maturity level 3 is still limited, it reflects a turning point where maintenance starts contributing actively to CE performance, not only through operation but also through design feedback and end-of-life strategies.

Level 4 - Advanced Metrics and Systemic CE Performance

Metrics in Level 4 are less commonly adopted and are perceived as difficult to manage. Examples include *Energy Efficiency*, *Maintenance Process Emissions*, and *Water Use in Maintenance*. These data types often require integration with environmental or energy monitoring systems and may involve site-level estimation methods, as noted in the interviews where it was explained by both the XPS Director and the Sustainability Manager that energy consumption data is often only available at the hall level rather than per machine. Tracking them consistently typically demands more developed digital infrastructure, as well as alignment with sustainability or environmental reporting systems. While not impossible to work with, these metrics require a deliberate effort to establish, maintain, and standardize across departments.

At this maturity level, maintenance teams can begin working with CE indicators that link operational data to broader system performance and material strategy. Indicators suited for this level include the *Material Circularity Indicator*, the *Product-Level Circularity Metric*, *Renewable Material Used*, *Value-Based Resource Efficiency*, and *Water Withdrawal*. These indicators typically require detailed data on material inputs and outputs, lifecycle performance, or sourcing profiles, and often depend on collaboration with procurement, product design, or sustainability functions.

For example, the *Material Circularity Indicator* assesses how restorative a product's material flows are by combining information about recycled content, virgin input, and unrecoverable waste. In a maintenance context, the *Material Circularity Indicator* can be used to evaluate the material flows of spare parts and components that are regularly replaced, especially when efforts are being made to shift toward reused or recycled alternatives. The *Product Level Circularity Metric* focuses on the proportion of recirculated value in a product, based on the economic share of reused or remanufactured parts. This can be especially relevant for spare part strategies in maintenance, where components are recovered or sourced through remanufacturing channels. By using this CE indicator, teams can evaluate whether their spare part decisions contribute to higher circularity from a value-chain perspective.

What distinguishes this level from earlier ones is that the indicators no longer assess internal performance alone. They begin to reflect how maintenance connects to the product system, including sourcing, lifecycle impacts, and recovery planning. As such, the ability to work with these indicators signals a more advanced level of maturity where CE data is integrated into strategic decision-making.

Level 5 - Strategic Metrics and System-Wide CE Integration

Level 5 includes the most advanced and least commonly adopted data types identified in the case study, such as *Procurement Sustainability* and *Component Lifecycle Impact.* These metrics often require data that extends beyond the maintenance function, drawing from procurement, lifecycle systems, or energy infrastructure. From a maintenance perspective, they demand structured traceability, integration with external systems, and the capacity to support decision-making that covers the entire product or equipment lifecycle.

At this stage, CE indicators focus less on direct operational performance and more on guiding strategic recovery decisions and system-wide outcomes. Indicators well suited for Level 5 include the *Product Recovery Multi-Criteria Decision Tool*, the *Reuse Potential Indicator*, *Renewable Energy Consumed*, and *Product Take-Back*. These indicators typically rely on structured processes and decision frameworks, even if the calculation itself is relatively straightforward.

The *Product Recovery Multi-Criteria Decision Tool* can help evaluate whether a component should be reused, remanufactured, recycled, or discarded, based on environmental and business-related criteria, and therefore covers a wide range of circular strategies to choose from. In maintenance, this supports structured decisions about EoL treatment for parts and systems that are routinely serviced or replaced. The *Reuse Potential Indicator* further supports this by assessing whether spare parts or materials can realistically be recovered using current technologies, guiding technicians and planners in prioritizing components for internal reuse rather than disposal. The *Renewable Energy Consumed* indicator becomes relevant at this level when energy consumption can be tracked at a more detailed level and tied to renewable sourcing. Maintenance activities such as improving machine uptime or replacing outdated equipment can then be linked to improvements in the site's overall renewable energy performance. Similarly, *Product Take-Back* tracking can be supported through maintenance activities that involve the return of worn or defective parts to suppliers or remanufacturers, providing data on what is returned, how frequently, and under what conditions.

What distinguishes Level 5 is not necessarily the complexity of the indicators themselves, but the strategic and system-level integration required to implement them. These indicators depend on collaboration across departments, structured decision models, and an organization-wide alignment with CE principles. Maintenance becomes a proactive contributor to sustainable resource management, influencing both the flow of materials and the decisions that influence their long-term value.

6.2.2 Visualizing the Framework

The previous section outlined how CE indicators can be gradually introduced across different levels of maintenance maturity based on the availability and complexity of relevant data types. Through this discussion, a structure emerged for how professional maintenance can support circular economy goals in a practical, staged way.

This section presents that structure in a more compact format, bringing together the outcome of the analysis into a single framework. Table 13 below summarizes which types of data are typically available at each maturity level, and links them to CE indicators that are both relevant and realistically implementable at that stage. The intention is not to prescribe a fixed path, but to show how data readiness in maintenance can guide the selection and rollout of circular economy metrics over time. By aligning indicator complexity with maintenance maturity, the framework provides a scalable foundation for integrating CE into existing practices, starting from basic tracking, and moving toward strategic measurement and cross-functional coordination.

Table 13: Suggested maturity framework for PM within XPS.

Maintenance Maturity Level	Suggested CE Indicators	Capabilities and Description
Level 1 – Foundational	No formal indicators in this stage. Focus at this level is on establishing routines and foundational maintenance data collection.	Basic operational metrics tracked within PM, such as downtime, failure frequency, and repair speed. Focus at this level for PM is on establishing routines and foundational operational performance related data collection.
Level 2 – Progressive	Longevity Indicator (LI) Material Reutilization Score (MRS)	Resource-related metrics such as spare part consumption, chemical usage, and basic reuse tracking. Moderate adoption with slight manual input. Introduce simple, maintenance-driven CE metrics related to reuse and lifetime extension.
Level 3 – Transitional	Recoverability Rate (RR) Ease of Disassembly Metric (EDM) Total Energy Consumed (TEC) Circular Economy Index (CEI) Full Time Employees (FTE)	Intermediate data such as machine energy use, waste generation, and disassembly or lifecycle tracking. Requires cross-system inputs. Begin evaluating recovery potential and material flows to support CE improvement.
Level 4 – Advanced	Material Circularity Indicator (MCI) Product-Level Circularity Metric (PLCM) Renewable Material Used (RMU) Value-Based Resource Efficiency (VRE)	Environmental performance and lifecycle data, such as energy efficiency, emissions, and renewable material usage. High complexity, low adoption. Link maintenance data to product system impacts, sourcing, and material strategy.
Level 5 – Strategic	Product Recovery Multi Criteria Decision-Tool (PRMCD) Reuse Potential Indicator (RPI) Renewable Energy Consumed (REC) Product Take-Back (PTB)	Strategic data including product take-back, recovery planning, and supplier-linked sustainability metrics. Requires full integration with external systems. Use maintenance insights to inform circular decision-making across the full lifecycle.

6.3 Deployment Considerations

This section analyzes how perceptions of barriers to CE indicator implementation vary across different levels of PM maturity, data adoption, CE familiarity, and cross-functional collaboration. It expands on earlier discussions by identifying which challenges diminish with increased experience and structural integration, and which persist regardless of maturity. The aim is to highlight key leverage points for reducing barriers and enhancing CE deployment in maintenance organizations.

6.3.2 Barrier Deployment Analysis

This chapter analyses the barrier data presented in the results by segmenting it according to data adoption level, PM maturity, familiarity with CE, and the degree of collaboration between maintenance and sustainability teams, to identify implementation implications.

Starting with data adoption, the segmentation of barrier perceptions based on respondents' level of data adoption maturity suggests that those with higher data adoption tend to perceive barriers as less significant (see Figure 15). Interestingly, in the interviews, the Director of XPS described how higher PM maturity leads to more collected data. Which suggests that an increase of PM maturity leads to an increase in data collection and when more data is being collected, then the barriers for CE in PM are perceived as lower. It could be that higher maturity PM organizations have experience or established routines for data collection improvements and thus more receptible for such improvement work. The sharp decrease in *Lack of knowledge* seem to suggest that a PM organization with higher data adoption believe they have the knowledge and tools to implement CE indicators in PM.

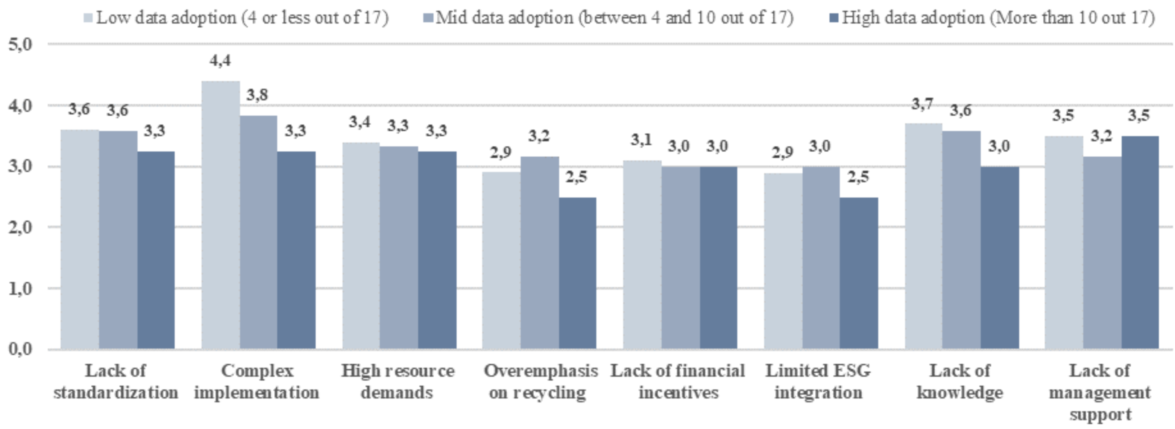

Figure 15: CE Indicator implementation barrier segmented on data adoption

Continuing, the barriers *High resource demands* and *Lack of financial incentives* are perceived similarly across all maturity levels, indicating that these may represent more substantial challenges that are not easily mitigated through increased data maturity. The fact that the perception of *High resource demands* stays the same regardless of data adoption level, may represent the fact that the PM organization always needs to balance the operational work with improvement work regardless of level, a Maintenance engineer, Technology

Manager and the Director of XPS described prioritization and how delivery is often prioritized over all other KPIs.

In contrast, *Complex implementation* emerges as a particularly prominent barrier among respondents with low data adoption. The decline in its perceived significance with increasing data maturity suggests that this barrier is especially pronounced during the early stages of data adoption. This may relate to *Lack of knowledge* which, as previously noted, declines as data adoption increases.
No clear trend is observed in the perception of Lack of management support indicating that this barrier is considered important across all levels of data adoption. The slight dip in its perceived importance among respondents with mid-level data adoption may suggest that management support is particularly critical in the early stages to drive initial efforts and remains important at higher levels to enable data stratification and leverage strategic benefits. The Director of XPS stressed both the importance and the challenge with data stratification and the combined perspectives may suggest that a push at high data adoption is needed to make the most of the new data maturity.

Having plotted the respondents input on barrier perception segmented on degree of data adoption, the same was done for maintenance maturity. The segmentation shows that it is not uncommon for respondents to have a similar perception of barriers, see Figure 16.

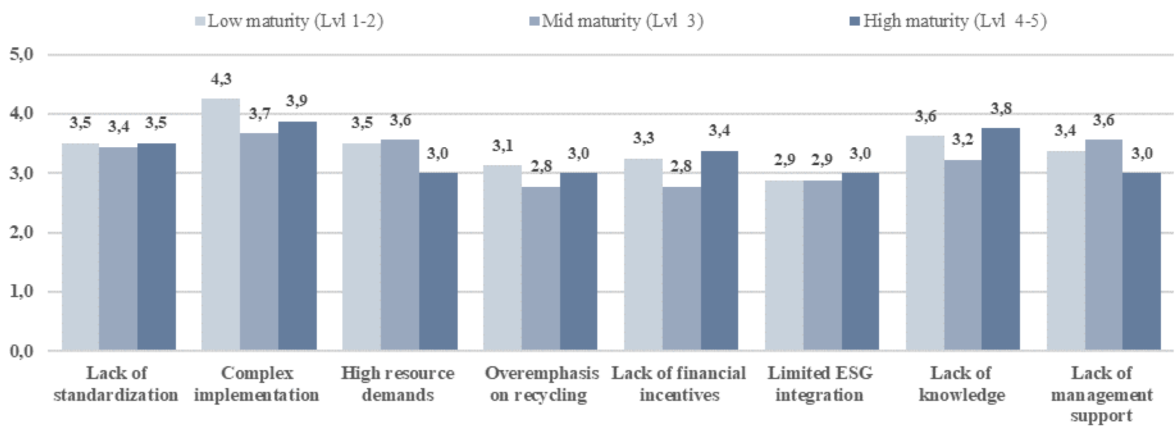

Figure 16: CE Indicator implementation barrier segmented on current PM maturity level

Respondents in the low maturity group perceive *Complex implementation* as the most severe barrier, which aligns with earlier findings when segmenting by data adoption. This perception may again be linked to a *Lack of knowledge*. The importance of learning and understanding

was stressed by the Sustainability Manager, the Technology Manager, and a Maintenance Engineer as the single most critical factor when implementing CE in PM. This suggests that increasing knowledge could directly reduce the perception of barriers.
Regarding *High resource demands,* respondents with high maturity levels view this as a less significant challenge, implying that more mature PM functions are more resource-efficient and which could mean that they spend less time on reactive tasks (Firefighting) and more on strategic development and preventive measures. This finding is consistent with the general idea of PM development, as maintenance maturity increases there should be a progressive shift toward preventive practices, see chapter 2.3.

Continuing the analysis by segmenting respondents' perceptions of barriers based on their familiarity with CE (see Figure 17), a clear trend emerges across all data types: the more familiar respondents are with CE, the less severe they perceive the barriers to be. This suggests that CE familiarity plays a critical role in overcoming implementation challenges. Increasing CE knowledge can significantly reduce perceived barriers in PM, making it a valuable starting point early in the transition process. This approach aligns with insights from the Director of XPS, who noted that a broad CE education had already been initiated at the site in question which seem like the right strategic move based on these findings.

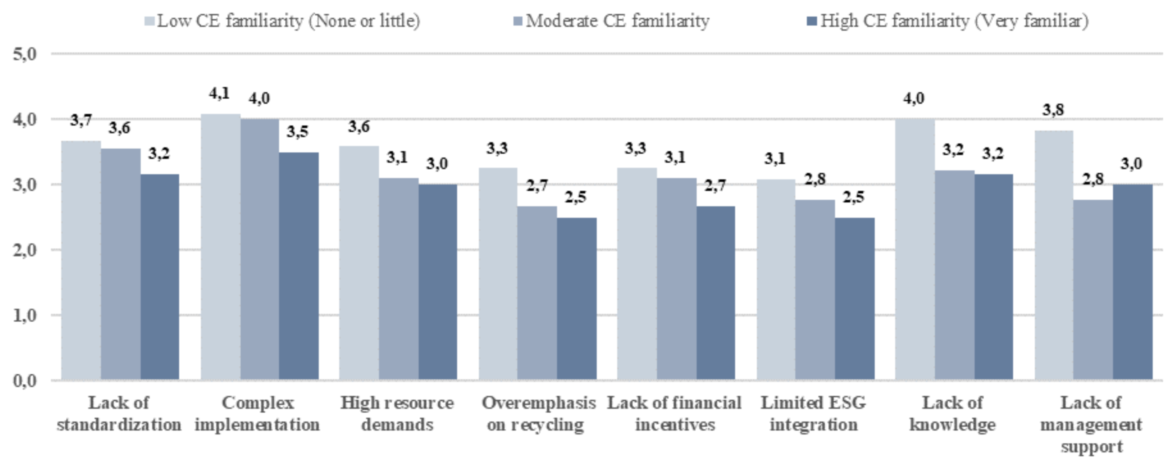

Figure 17: CE Indicator implementation barrier segmented on CE familiarity

Moreover, *Complex implementation* is perceived as significantly less challenging by respondents who are highly familiar with CE, further supporting the notion that much of the perceived complexity stems from a lack of knowledge and understanding. Once again, this highlights the importance of prioritizing CE education early in the implementation journey.

To conclude the segmentation of perceived barrier data, Figure 18 presents the results based on the degree of collaboration between the maintenance and sustainability functions. A clear trend emerges; barriers are perceived as less difficult to overcome when there is strong collaboration between these teams.

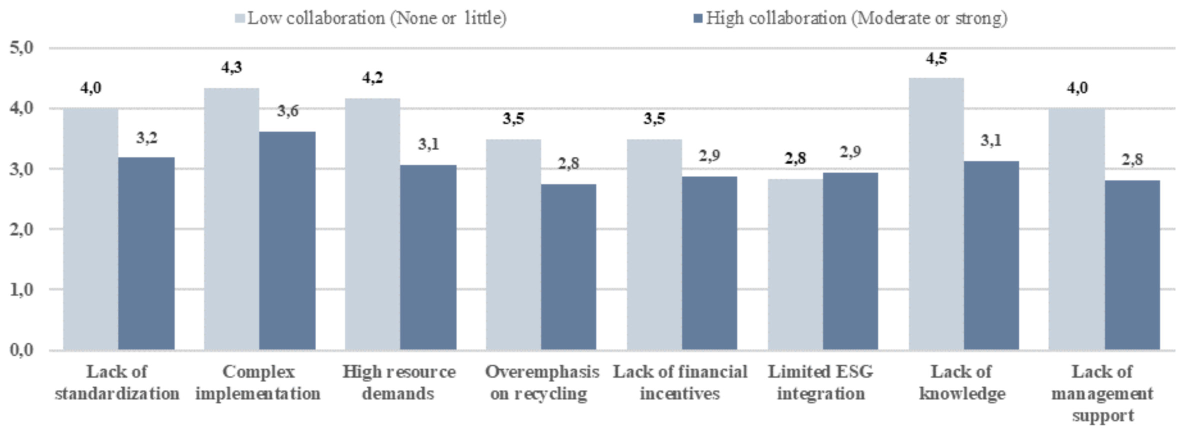

Figure 18: CE Indicator implementation barriers segmented on collaboration between maintenance and sustainability teams

This indicates that collaboration is a foundational barrier to CE implementation and should be established as early as possible. Interestingly, the Technology manager provided some insight which might give light to this observation by describing how maintenance becomes more and more connected with other functions as it becomes more mature in terms of PM development. Consequently, it suggests that when the PM organization handles complex topics such as CE, there is a need for cross-functional collaboration which significantly decreases the barriers. This insight is reflected in the literature where Baumer-Cardoso et al. (2021) highlight that multi-department coordination is frequently a barrier to CE implementation. Consequently, there is high evidence, for example, the perceived difficulty of *Lack of knowledge* drops sharply in contexts with high collaboration, suggesting that closer cooperation helps mitigate this barrier. Similarly, notable reductions in the perceived severity of *Lack of standardization*, *Complex implementation* and *Lack of management support* are observed. This may imply that stronger collaboration enables the maintenance function to address CE challenges more independently, reducing reliance on managerial oversight and external guidance.

Interestingly, *Lack of standardization* was perceived rather equally by the respondents regardless of segmentation. The severity of *Lack of standardization* is much more prevalent when compared with the literature review and the fact that 74% of companies use their own

CE frameworks (Roos Lindgreen et al., 2021). If PM organization implements their own solutions, it will create a problem with non-comparable, both within the case company, but mainly externally. On the topic of external communication, *Limited ESG integration* was routinely perceived as a low barrier but provides an important insight that perhaps the external perspective is underrepresented by the respondents.

6.3.1 Enabler Deployment Analysis

The segmentation of enablers by data adoption level presented in Figure 19 reveals several important trends related to how readiness for CE indicator implementation evolves as sites become more data mature.

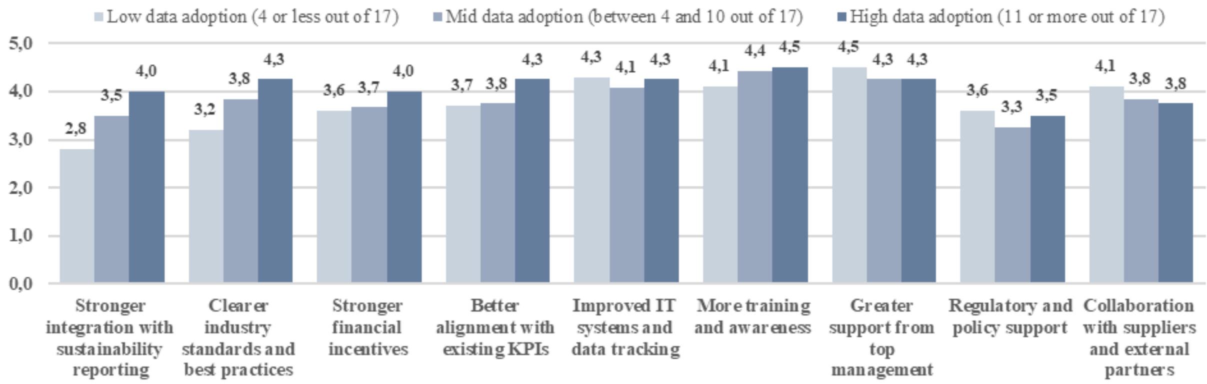

Figure 19: CE Indicator implementation enabler segmented on data adoption

One of the clearest patterns is the increasing perceived importance of "*Stronger integration with sustainability reporting*" as data adoption rises. This could suggest that as maintenance organizations begin collecting and working with a broader range of metrics, there is growing pressure, or opportunity, to connect that data to broader environmental, social, and governance (ESG) goals. When more data becomes available, the demand for aligning with external reporting frameworks and demonstrating progress toward CE targets also tends to increase. In this way, the segmentation indicates that sustainability reporting does not just become relevant after data is available, it becomes a driver for structuring and justifying further indicator development.

A similar trend can be observed in the enablers "*Clearer industry standards and best practices*", "*Better alignment with existing KPI's*", and "*Stronger financial incentives*" which gains importance as data maturity increases. This may reflect a shift in focus from internal development to external alignment. While low-maturity organizations are still building internal processes, those with more advanced data capabilities are likely to seek guidance on how to benchmark, compare, or align their practices with external expectations, whether it is through industry comparisons, legislation, or corporate standards.

Interestingly, "*Greater support from top management*" is rated consistently high across all levels of data maturity. This consistency reinforces a key insight from the barrier analysis: that strategic support is necessary not only to initiate CE efforts, but also to maintain momentum and ensure consistency, regardless of how advanced data collection and analysis have become. Whether an organization is just beginning to integrate CE metrics or indicators into reporting systems, leadership engagement remains critical.

Together, these patterns suggest that as maintenance organizations improve their data capabilities, external alignment becomes a more important part of CE implementation. In the early stages, the focus is often on setting up basic data structures and trying out initial metrics. But as data maturity increases, so does the expectation to connect that data to broader sustainability reporting systems. This is supported by the literature. Several articles highlight the benefits of aligning CE indicators with existing tools such as LCA, MFA, and ESG reporting frameworks. Doing so can make indicators less complex and more valuable across the organization (Baumer Cardoso et al., 2023; Jerome et al., 2022; Valls Val et al., 2022).

Jerome et al. (2022) explains that combining CE indicators with LCA gives a fuller picture of environmental impact, while Valls Val et al. (2022) and Baumer Cardoso et al. (2023) show that using existing reporting structures reduces the extra work needed to track circularity. Therefore, the data suggests that "*Stronger integration with sustainability reporting*" becomes more important for sites with high data maturity. It indicates a shift from using indicators for internal tracking, toward making them part of strategic reporting and cross-company comparisons.

As PM maturity increases, the way organizations perceive enablers for CE indicator implementation also changes (see Figure 20). While some factors remain important across all levels, others become more prominent or fade in relevance depending on the context.

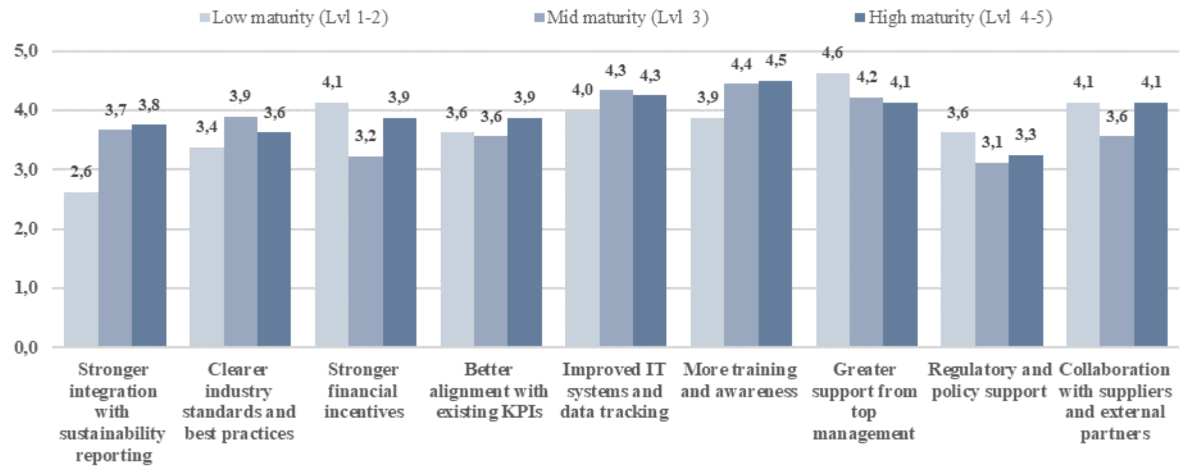

Figure 20: CE Indicator implementation enablers segmented on current PM maturity level

From a PM maturity segmentation perspective, one of the clearest signals is that sites at mid and high maturity level place much greater emphasis on *Stronger integration with sustainability reporting*. This difference could reflect the increasing difficulty of turning complex data into meaningful insights as organizations move beyond basic performance indicators. As noted in interviews, many mature sites have large volumes of performance data, but the challenge lies in stratifying and organizing that data to support the sustainability strategy. This enabler could possibly therefore not just be about technical systems but about building the capability to turn data into value.

Another important finding is that mid-maturity sites view *Clearer industry standards and best practices* as especially critical. This result could make sense in a transitional stage, where the foundation for CE implementations has been laid but clarity is still missing about what to measure and how. The quote from the Sustainability Manager captures this well: “We want an R index to measure circularity at site level… but we don’t know how to do that yet.” In other words, one possibility is that increased maturity brings awareness of the need for structure and often exposes the lack of it.

Lastly, the data suggests that more mature sites place greater importance on *More training and awareness* than those at earlier stages. One possible interpretation of this is that as organizations progress, they become more aware of the complexity involved in implementing CE practices, which in turn increases the perceived value of continued learning. In contrast, respondents from lower-maturity sites may not yet view training as a central enabler, possibly because their current focus is on more immediate operational challenges. This contrast highlights how the need for training may become more apparent as organizations gain experience and begin working with more advanced systems and indicators.

Taken together, the findings suggest that maturity level may not only influence which enablers are prioritized, but also how they are understood. The data indicates that lower-maturity sites may place more weight on top-down support and guidance to get started, while more mature sites tend to focus on issues related to structure, knowledge sharing, and scaling.

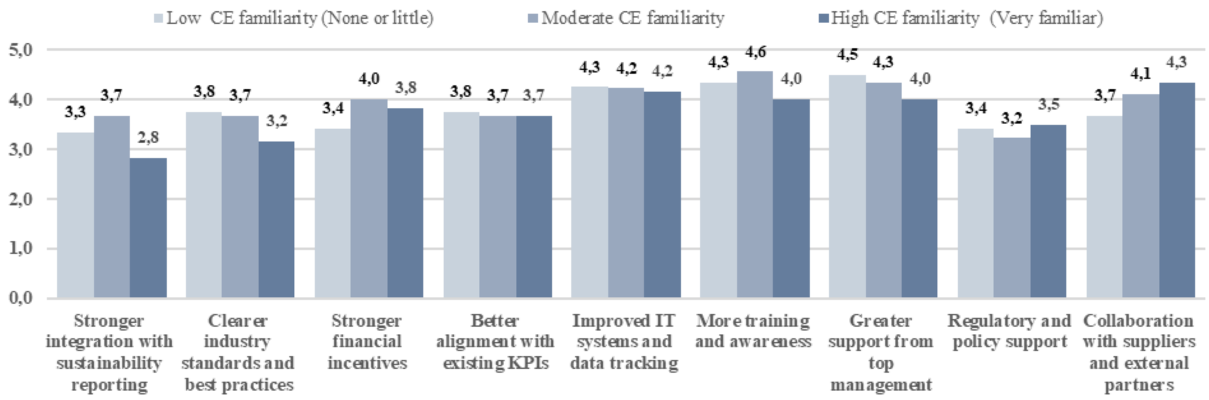

Figure 21: CE Indicator implementation enablers segmented on CE familiarity

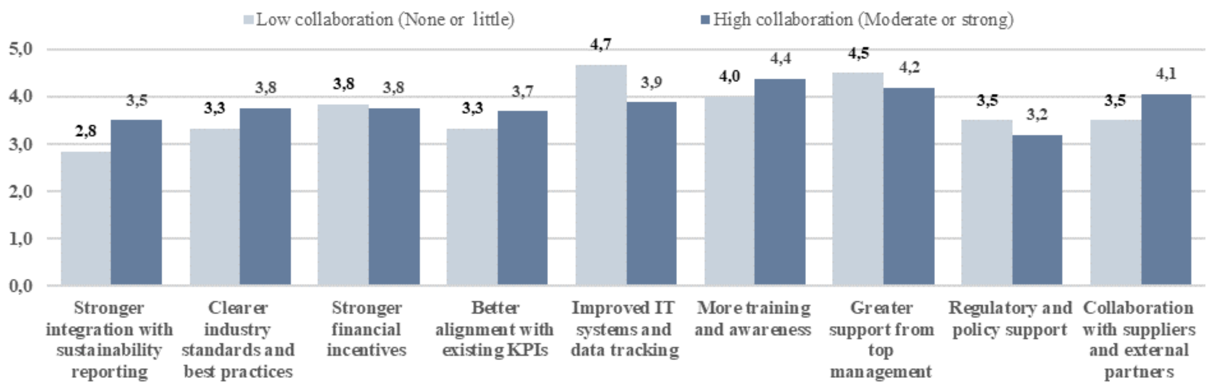

Figure 22: CE Indicator implementation enablers segmented on collaboration between maintenance and sustainability teams

By segmenting the data by respondents' familiarity with CE as well as collaboration between maintenance and sustainability teams, a few interesting differences appear in how enablers are perceived (see Figure 21). These findings point to how knowledge and experience with CE and cross-functional collaboration may shape not only technical readiness but also broader views on responsibility.

One of the clearest trends is that *Collaboration with suppliers and external partners* is seen as more important both by those with high CE familiarity and high collaboration. This could imply that once individuals understand how CE functions in practice, they become more aware of the role external actors play in enabling circularity. Rather than seeing CE as something managed entirely within operations, those with stronger CE knowledge and high collaboration may recognize how supplier relationships, sourcing decisions, and take-back processes are central to circular performance. This is consistent with an insight from the XPS Director, who explained that sustainability parameters are becoming increasingly important in purchasing decisions.

In contrast, *Greater support from top management* is rated as less important among those most familiar with CE and those that has high collaboration. This trend might suggest that individuals with more knowledge feel better equipped to act independently, without needing as much top-down support. While leadership is likely still valued, the relative importance may decrease as internal motivation and technical understanding increase.

At the same time, some enablers appear unaffected by CE knowledge. For example, *Improved IT systems and data tracking* and *Better alignment with existing KPIs* is consistently rated as important regardless of familiarity. An interpretation of this could suggest that certain challenges are more structural than conceptual and cannot be solved by increasing awareness or cross functional collaboration alone. In other words, education is necessary, but not sufficient, and needs to be supported by technical infrastructure and operational alignment. However, at the same time, as CE familiarity increases, the focus appears to shift from internal structures to broader collaboration and independent action, supporting the insight that CE maturity is much about changing perspective, rather than just about building, and improving systems.

6.4 Finalized Framework

This final section presents the completed framework developed to support the integration of CE indicators into the PM maturity model within XPS. The framework builds on the foundation laid in Chapter 6.2, where appropriate CE indicators were matched to maturity levels based on data availability and collection difficulty. In Chapter 6.3, this structure was extended with an analysis and discussion of key organizational enablers and barriers that influence the successful deployment of CE initiatives. Together, these two perspectives form a combined model that is both technically grounded and paired with the organizational context in which it will be applied. The framework is structured across all five maturity levels, but consolidated into low, mid, and high maturity categories to reduce redundancy and improve clarity. Each level includes suggested indicators, associated data types, and corresponding deployment considerations. The insights are drawn directly from the case study and survey data, and supported by relevant literature, making the framework grounded in both empirical data and studied literature.

In the following sections, the final framework is presented both in table format (see Table 14) and corresponding deployment considerations for each maturity phase as a brief level-by-level narrative.

Table 14: Finalized PM maturity framework, addressing all three thesis research questions

Maintenance Maturity Level	**Suggested CE Indicators**	**Capabilities and Description**	**Deployment considerations**
Level 1 – Foundational	No formal indicators in this stage. Focus at this level is on establishing routines and foundational maintenance data collection.	Basic operational metrics tracked within PM, such as downtime (MDT), failure frequency (MTBF), and repair speed (MTTR). Focus at this level for PM is on establishing routines and foundational operational performance-related data collection.	At low maturity (level 1-2), the main barriers include lack of knowledge, limited collaboration, and perceived complexity. These are often due to unclear roles and little experience with CE practices. To move forward, strong top management support is essential, along with basic training and early collaboration between maintenance and sustainability teams. The focus should be on awareness and creating readiness, not on implementing complex indicators.
Level 2 – Progressive	Longevity Indicator (LI) Material Reutilization Score (MRS)	Resource-related metrics such as spare part consumption, chemical usage, and basic reuse tracking. Moderate adoption with slight manual input. Introduce simple, maintenance-driven CE metrics related to reuse and lifetime extension.	
Level 3 – Transitional	Recoverability Rate (RR) Ease of Disassembly Metric (EDM) Total Energy Consumed (TEC) Circular Economy	Intermediate data such as machine energy use, waste generation, and disassembly or lifecycle tracking. Requires cross-system inputs. Begin evaluating recovery potential and material flows to support CE improvement.	At mid-maturity (level 3), the focus shifts toward structuring and scaling initial efforts. Common barriers include lack of standardization and uncertainty around measurement. These challenges reflect a growing awareness of what is missing.

	Index (CEI) Full Time Employees (FTE)		Enablers at this level include clearer CE methods, improved IT systems, and alignment with existing KPIs.
Level 4 – Advanced	Material Circularity Indicator (MCI) Product-Level Circularity Metric (PLCM) Renewable Material Used (RMU) Value-Based Resource Efficiency (VRE)	Environmental performance and lifecycle data, such as energy efficiency, emissions, and renewable material usage. High complexity, low adoption. Link maintenance data to product system impacts, sourcing, and material strategy.	At high maturity (level 4-5), barriers relate to managing complexity, especially organizing, and visualizing large volumes of data, and maintaining engagement across teams. Resource demands remain high, particularly for strategic alignment and external communication. Key enablers include automated systems, supplier partnerships, and integration with ESG reporting. Efforts should focus on making CE work scalable, standardized, and embedded in long-term strategy.
Level 5 – Strategic	Product Recovery Multi Criteria Decision-Tool (PRMCD) Reuse Potential Indicator (RPI) Renewable Energy Consumed (REC) Product Take-Back (PTB)	Strategic data including product take-back, recovery planning, and supplier-linked sustainability metrics. Requires full integration with external systems. Use maintenance insights to inform circular decision-making across the full lifecycle.	

Low maturity sites - Deployment considerations for CE initiatives

At the lowest levels of maturity, PM organizations are primarily focused on establishing operational stability through basic data collection and routine-based practices. As highlighted in the case study, metrics such as machine downtime, failure frequency, repair speed, and the move towards recycling and reuse rates are commonly tracked and integrated into daily maintenance work. These metrics are typically system-generated and widely understood, making them well suited to support foundational monitoring but not yet advanced enough to enable more strategic CE indicator use.

In terms of deployment, the introduction of CE initiatives at this level is limited by several organizational conditions. Barriers such as lack of knowledge, complex implementation, and limited cross-functional collaboration are especially prominent in this stage. Interviews with site personnel confirmed that CE is often not structurally integrated into maintenance activities and that the connection between maintenance and sustainability is still loosely defined. As the Maintenance Technician explained, "*There isn't a lot of PM understanding which is really holding us back in terms of maturity.*" This points to a knowledge gap not only in CE concepts but in structured maintenance development more broadly.

For organizations in the early stages of PM maturity, the deployment of CE initiatives should focus on building foundational readiness. The most important enablers at this level are strong top management support, basic CE training and awareness, and the initiation of collaboration between maintenance and sustainability teams. These elements help reduce perceived complexity and make early CE efforts more tangible and achievable. Key barriers to address include limited CE knowledge, perceived complex implementation and high resource demands, and the absence of simple, shared routines for integrating CE considerations. Overcoming these obstacles can establish the conditions necessary for more advanced CE deployment at higher maturity levels.

Mid maturity sites - Deployment considerations for CE initiatives

At the mid-point of maturity, maintenance organizations typically move from routine data tracking and begin integrating more advanced data such as energy use, component lifecycle tracking, and waste generation. As this integration of advanced data develops, PM begins to play a wider role by also supporting the company's sustainability goals.

Deployment of CE initiatives at this level is no longer limited by basic understanding but instead challenged by how to structure, standardize, and scale efforts. According to the segmentation analysis, lack of standardization and uncertainty around what to measure become prominent barriers. This is also reflected in interviews, where the Sustainability Manager noted that they would like to measure circularity at site level, but that they don't know how to do that yet. These insights point to a growing demand for practical tools, shared methods, and clearer indicator frameworks.

In mid-maturity levels, deployment success depends on translating awareness into structure. Key enablers include clearer industry standards, alignment with existing KPIs, and improved IT systems that can handle more advanced data inputs. At the same time, resource constraints and the absence of standardized CE routines can slow progress if not addressed. To move forward, organizations at this stage should prioritize coordinating practices across teams and implementing CE tracking into existing performance systems, laying the groundwork for more advanced integration at higher maturity levels.

High maturity sites - Deployment considerations for CE initiatives

In high-maturity maintenance organizations, systems are in place, indicators are more advanced, and reporting often linked to broader sustainability goals. But while the technical data foundation is strong, the case study shows that new barriers emerge when CE becomes part of everyday operations. One of the most prominent barriers at this level is the difficulty of stratifying and organizing large volumes of data. As the XPS Director described in the interviews, it is very hard to stratify data and to analyze it in a way that supports the overarching goals. This reflects a shift from collecting data to making it usable and valuable, which is a challenge that becomes more visible only when data maturity is already high. The segmentation also supports this: mature sites consistently rate "*Integration with sustainability reporting*" as more important than less mature ones, suggesting that the barrier is not data absence, but the effort required to structure and align data with strategic goals.

Another key challenge is sustaining progress without overloading the organization. Respondents described how high-maturity teams still face resource constraints, but of a different kind. Rather than lacking time to get started, they now struggle with the long-term effort needed to maintain CE initiatives, engage suppliers, and update digital systems.

To overcome these challenges, the most important enablers are scaling and reporting mechanisms. Mature sites benefit from automated tracking systems that reduce the burden of manual reporting and help translate more advanced data into visual, actionable insights. They also need strategic partnerships, particularly with suppliers, to expand the scope of CE work beyond the plant level. Finally, alignment with ESG reporting becomes not just a compliance need, but a way to ensure that CE indicators are embedded into the company's long-term planning and investments.

7 Conclusion

PM’s role and contribution are essential to advancing sustainability within manufacturing systems. Despite growing CE awareness, its practical integration into established, traditionally cost-driven XPS framework remains limited, particularly in the domain of PM. In response, this thesis set out to explore how CE indicators can be deployed within PM to support a transition from cost-efficiency models to sustainability-oriented strategies.

Through a systematic literature review and a case study at the company this study identified 16 indicators deemed suitable for PM which preferred quantitative, automatic, decision-supporting and standardised indicators. These indicators were then mapped towards appropriate levels in the parallel framework based on data adoption and perceived difficulty. Lastly, deployment considerations for the model were discussed with top-management support, increased cross-functional collaboration and training in low maturity. Mid maturity needs to align CE methods internally to match IT-infrastructure and existing KPIs while high maturity needs to consider the difficulties associated with strategic alignment, external reporting and data stratification.

This research contributes academically and industrially by offering a way to contextualize and prioritize CE indicators within PM. The framework not only highlights which indicators are feasible at various stages of maintenance maturity but also considers practical deployment enablers and barriers.

The limitations of this study include its focus on a single company, which restricts the generalizability of findings, and the framework is not verified in its application. Nonetheless, the methodology and framework presented offer a replicable approach for other organizations seeking to integrate CE into PM. Future research could expand on this by applying the framework across different sectors cross-sectionally, validating indicator effectiveness, deployment considerations, through longitudinal studies, and exploring integration the relationship between CE and PM.

By bridging theoretical insights with industrial practice, this thesis offers an industry-grounded yet forward-looking approach to embedding circularity into PM, ultimately contributing to a broader transition towards sustainable manufacturing systems.

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Appendices

Appendix A – Extracted CE Indicators from SLR

Author	Indicator
Aranda-Usón et al. (2020)	material circularity indicator
Aranda-Usón et al. (2020)	circular economy index
S. G. Baratsas et al. (2022)	% of Diverted waste over Total waste generated
S. G. Baratsas et al. (2022)	% of Hazardous waste over Total waste generated
S. G. Baratsas et al. (2022)	% of Material to be reclaimed/recovered
S. G. Baratsas et al. (2022)	% of Non fossil fuel energy generated over Total energy generated
S. G. Baratsas et al. (2022)	% of Other water discharge over Total water discharge
Baratsas et al. (2022)	% of Packaging material to be reclaimed/recovered
Baratsas et al. (2022)	% of Recycled input material used
Baratsas et al. (2022)	% of Recycled packaging material used
Baratsas et al. (2022)	% of Recycled/reused water over Total water withdrawal
Baratsas et al. (2022)	% of Renewable energy consumed over Total energy consumed
Baratsas et al. (2022)	% of Renewable material used
Baratsas et al. (2022)	% of Renewable packaging material used
Baratsas et al. (2022)	% of Reusable, compostable or recyclable material used
Baratsas et al. (2022)	% of Reusable, compostable or recyclable packaging material used
Baratsas et al. (2022)	% of Water consumed over Total water withdrawa
Baratsas et al. (2022)	Average lifespan of product or Warranty provided
Baratsas et al. (2022)	Average lifespan of product or Warranty provided
Baratsas et al. (2022)	Average specific CO2 emissions
Baratsas et al. (2022)	Average specific CO2 emissions
Baratsas et al. (2022)	Certified buildings and facilities i.e LEED
Baratsas et al. (2022)	Circular Economy Indicator Prototype
Baratsas et al. (2022)	Circular Economy Toolkit
Baratsas et al. (2022)	Direct GHG emissions
Baratsas et al. (2022)	Diverted waste from disposal
Baratsas et al. (2022)	Emissions neutralized by carbon offset projects
Baratsas et al. (2022)	Emissions of ODS over Number of products sold
Baratsas et al. (2022)	Emissions of ODS over Operational space
Baratsas et al. (2022)	Emissions of ODS over Products sold
Baratsas et al. (2022)	Emissions of ODS over Total energy delivered
Baratsas et al. (2022)	Emissions of ozone-depleting substances
Baratsas et al. (2022)	Energy indirect GHG emissions
Baratsas et al. (2022)	Environmental fines
Baratsas et al. (2022)	Environmental fines over Number of products sold
Baratsas et al. (2022)	Environmental fines over Operational space
Baratsas et al. (2022)	Environmental fines over Products sold
Baratsas et al. (2022)	Environmental fines over Total energy delivered
Baratsas et al. (2022)	Fresh water discharge
Baratsas et al. (2022)	Full time employees
Baratsas et al. (2022)	material circularity indicator

Baratsas et al. (2022)	Material to be reclaimed/recovered
Baratsas et al. (2022)	Net total emissions over Number of products sold
Baratsas et al. (2022)	Net total emissions over Operational space
Baratsas et al. (2022)	Net total emissions over Products sold
Baratsas et al. (2022)	Net total emissions over Total energy delivered
Baratsas et al. (2022)	Nitrogen oxides [NOx], sulfur oxides [SOx] & other significant air emissions
Baratsas et al. (2022)	Non-renewable material used
Baratsas et al. (2022)	Non-renewable packaging material used
Baratsas et al. (2022)	NOx, SOx, and other significant air emissions over Number of products sold
Baratsas et al. (2022)	NOx, SOx, and other significant air emissions over Operational space
Baratsas et al. (2022)	NOx, SOx, and other significant air emissions over Products sold
Baratsas et al. (2022)	NOx, SOx, and other significant air emissions over Total energy delivered
Baratsas et al. (2022)	Operational building/facilities
Baratsas et al. (2022)	Other water discharge
Baratsas et al. (2022)	Packaging Material to be reclaimed/recovered
Baratsas et al. (2022)	Paper consumption
Baratsas et al. (2022)	Paper consumption over Full Time Employees
Baratsas et al. (2022)	Product-level Circularity Metric
Baratsas et al. (2022)	Products sold
Baratsas et al. (2022)	Recycled input material used
Baratsas et al. (2022)	Recycled packaging material used
Baratsas et al. (2022)	Renewable energy consumed
Baratsas et al. (2022)	Renewable material used
Baratsas et al. (2022)	Reusable, compostable or recyclable material
Baratsas et al. (2022)	Reusable, compostable or recyclable packaging material
Baratsas et al. (2022)	Revenues
Baratsas et al. (2022)	Single-use plastics consumption
Baratsas et al. (2022)	Single-use plastics consumption over Full Time Employees
Baratsas et al. (2022)	Total energy consumed
Baratsas et al. (2022)	Total energy consumed over Number of products sold
Baratsas et al. (2022)	Total energy consumed over Operational space
Baratsas et al. (2022)	Total energy consumed over Products sold
Baratsas et al. (2022)	Total energy generated
Baratsas et al. (2022)	Total non fossil fuel energy generated
Baratsas et al. (2022)	Total social investment for environmental sustainability and circular economy
Baratsas et al. (2022)	Total use of products
Baratsas et al. (2022)	Volume of flared hydrocarbon
Baratsas et al. (2022)	Volume of vented hydrocarbon
Baratsas et al. (2022)	Waste generated - Hazardous
Baratsas et al. (2022)	Waste generated - Non Hazardous
Baratsas et al. (2022)	Waste generated over Full Time Employees
Baratsas et al. (2022)	Waste generated over Number of products sold
Baratsas et al. (2022)	Waste generated over Products sold
Baratsas et al. (2022)	Water consumption over Full Time Employees

Baratsas et al. (2022)	Water consumption over Number of products sold
Baratsas et al. (2022)	Water recycled or reused
Baratsas et al. (2022)	Water withdrawal
Baratsas et al. (2022)	Water withdrawal over Products sold [m3 water over tons of product]
Baumer-Cardoso et al. (2021)	Circular Transition Indicators
Baumer-Cardoso et al. (2021)	Circularity Facts
Baumer-Cardoso et al. (2021)	Circularity Measurement Toolkit
Baumer-Cardoso et al. (2021)	Circulytics
Baumer-Cardoso et al. (2021)	Expanded Zero Waste
Baumer-Cardoso et al. (2021)	Indicators for Organizations considering Sustainability and Business Models
Baumer-Cardoso et al. (2021)	Material Circularity Indicator
Baumer-Cardoso et al. (2021)	Sustainable Circular Index
Baumer-Cardoso et al. (2023)	CE readiness – MATChE
Baumer-Cardoso et al. (2023)	Circularity and Maturity Firm-Level Assessment tool
Baumer-Cardoso et al. (2023)	Circularity Facts
Baumer-Cardoso et al. (2023)	Circularity Measurement Toolkit
Baumer-Cardoso et al. (2023)	Circulytics 2.0
Baumer-Cardoso et al. (2023)	Indicators for Organizations considering Sustainability and Business Models
Baumer-Cardoso et al. (2023)	Overall Circularity Effectiveness
Baumer-Cardoso et al. (2023)	Sustainable Circular Index
Cottafava and Ritzen (2021)	Building Circularity Indicator
Cottafava and Ritzen (2021)	Demolition EE
Cottafava and Ritzen (2021)	Design for Adaptability
Cottafava and Ritzen (2021)	Design for Deconstruction criteria
Cottafava and Ritzen (2021)	Design for Flexibility
Cottafava and Ritzen (2021)	Embodied CO2
Cottafava and Ritzen (2021)	Embodied Energy
Cottafava and Ritzen (2021)	FLEXI
Cottafava and Ritzen (2021)	Initial Embodied Energy
Cottafava and Ritzen (2021)	Material Circularity Indicator
Cottafava and Ritzen (2021)	Predictive BCI
Cottafava and Ritzen (2021)	Recurrent EE
de Oliveira et al. (2021)	Assessment of Circular Economy Strategies at the Product Level
de Oliveira et al. (2021)	BIM-based Whole-life Performance Estimator
de Oliveira et al. (2021)	Building Circularity Indicators
de Oliveira et al. (2021)	C2C Indicators
de Oliveira et al. (2021)	Circ
de Oliveira et al. (2021)	Circular Building Assessment Prototype
de Oliveira et al. (2021)	Circular Business Model Set of Indicators based on Sustainability
de Oliveira et al. (2021)	Circular Economic Value
de Oliveira et al. (2021)	Circular Economy Benefit Indicators
de Oliveira et al. (2021)	Circular Economy Index
de Oliveira et al. (2021)	Circular Economy Indicator Prototype
de Oliveira et al. (2021)	Circular Economy Measurement Scale
de Oliveira et al. (2021)	Circular Economy Performance Indicator
de Oliveira et al. (2021)	Circular Economy Toolkit
de Oliveira et al. (2021)	Circular Gap

de Oliveira et al. (2021)	Circular Pathfinder
de Oliveira et al. (2021)	Circularity Assessment Model
de Oliveira et al. (2021)	Circularity Calculator
de Oliveira et al. (2021)	Circularity Check
de Oliveira et al. (2021)	Circularity Index
de Oliveira et al. (2021)	Circularity Measurement Toolkit
de Oliveira et al. (2021)	Circularity of Material Quality
de Oliveira et al. (2021)	Circularity Transition Indicators
de Oliveira et al. (2021)	Circulytics
de Oliveira et al. (2021)	Closed Loop Calculator
de Oliveira et al. (2021)	Ease of Disassembly Metric
de Oliveira et al. (2021)	Economic-environmental Indicators
de Oliveira et al. (2021)	Economic-Environmental Remanufacturing
de Oliveira et al. (2021)	End of Life Best Practice Indicators
de Oliveira et al. (2021)	End-of-Life Index
de Oliveira et al. (2021)	Environmental Sustainability of Food Packaging indicators
de Oliveira et al. (2021)	EoL indices
de Oliveira et al. (2021)	Evaluation Index System of CE for PCFs
de Oliveira et al. (2021)	Expended Zero Waste Practice Model
de Oliveira et al. (2021)	Global Resource Indicator
de Oliveira et al. (2021)	Improved Water Circularity Index
de Oliveira et al. (2021)	Input-Output Balance Sheet
de Oliveira et al. (2021)	Longevity and Circularity
de Oliveira et al. (2021)	Material and Energy Circularity Indicators
de Oliveira et al. (2021)	Material Circularity Indicator
de Oliveira et al. (2021)	Material Efficiency in Supply Chains Spreadsheets
de Oliveira et al. (2021)	Material Input Per Service Delivered
de Oliveira et al. (2021)	Mine site MFA Indicator
de Oliveira et al. (2021)	Multi-Criteria Evaluation Method of Product-Level Circularity Strategies
de Oliveira et al. (2021)	Multidimensional Indicator Set
de Oliveira et al. (2021)	Product Circularity Improvement Program
de Oliveira et al. (2021)	Product Recovery Multi-Criteria Decision Tool
de Oliveira et al. (2021)	Product Recycling Desirability Index
de Oliveira et al. (2021)	Product-Level Circularity Metric
de Oliveira et al. (2021)	PRP Circular e-Procurement Tool and The ReNtryR -module
de Oliveira et al. (2021)	Recycling Indices for the CE
de Oliveira et al. (2021)	Resource Duration Indicator
de Oliveira et al. (2021)	Resource Efficiency Assessment of Products
de Oliveira et al. (2021)	Reuse Potential Indicator
de Oliveira et al. (2021)	Set of Indicators to Assess Sustainability
de Oliveira et al. (2021)	Sustainability Performance Indicators
de Oliveira et al. (2021)	Sustainable Circular Index
de Oliveira et al. (2021)	Systems Indicators for Circular Economy Dashboard
	Circular Business Model Set of Indicators based on Sustainability
de Oliveira et al 2023	End of Life Best Practice Indicators
de Oliveira et al 2023	Expended Zero Waste Practice Model
de Oliveira et al 2023	Multi-Criteria Evaluation Method of Product-Level Circularity Strategies

de Oliveira et al 2023	Product Recovery Multi-Criteria Decision Tool
de Oliveira et al 2023	Set of Indicators to Assess Sustainability
de Oliveira et al 2023	Sustainability Performance Indicators
de Oliveira et al 2023	Sustainable Circular Index
Drofenik et al 2025	Diverted waste from disposal
Drofenik et al 2025	Fresh water discharge
Drofenik et al 2025	Hazardous waste generated
Drofenik et al 2025	Input materials
Drofenik et al 2025	Non-Hazardous waste generated
Drofenik et al 2025	NOx, SOx and other significant air emissions
Drofenik et al 2025	NOx, SOx and other significant air emissions generated over products sold
Drofenik et al 2025	Other water discharge
Drofenik et al 2025	Packaging materials
Drofenik et al 2025	Products sold – weight
Drofenik et al 2025	Recycled, reusable, compostable and recyclable materials used
Drofenik et al 2025	Recycled, reusable, compostable and recyclable packaging materials used
Drofenik et al 2025	Renewable energy consumed
Drofenik et al 2025	Revenue
Drofenik et al 2025	Share of hazardous waste over total waste generated
Drofenik et al 2025	Share of other water discharge over total water discharge
Drofenik et al 2025	Share of recycled, renewable and reusable materials used
Drofenik et al 2025	Share of recycled, renewable and reusable packaging materials used
Drofenik et al 2025	Share of renewable energy consumed over total energy consumed
Drofenik et al 2025	Share of waste diverted from disposal over total waste generated
Drofenik et al 2025	Share of water consumed over total water withdrawal

Drofenik et al 2025	Total energy consumed
Drofenik et al 2025	Total energy consumed over products sold
Drofenik et al 2025	Total GHG emissions
Drofenik et al 2025	Total GHG emissions generated over products sold
Drofenik et al 2025	Total input materials used over products sold
Drofenik et al 2025	Waste generated over products sold
Drofenik et al 2025	Water recycled or reused
Drofenik et al 2025	Water withdrawal
Drofenik et al 2025	Water withdrawal over products sold
Gursel et al 2023	Circ(T)
Gursel et al 2023	Circular economy benefit indicators
Gursel et al 2023	Circular Economy Index
Gursel et al 2023	Circular Economy Toolkit
Gursel et al 2023	Circular Economy Indicator Prototype
Gursel et al 2023	Circular Economy Performance Indicator
Gursel et al 2023	Circularity calculator
Gursel et al 2023	Circularity Index
Gursel et al 2023	Circularity Measurement Toolkit
Gursel et al 2023	Circularity of material quality
Gursel et al 2023	Combination Matrix
Gursel et al 2023	Eco-efficient Value Ratio
Gursel et al 2023	Global Resource Indicator
Gursel et al 2023	In-use occupation indicator
Gursel et al 2023	Longevity Indicator
Gursel et al 2023	Material Circularity Indicator
Gursel et al 2023	Product Circularity Indicator
Gursel et al 2023	Product Recovery MultiCriteria Decision Tool
Gursel et al 2023	Product-Level Circularity Metric
Gursel et al 2023	Recycling Desirability Index

Gursel et al 2023	Recycling indicator set
Gursel et al 2023	Recycling Indices
Gursel et al 2023	Reuse Potential Indicator
Gursel et al 2023	Sustainable Circular Index
Gursel et al 2023	Value-based Resource Efficiency
Jerome et al 2022	Circular Economic Value
Jerome et al 2022	Circularity
Jerome et al 2022	Circularity Index
Jerome et al 2022	Circular-process energy intensity
Jerome et al 2022	Circular-process feedstock intensity
Jerome et al 2022	Circular-process waste factor
Jerome et al 2022	Collection rate
Jerome et al 2022	End-of-life recycling rate
Jerome et al 2022	Energy intensity
Jerome et al 2022	Feedstock intensity
Jerome et al 2022	Landfill to recycle ratio
Jerome et al 2022	Linear flow index for product families
Jerome et al 2022	Longevity
Jerome et al 2022	Material Circularity Indicator
Jerome et al 2022	Material Reutilization Score
Jerome et al 2022	MCI for bio-based and biodegradable products
Jerome et al 2022	Old scrap collection rate
Jerome et al 2022	Old scrap ratio
Jerome et al 2022	Potential recycle index
Jerome et al 2022	Potential reuse index
Jerome et al 2022	Process material circularity
Jerome et al 2022	Product Circularity Indicator
Jerome et al 2022	Product renewability
Jerome et al 2022	Recoverability rate
Jerome et al 2022	Recyclability rate
Jerome et al 2022	Recycle benefit ratio
Jerome et al 2022	Recycle yield ratio
Jerome et al 2022	Recycled content
Jerome et al 2022	Recycled content rate
Jerome et al 2022	Recycling process efficiency rate
Jerome et al 2022	Recycling rate
Jerome et al 2022	Relative net loss
Jerome et al 2022	Resource efficiency indicator for electrical and electronic equipment
Jerome et al 2022	Reusability rate
Jerome et al 2022	Specific Energy and Resource Indicator
Jerome et al 2022	Waste factor
Khadim et al 2022	Alba Concepts BCI
Khadim et al 2022	ARCH Circular Environmental Indicator Framework
Khadim et al 2022	BIM Based Building Circularity Assessment
Khadim et al 2022	BIM-based Whole-life

	Performance Estimator
Khadim et al 2022	Bridge Circularity Assessment Framework
Khadim et al 2022	Building Circularity Indicator
Khadim et al 2022	Building Circularity Indicator
Khadim et al 2022	C-CALC
Khadim et al 2022	Circular Assessment Criteria for Envelope
Khadim et al 2022	Circular Building Assessment Prototype
Khadim et al 2022	Circular Business Models (CBM) Based Circularity Indicator
Khadim et al 2022	Circular Construction Evaluation Framework
Khadim et al 2022	Circular Economy Measurement Scale
Khadim et al 2022	Circular Economy Scale
Khadim et al 2022	Circularity Indicator for Pedestrian Bridges
Khadim et al 2022	Cirulytics
Khadim et al 2022	FLEX
Khadim et al 2022	Gypsum End of Life Measurement Indicator
Khadim et al 2022	Integrated Energy Performance and Circularity
Khadim et al 2022	MADASTER Circularity Indicator
Khadim et al 2022	Material Circularity Indicator
Khadim et al 2022	Material Circularity Indicator for Construction
Khadim et al 2022	Modified Alba Concept
Khadim et al 2022	Modified Building Circularity Indicator
Khadim et al 2022	Platform CB' 23 Circularity Calculator
Khadim et al 2022	Predictive Building Circularity Mode
Khadim et al 2022	RIPAT 1.0 Framework for Circular Buildings
Khadim et al 2022	Synthetic Economic Environmental Indicator
Kristensen et al 2020	Circular Economy Index
Kristensen et al 2020	Circular Economy Indicator Prototype
Kristensen et al 2020	Circular Economy Toolkit
Kristensen et al 2020	Circularity Calculator
Kristensen et al 2020	Circularity Design Guidelines
Kristensen et al 2020	Combination Matrix
Kristensen et al 2020	Decision Support Tool for Remanufacturing
Kristensen et al 2020	Design Method for End-of-use Product Value Recovery
Kristensen et al 2020	Disassembly Effort Index
Kristensen et al 2020	Ease of Disassembly Metric

Kristensen et al 2020	Eco-cost/Value Ratio
Kristensen et al 2020	Eco-efficient Value Creation
Kristensen et al 2020	Effective Disassembly Time
Kristensen et al 2020	End-of-life Index
Kristensen et al 2020	End-of-life Indices
Kristensen et al 2020	Longevity Indicator
Kristensen et al 2020	Material Circularity Indicator
Kristensen et al 2020	Material Reutilization Score
Kristensen et al 2020	Mathematical Model to Assess Sustainable Design and End-of-life Options
Kristensen et al 2020	Model of Expanded Zero Waste Practice
Kristensen et al 2020	Multi-criteria Decision Analysis Combining Material Circularity Indicators & Life-cycle based Indicators
Kristensen et al 2020	Product Recovery Multi-criteria Decision Tool
Kristensen et al 2020	Product-level Circularity Metric
Kristensen et al 2020	Recycling Desirability Index
Kristensen et al 2020	Recycling Indices
Kristensen et al 2020	Remanufacturing Product Profiles
Kristensen et al 2020	Reuse Potential Indicator
Kristensen et al 2020	Sustainability Indicators in CE
Kristensen et al 2020	Typology for Quality Properties
Kristensen et al 2020	Value-based Resource Efficiency Indicator
Lindgren et al 2020	CE Evaluation Index System
Lindgren et al 2020	Circular Performance Indicator
Lindgren et al 2020	Circular Product Assessment
Lindgren et al 2020	Circular Product Index
Lindgren et al 2020	Circularity Indicator
Lindgren et al 2020	Circularity Measurement Tool
Lindgren et al 2020	Environmental Business Evaluation Process
Lindgren et al 2020	Environmental Value Propositions Table
Lindgren et al 2020	Environmental-Economic Assessment Framework
Lindgren et al 2020	Hybrid LCA Approach
Lindgren et al 2020	Longevity Indicator
Lindgren et al 2020	Material Reutilization Score
Lindgren et al 2020	Product Recyclability Multi-Criteria Decision Tool
Lindgren et al 2020	Product-Level Circularity Metric
Lindgren et al 2020	Recyclability Benefit Rate
Lindgren et al 2020	Repairability Indicator
Lindgren et al 2020	Resource Efficiency Assessment Process
Lindgren et al 2020	Resource Sustainability Index
Lindgren et al 2020	Reuse Potential Metric
Lindgren et al 2020	Sustainable Circular Index
Lindgren et al 2020	Value Retention Efficiency
Lindgren et al 2021	Benchmark Circular Business Practices
Lindgren et al 2021	Circular Economy Toolkit
Lindgren et al 2021	Circularity Calculator
Lindgren et al 2021	IDEAL&CO Explore BV
Lindgren et al 2021	Material Circularity Indicator

Lindgren et al 2021	Material Reutilization Score
Matos et al 2023	Circular Economy Index
Matos et al 2023	Circularity Calculator
Matos et al 2023	Circularity Design Guidelines
Matos et al 2023	Decision Support Tool for Remanufacturing
Matos et al 2023	Ease of Disassembly Metric
Matos et al 2023	Eco-cost/value Creation
Matos et al 2023	Effective Disassembly Time
Matos et al 2023	End-of-use product value recovery
Matos et al 2023	Longevity Indicator
Matos et al 2023	Material Circularity Indicator
Matos et al 2023	Material Reutilization Score
Matos et al 2023	Model of Expanded Zero Waste Practice
Matos et al 2023	Product Recovery Multi-criteria Decision Tool
Matos et al 2023	Product-level Circularity Metric
Matos et al 2023	Recycling Desirability Index
Matos et al 2023	Recycling Indices
Matos et al 2023	Remanufacturing Product Profiles
Matos et al 2023	Reuse Potential Indicator
Matos et al 2023	Sustainable design and end-of-life options
Matos et al 2023	Typology for Quality Properties
Matos et al 2023	Value-Based Resource Efficiency
Moreno et al 2021	Value-based Resource Efficiency
Moreno et al 2021	Circular Economy Indicator Prototype
Moreno et al 2021	Circular Economy Toolkit
Moreno et al 2021	Circular material use rate
Moreno et al 2021	End-of-life recycling input rates
Moreno et al 2021	EU self-sufficiency for raw materials
Moreno et al 2021	Generation of municipal waste per capita
Moreno et al 2021	Generation of waste excluding major mineral waste per GDP unit
Moreno et al 2021	Generation of waste excluding major mineral waste per domestic material consumption unit
Moreno et al 2021	Green public procurement
Moreno et al 2021	Gross investment in tangible goods
Moreno et al 2021	Number of persons employed
Moreno et al 2021	Recovery rate of construction and demolition waste
Moreno et al 2021	Recycling of bio-waste per capita
Moreno et al 2021	Recycling rate of all waste excluding major mineral waste
Moreno et al 2021	Recycling rate of electrical and electronic waste
Moreno et al 2021	Recycling rate of municipal waste
Moreno et al 2021	Recycling rate of overall packaging waste
Moreno et al 2021	Recycling rate of plastic packaging waste
Moreno et al 2021	Recycling rate of wooden packaging
Moreno et al 2021	The Material Circularity Indicator
NG Franco 2021	Consumers awareness about remanufacturing benefits
NG Franco 2021	Consumers awareness about

	reuse benefits
NG Franco 2021	Design for disassembly
NG Franco 2021	Durability of product
NG Franco 2021	Energy recoverability benefit rate
NG Franco 2021	Energy recovery
NG Franco 2021	Engaging with consumers to raise awareness about repair advantages
NG Franco 2021	Engaging with consumers to raise awareness about refurbishment advantages
NG Franco 2021	Extension of producer responsibility or product stewardship
NG Franco 2021	Hazardous waste diverted from disposal
NG Franco 2021	Improving materials selection
NG Franco 2021	Input materials or design characteristics of outputs that limit or prevent their recovery or limit the length of their life
NG Franco 2021	New materials required
NG Franco 2021	Non- hazardous waste diverted from disposal
NG Franco 2021	Non-virgin material consumption (%)
NG Franco 2021	Overall recycling rates
NG Franco 2021	Potential use during lifetime
NG Franco 2021	Potential use during lifetime
NG Franco 2021	Product longevity extension
NG Franco 2021	Product take-back
NG Franco 2021	Product take-back
NG Franco 2021	Products directed to reuse
NG Franco 2021	Products repair
NG Franco 2021	Products successfully refurbished
NG Franco 2021	Quantity of the total refurbished parts
NG Franco 2021	Raw materials input
NG Franco 2021	Reclaimed products
NG Franco 2021	Reclaimed products - (% product take-back)
NG Franco 2021	Recycling rate for specific waste streams
NG Franco 2021	Reduction of energy intensity
NG Franco 2021	Reduction of energy

	consumption
NG Franco 2021	Reduction of materials consumption
NG Franco 2021	Reduction of waste generation
NG Franco 2021	Reduction of waste intensity – material losses
NG Franco 2021	Refurbish sales
NG Franco 2021	Remanufactured content
NG Franco 2021	Remanufactured products
NG Franco 2021	Remanufacturing business sales (%)
NG Franco 2021	Repair business model
NG Franco 2021	Residual products
NG Franco 2021	Reuse business model
NG Franco 2021	Reuse rate
NG Franco 2021	Reverse logistics processes to divert products and materials from disposal
NG Franco 2021	Reverse logistics processes to divert products and materials from disposal
NG Franco 2021	Secondary raw materials
NG Franco 2021	Shared use
NG Franco 2021	Substitution of hazardous substances
NG Franco 2021	Substitution of non-renewable energy
NG Franco 2021	Substitution of non-renewable raw materials
NG Franco 2021	Substitution of non-virgin content
NG Franco 2021	Total waste diverted from disposal
NG Franco 2021	Total weight of hazardous waste directed to disposal
NG Franco 2021	Total weight of non-hazardous waste directed to disposal
NG Franco 2021	Transitioning to and applying new circular business models
NG Franco 2021	Waste diversion from landfills
NG Franco 2021	Waste generation
NG Franco 2021	Water consumption reduction
NG Franco 2021	Water intensity reduction
Saidini et al 2020	circular economy indicator prototype
Saidini et al 2020	circular economy toolkit
Saidini et al 2020	Circular Spider Map

Saidini et al 2020	circularity potential indicator
Saidini et al 2020	material circularity indicator
Saidini et al 2020	product circularity metric
Valls-Val et al 2022	Acodea
Valls-Val et al 2022	CAS2.0
Valls-Val et al 2022	CE-Diagnosis
Valls-Val et al 2022	CEEI
Valls-Val et al 2022	CIRCelligence
Valls-Val et al 2022	CIRCelligence
Valls-Val et al 2022	Circle assessment
Valls-Val et al 2022	CircularTRANS
Valls-Val et al 2022	CircularTRANS
Valls-Val et al 2022	Circulytics
Valls-Val et al 2022	Circulytics
Valls-Val et al 2022	CM-FLAT
Valls-Val et al 2022	CM-FLAT
Valls-Val et al 2022	CTI Tool
Valls-Val et al 2022	CTI Tool
Valls-Val et al 2022	Inedit
Valls-Val et al 2022	INEDIT
Valls-Val et al 2022	MATChE
Valls-Val et al 2022	MATChE Readiness Assessment
Valls-Val et al 2022	Material Circularity Indicator
Valls-Val et al 2022	Material Circularity Indicator
Valls-Val et al 2022	TECNUN

Appendix B - Interview questions

- **Q1:** What types of maintenance-related data do you find most valuable when working toward sustainability goals, and how is that data currently used (if at all)?
- **Q2:** Can you describe how maintenance activities at your site currently support, or could support, circular economy or sustainability goals?
- **Q3:** What are the biggest practical or organizational challenges you've faced (or anticipate) when trying to align maintenance with Circular Economy or sustainability efforts?
- **Q4:** From your perspective, what does it take for a site to move from one level to the next in the Professional Maintenance maturity model?
- **Q5:** What types of support, tools, or changes do you believe would make the biggest difference in successfully implementing CE indicators or sustainability-focused maintenance practices?

Appendix C - Questionnaire layout

1. **Which department or function do you primarily work in? (Select all that apply)**
   - ☐ Maintenance
   - ☐ Production/Manufacturing
   - ☐ Sustainability/Environmental Management
   - ☐ Human Resources
   - ☐ Supply Chain/Logistics
   - ☐ Other (Please Specify)

2. **How many years of experience do you have in your current field?**
   - o < 2 years
   - o 2-5 years
   - o 6 -10 years
   - o > 10 years
   - o Don’t know/Prefer not to answer

3. In which country are you primarily based?

- o Sweden
- o Belgium
- o USA
- o France
- o Brazil
- o UK
- o Australia
- o NewZeeland
- o India
- o China
- o SouthKorea

4. How familiar are you with the concept of Circular Economy (CE)? (Select one option)

- o Not familiar at all
- o Somewhat familiar - I do not apply CE principles in my work.
- o Moderately familiar - I have applied CE principles occasionally in my role
- o Very familiar - I work directly with CE initiatives
- o Don’t know/Prefer not to answer

5. How familiar are you with the 7-step model used at the company’s XPS audit?

- o Not familiar at all - I have never heard of this model
- o I have heard of it - but I am unsure of its details or application
- o Somewhat familiar - I know the basic concept but have not actively worked with it
- o Moderately familiar - I have applied some parts of the model in my work occasionally
- o Very familiar - I work with the framework regularly and apply its principles
- o Don’t know/Prefer not to answer

6. **How is maintenance planned and prioritized at your site? (Select one option)**
   - o Primarily reactive (fixing equipment after failure)
   - o Mostly preventive (scheduled maintenance to reduce breakdowns)
   - o Predictive (using data and monitoring to anticipate failures)
   - o Proactive (extending equipment life through design changes and upgrades)
   - o Don’t know/Prefer not to answer

7. **Do you track any Operational Performance data related to maintenance at your site?**
   - o Yes
   - o No

8. **What Operational Performance Data do you track at your site? (Select all that apply)**
   - ☐ Machine Downtime – Measuring unplanned stoppages and lost production time
   - ☐ Failure Frequency – Tracking how often breakdowns occur
   - ☐ Repair Speed – Measuring how quickly maintenance teams restore equipment
   - ☐ Maintenance Task Completion Rate – Monitoring the percentage of scheduled maintenance tasks completed on time
   - ☐ Maintenance Quality – Monitoring repairs that require additional intervention due to initial fix failure
   - ☐ Other / Please specify

9. **Do you track any Energy and Environmental impact data related to maintenance at your site?**
   - o Yes
   - o No

10. **What Energy and Environmental Impact Data do you track at your site?**

(Select all that apply)

☐ Machine Energy Use – Tracking energy consumption of equipment and processes

☐ Energy Efficiency – Measuring energy savings from maintenance activities

☐ Maintenance Process Emissions – Environmental impact of lubrication, cleaning, and repairs

☐ Water Use in Maintenance – Tracking water consumption in maintenance tasks

☐ Chemical Usage – Monitoring lubricants, degreasers, and hazardous materials

☐ Component Lifecycle Impact – Embedded emissions of spare parts and materials

☐ Other / Please specify

11. Do you track any Material and Resource Efficiency Data related to maintenance at your site?

o Yes

o No

12. What Material and Resource Efficiency Data do you track at your site? (Select all that apply)

☐ Spare part and equipment consumption – Tracking usage rates, inventory levels, and procurement needs

☐ Component Reuse & Refurbishment – Assessing how often parts are repaired or reused

☐ Component Recycling and Remanufacturing rate – Assessing how often parts are recycled or remanufactured

☐ Waste generation – Monitoring scrap rate, disposal, and material losses

☐ Lifecycle tracking of components usage – Monitoring wear, longevity, and replacement cycles

☐ Procurement sustainability – Recycled content of sourced spare parts and equipment

☐ Other / Please specify

13. Are maintenance practices currently used to improve circular economy performance?

- o No, CE is not considered in maintenance
- o Occasionally, but not in a structured way
- o Yes, CE-related KPIs are tracked in maintenance reporting
- o Yes, CE and maintenance data are fully integrated into sustainability tracking
- o Don't know / Prefer not to answer

14. How well are maintenance and sustainability teams aligned in your organization?

- o Not at all - they work separately
- o Somewhat - sustainability teams set targets, but maintenance is not involved
- o Moderately - there is occasional collaboration
- o Strongly - maintenance is an active part of sustainability and CE initiatives
- o Don't know / Prefer not to answer

15. On a scale of 1-5, how significant do you consider these barriers to be when implementing Circular Economy KPIs in your organization? (Likert scale)

- ☐ Lack of standardization – No universally accepted KPIs
- ☐ Complex implementation – Difficult to define, track, and analyse
- ☐ High resource demands – Requires significant time, cost, and expertise
- ☐ Overemphasis on recycling – Limited focus on reuse, remanufacturing, or life extension
- ☐ Lack of financial incentives – No clear economic benefits
- ☐ Limited ESG integration – Difficult to align with corporate sustainability reporting
- ☐ Lack of knowledge – Unclear how or why CE KPIs should be implemented
- ☐ Lack of management support – No strong backing from leadership

16. On a scale of 1-5, how difficult do you consider it to be to collect and

analyse the following Operational Performance Data at your site? (Likert scale)

- ☐ Machine Downtime – Measuring unplanned stoppages and lost production time
- ☐ Failure Frequency – Tracking how often breakdowns occur
- ☐ Repair Speed – Measuring how quickly maintenance teams restore equipment
- ☐ Maintenance Task Completion Rate – Monitoring the percentage of scheduled maintenance tasks completed on time
- ☐ Maintenance Quality – Monitoring repairs that require additional intervention due to initial fix failure

17. On a scale of 1-5, how difficult do you consider it to be to collect and analyse the following Energy & Environmental Impact Data at your site? (Likert scale)

- ☐ Machine Energy Use – Tracking energy consumption of equipment and processes
- ☐ Energy Efficiency – Measuring energy savings from maintenance activities
- ☐ Maintenance Process Emissions – Environmental impact of lubrication, cleaning, and repairs
- ☐ Water Use in Maintenance – Tracking water consumption in maintenance tasks
- ☐ Chemical Usage – Monitoring lubricants, degreasers, and hazardous materials
- ☐ Component Lifecycle Impact – Embedded emissions of spare parts and materials

18. On a scale of 1-5, how difficult do you consider it to be to collect and analyse the following Material & Resource Efficiency Data at your site? (Likert scale)

- ☐ Spare part and equipment consumption - Tracking usage rates, inventory levels, and procurement needs.

- ☐ Component Reuse & Refurbishment - Assessing how often parts are repaired or reused
- ☐ Component Recycling and Remanufacturing rate – Assessing how often parts are recycled or remanufactured
- ☐ Waste generation – Monitoring scrap rate, disposal, and material losses
- ☐ Lifecycle tracking of components usage – Monitoring wear, longevity, and replacement cycles
- ☐ Procurement sustainability – Recycled content of sourced spare parts and equipment

19. Based on the model shown in the picture, which level best represents the current maturity level of professional maintenance at your site? (Select one option)

- o Level 1
- o Level 2
- o Level 3
- o Level 4
- o Level 5
- o Don't know/Prefer not to answer

20. Based on the model shown in the picture, which level do you expect to best represent the maturity level of professional maintenance at your site in 3 years? (Select one option)

- o Level 1
- o Level 2
- o Level 3
- o Level 4
- o Level 5
- o Don't know/Prefer not to answer

21. What main factors do you think will influence your site's maintenance maturity level in the next 3 years?

- o ____Enter text here____

22. On a scale of 1-5, how significalt do you consider these enablers to be in integrating Circular Economy principles and KPI's into the company's maintenance practices? (Likert scale)

- ☐ Stronger integration with sustainability reporting – Embedding CE indicators into Life Cycle Assessment (LCA), Material Flow Analysis (MFA), or ESG frameworks
- ☐ Clearer industry standards and best practices – More structured frameworks for defining and measuring CE KPIs
- ☐ Stronger financial incentives – Funding, tax benefits, or cost-saving opportunities linked to circularity efforts
- ☐ Better alignment with existing KPIs – Ensuring CE indicators connect with current maintenance, cost, and efficiency metrics
- ☐ Improved IT systems and data tracking – Easier to measure and analyse circularity-related maintenance data
- ☐ More training and awareness – Increasing knowledge on how CE KPIs impact maintenance and operations
- ☐ Greater support from top management – Leadership commitment to driving CE integration in maintenance
- ☐ Regulatory and policy support – Clearer government or industry regulations encouraging CE KPI adoption
- ☐ Collaboration with suppliers and external partners – Working with external stakeholders to improve circularity in spare parts and maintenance strategies

Appendix D - CE Indicator Description

Indicator name	Description	Required data	Source
Material Circularity Indicator	The Material Circularity Indicator (MCI) is a metric developed to quantify how restorative and regenerative a product's material flows are within the context of a circular economy. It evaluates the proportion of virgin materials used, the amount of unrecoverable waste generated, and the product's utility (a function of how long and intensively it's used compared to the industry average). An MCI score ranges from 0 (fully linear) to 1 (fully circular), promoting the use of recycled/reused content, longer product life, and efficient end-of-life recovery processes, all while considering both technical and biological material cycles	**Material Sourcing Data** – Information on the proportion of virgin, recycled, reused, and biologically sourced materials. **End-of-Life Fate Data** – Data on collection rates for recycling, component reuse, composting, or energy recovery. **Recycling Process Efficiency** – Efficiency of the recycling processes for both feedstock generation and end-of-life product treatment. **Product Utility Data** – Actual lifetime and usage intensity (functional units) compared to industry average. **Waste Data** – Quantities of unrecoverable waste produced during both production and end-of-life stages.	Ellen MacArthur Foundation and Design (2015)
Renewable material used	The indicator measures the percentage of renewable materials (as opposed to non-renewable or virgin materials) used by a company in its production or packaging processes. It is directly aligned with Circular Economy (CE) Goal #3: "Increase in the share of renewable resources and energy: Replacement of non-renewable resources with renewable ones, limiting the use of virgin materials." This metric reflects how effectively a company is reducing dependency on finite natural resources by shifting toward materials that are sustainably sourced and regenerative.	**Material Composition Data** Quantities (weight or volume) of renewable vs. non-renewable materials used. **Production Volume Data** Number or volume of units produced to normalize material usage. **Financial or Operational Data** Company revenue or number of full-time employees to allow for performance benchmarking. **Sector-Specific Material Classifications** Definitions of what counts as "renewable" material in the context of the company's industry (aligned with GRI standards).	Stefanos G. Baratsas et al. (2022)

Product-level Circularity Metric	The Product-Level Circularity Metric (PLCM) is designed to measure how circular a product is, based solely on the proportion of its components and materials that come from previously used products. It defines circularity as: "The fraction of a product that comes from used products (i.e., from closed- or open-loop cycles)." The core idea is to assess this using economic value (specifically value chain costs) rather than mass or other units, allowing for better aggregation of diverse product parts. The metric is calculated as: Circularity (c) = Economic value of recirculated parts / Economic value of all parts This can be approximated using cost data from suppliers or internal production. The method supports iterative calculation along a supply chain, accommodating complex products and varying supplier setups.	**Component-Level Economic Value (Cost-Based)** Cost of individual parts (both virgin and recirculated) Cost estimations for work activities (e.g., remanufacturing, inspection) **Material Recirculation Status:** Whether a part is recirculated or virgin, Proportion of used components in a given part **Value Chain Activities:** Costs and steps of activities applied to parts (cleaning, transport, remolding, etc.), Attribution of circularity to work vs. material input **Procurement and Handling Costs:** Logistics, packaging, and administrative costs. Used as a proxy when market prices or direct cost data are not available **Market Price References** (Optional/Alternative): Prices for virgin materials, Secondhand market prices for components (if available)	Linder et al. (2017)
Total energy consumed		Total energy of plant, department or line	N/A

Longevity Indicator	The Longevity Indicator is a value-based metric designed to measure the duration that a material is retained in a product system, aligning with Circular Economy goals of maximizing resource use through reuse and recycling. It is composed of three main components: the initial lifetime, the earned refurbished lifetime, and the earned recycled lifetime. These components reflect the time a resource spends in use, including reuse cycles and recycling-based reincorporation into new products. The indicator quantifies how long resources contribute value within a system and aids managers in assessing and enhancing circularity at the organizational level.	**Initial Product Use Data** – Time duration (e.g. months) a product is used initially before being discarded or reused. **Refurbishment & Reuse Dat**a – Proportions of products returned and refurbished, and the typical duration of second-hand usage. **Recycling Data** – Rates of product recycling and the efficiency (material recovery rates) of those recycling processes. **Product Return Rates** – Percentages of products returned after first and second use for either refurbishment or recycling. **Material Loss Rates** – Percentages of materials that are lost or unrecoverable during the recycling process.	Franklin-Johnson et al. (2016)
Product Recovery Multi-Criteria Decision Tool	The Product Recovery Multi-Criteria Decision Tool (PR-MCDT) is an evaluation method designed to help companies choose the most appropriate circular economy strategy at the product end-of-life (EoL) stage. It employs a multi-criteria decision-making (MCDM) framework that evaluates and compares circularity strategies, such as repair, reuse, remanufacturing, and recycling, against traditional business-as-usual models. The tool takes into account both how well a strategy supports circular economy principles (e.g., environmental and economic performance) and its feasibility for the business (e.g., technical and market conditions). The approach is flexible, allowing decision-makers to adjust criteria, sub-criteria, and weightings based on context-specific needs	**Environmental** – Indicators like Life Cycle Assessment (LCA) results, greenhouse gas emissions, ecosystem impact. **Economic** – Cost-related metrics such as Life Cycle Costing (LCC), disassembly costs, net recoverable value. **Social** – Qualitative factors like job creation potential and employee safety. **Technical/Business Feasibility** – Product condition, availability of recovery facilities, market demand, technological compatibility, and business model aspects	Alamerew et al. (2020)

Reuse Potential Indicator	The Reuse Potential Indicator (RPI) is a quantitative tool designed to assess how "resource-like" versus "waste-like" a material is, based on available reuse technologies. It measures the technical feasibility of reusing waste materials, independent of market conditions, by evaluating the extent to which they can be recovered through currently commercialized technologies. The indicator ranges from 0 (entirely waste-like) to 1 (entirely resource-like), and its value is dynamic, reflecting changes in technological innovation, regional capacity, and material quality. It supports a shift from a waste-based to a resource-based paradigm in waste management, emphasizing the view that waste should be considered a potential resource until proven otherwise.	**Material Generation Quantities** – Total volume or mass of waste produced. **Technological Availability** – Types and capacities of reuse technologies developed and commercialized. **Technical Specifications for Reuse** – Quality and suitability of the material for various reuse applications. **Economic Viability – Cost-benefit data**, including net marginal revenue and disposal costs.	Park and Chertow (2014)
Circular Economy Index	The Circular Economy Index (CEI) is a performance indicator designed to evaluate the effectiveness of recycling by comparing the economic value of materials recovered from end-of-life (EoL) products with the value of the original materials required to reproduce those products. Unlike traditional recycling rates based solely on mass, the CEI focuses on material value, making it more aligned with economic, environmental, and strategic policy goals. It is easy to compute, using data from financial records, and serves as a practical tool for both industry management and policymakers. The CEI encourages innovation in recycling technologies	**Material Composition** – Types of materials in EoL products, including standards if available. **Mass Information** – Weight of each material or component in the product. **Chemical Composition** – Detailed breakdown of materials, useful for assessing purity and value. **Smallest Component Details** – Identification of minimal parts like screws or foils to ensure thorough disassembly. **Market and Intrinsic Values** – Economic valuation of materials at entry and output stages of the recycling process.	Di Maio and Rem (2015)

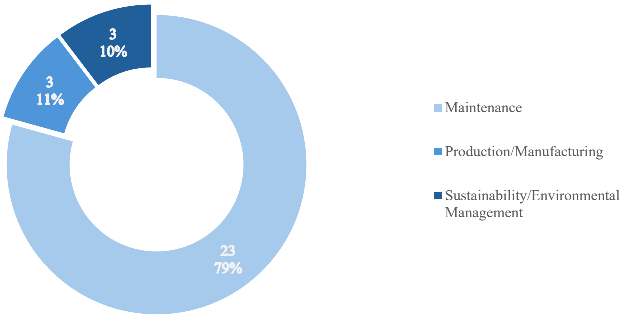
	by rewarding value creation rather than just volume processed		
Renewable energy consumed		Metric of how much renewable energy is consumed in a given period	N/A
Material Reutilization Score	The Material Reutilization Score is a circular economy indicator used in the Cradle to Cradle Certified™ Product Standard to measure how well a product is designed for recycling or composting. It quantifies the percentage of a product's materials that are recoverable and actively cycled in either biological or technical nutrient pathways. The score also considers whether a product has a nutrient management strategy and systems in place to support actual material recovery. The goal is to minimize waste and ensure materials remain in continuous use, enabling true circularity.	**Material Composition Data** – Detailed breakdown of all homogeneous materials in the product, including their weights and percentages of total product weight. **Recyclability and Compostability Information** – Determination of whether each material is recyclable or compostable, based on current infrastructure or design intent. **Product Cycle Designation** – Identification of whether the product or components are designed for the biological or technical cycle. **Material Recovery Systems** – Information on systems in place or planned for recovering materials at end-of-use (e.g., take-back schemes, recycling partnerships). **Implementation Strategy Documentation** – Details of any nutrient management strategies including timelines, scope, and budgets for logistics and recovery systems.	Institute. (2016)

Full time employees		How many of operational personel which is considered full-time employed	N/A
Value-based Resource Efficiency	The Value-based Resource Efficiency (VRE) indicator is a circular economy metric that measures how efficiently economic actors (like industries) use stressed resources by considering the market value of those resources rather than their mass. Unlike traditional mass-based metrics, VRE uses the monetary value of inputs (which captures both scarcity and societal impacts like taxes) to assess the added value generated. The indicator is designed to be simple, policy-aligned, and applicable using existing national statistics. It helps distinguish between resource efficiency at the product level (for consumers) and the process level (for industries and governance).	**Value added of economic output** – Monetary value of products or services generated. **Monetary value of inputs** – Includes prices of materials, energy, and services used in production. **Volume of resource inputs** – Quantities of materials, energy, and services used (to be combined with prices). **Market prices** – For all resource inputs to weight their societal and environmental impact. **Sector-level economic data** – From national accounts (e.g., System of National Accounts, Material Flow Monitor)	Di Maio et al. (2017)
Recoverability rate	The Recoverability Rate is a circular economy indicator that measures the extent to which a product's components can be recovered at end-of-life (EoL) for reuse, recycling, or energy recovery. It is expressed as a percentage of the product's total mass or environmental impact that can be potentially recovered using current technologies and EoL scenarios. The REAPro method further refines this by calculating not just mass-based recoverability but also environmental benefits (e.g., reduced emissions or resource depletion) from recovery. This indicator helps identify "hot spots" in products where recoverability is limited, guiding improvements in product design.	**Bill of Materials (BoM)** – Information on product components, their mass, and material types. **End-of-Life Scenarios** – Assumptions and descriptions of how the product is treated after disposal (e.g., dismantling vs. shredding). **Lifecycle Impact Data** – Environmental impacts of material production, product use, recycling, and disposal. **Material Recovery Characteristics** – Data on how different materials can be reused, recycled, or recovered, including efficiencies and downcycling factors. **Hazardous Substance Content** – Information on the presence and type of hazardous materials in components affecting recoverability	Ardente and Mathieux (2014)
Water withdrawal		How much water is used by the company, department or line	N/A

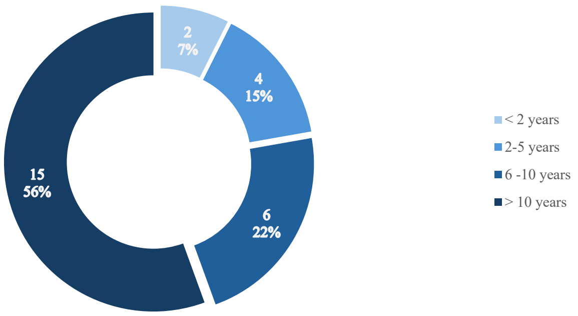
Ease of Disassembly Metric	The Ease of Disassembly Metric (eDiM) is a circular economy indicator developed to quantify how easily a product can be disassembled, primarily to support strategies like repair, reuse, remanufacturing, and recycling. It estimates disassembly time in seconds using a calculation method based on the Maynard Operation Sequence Technique (MOST). eDiM categorizes disassembly into six basic tasks and calculates time using a standardized spreadsheet, enabling transparent and verifiable evaluations. This method aims to provide designers, regulators, and recyclers with actionable insights to improve product disassemblability and support policy compliance	**Disassembly Sequence Data** – Order in which components are disassembled. **Connector Information** – Type, number, and characteristics of fasteners used. **Tool Requirements** – Tools needed for disassembly actions. **Product Manipulation & Identification** – Visibility and accessibility of connectors, number of manipulations needed. **Component Details** – Names and roles of the components being removed, to link disassembly steps to the product structure.	Vanegas et al. (2018)
Product take-back		How many products are sent back to its producer	N/A

Appendix E – Complete Questionnaire Results

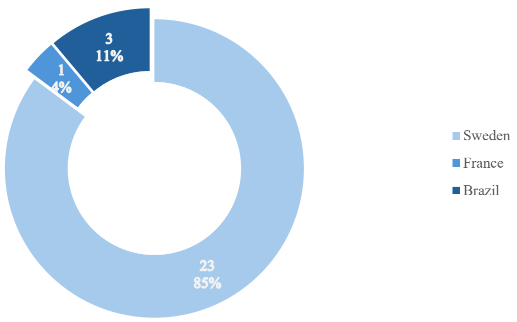
Q1: Which department or function do you primarily work in? (Select all that apply)



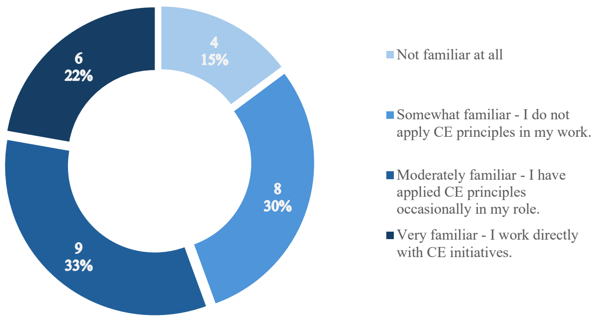
Q2: How many years of experience do you have in your current field?



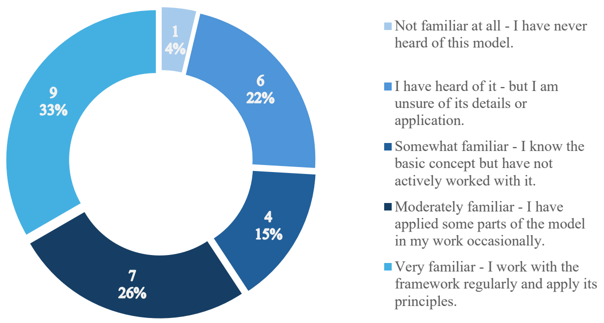
Q3: In which country are you primarily based?



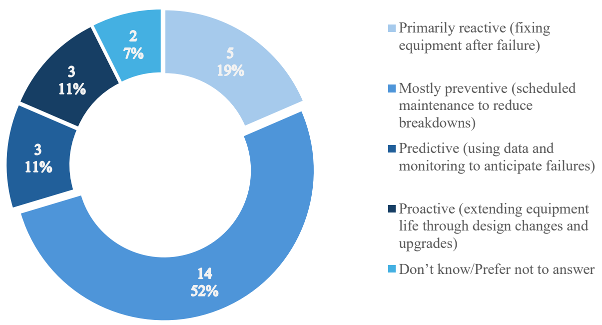
Q4: How familiar are you with the concept of Circular Economy (CE)? (Select one option)



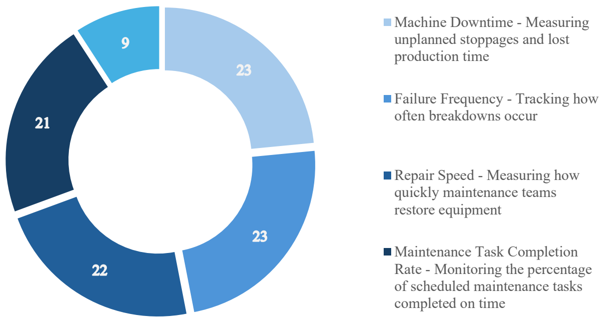
Q5: How familiar are you with the 7-step model used at the company's XPS audit?



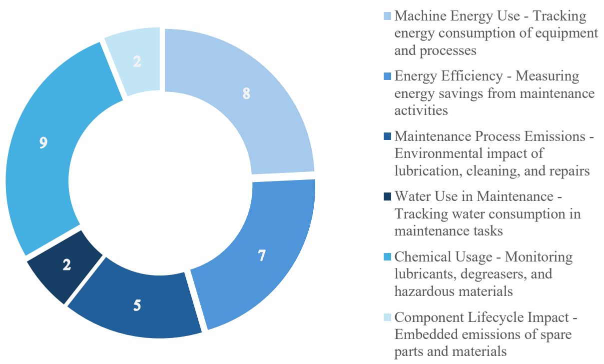
Q6: How is maintenance planned and prioritized at your site? (Select one option)



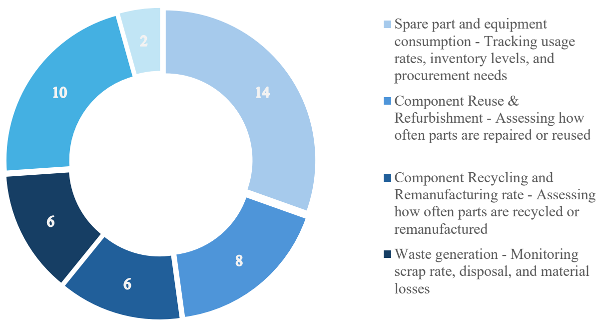
Q7: What Operational Performance Data do you track at your site? (Select all that apply)



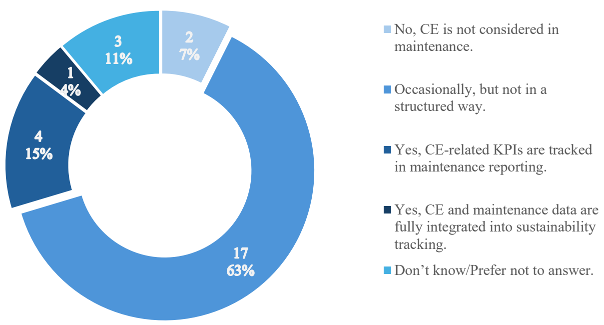
Q8: What Energy and Environmental Impact Data do you track at your site? (Select all that apply)



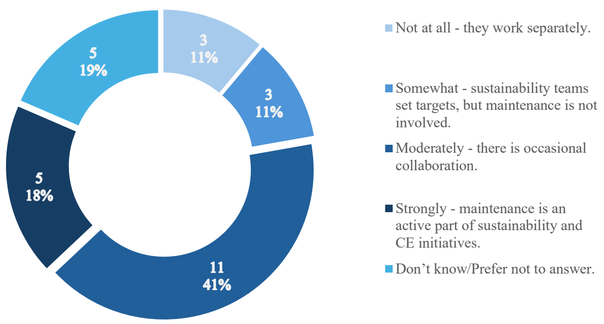
Q9: What Material and Resource Efficiency Data do you track at your site? (Select all that apply)



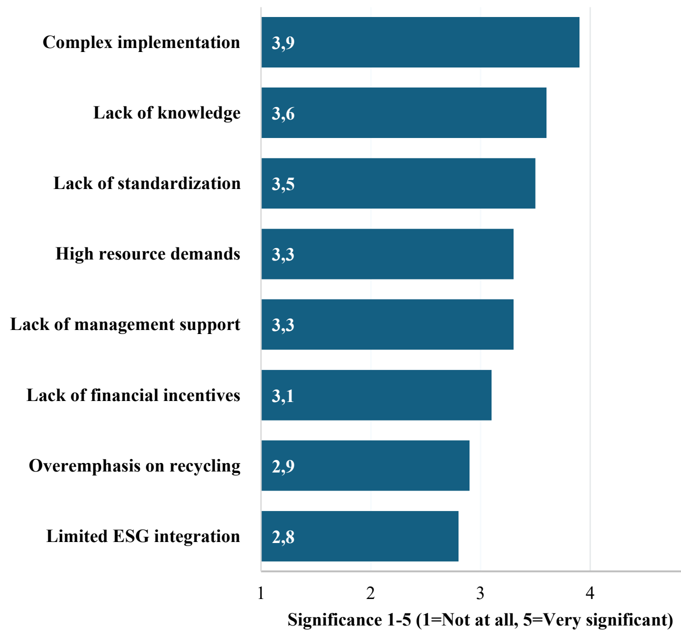
Q10: Are maintenance practices currently used to improve circular economy performance?



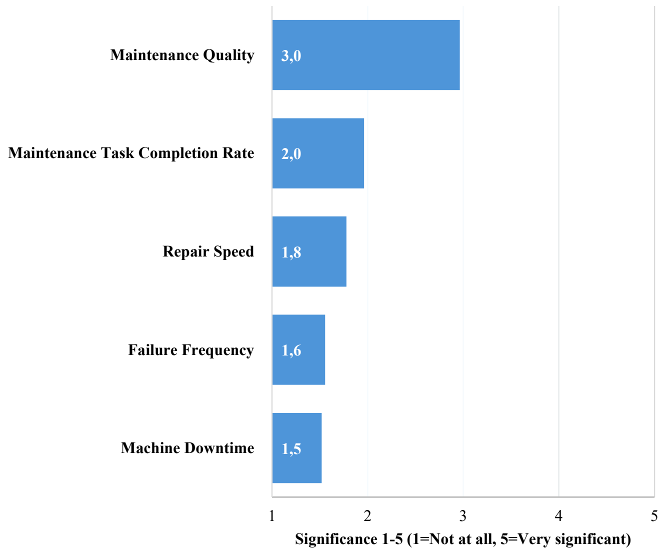
Q11: How well are maintenance and sustainability teams aligned in your organization?



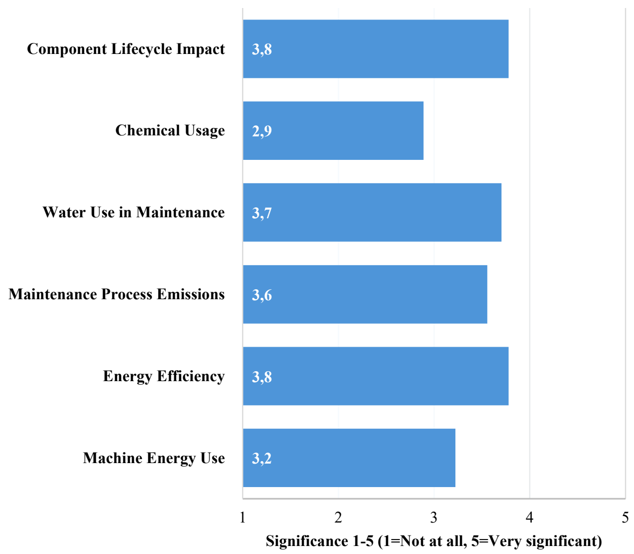
Q12: On a scale of 1-5, how significant do you consider these barriers to be when implementing Circular Economy KPIs in your organization?



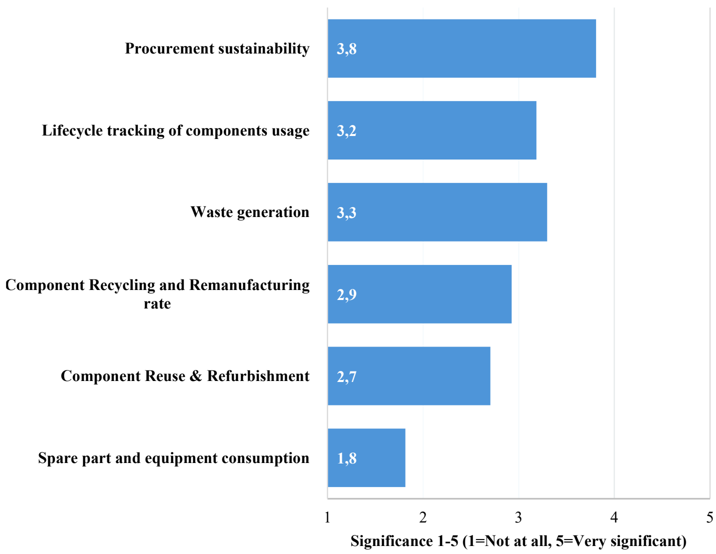
Q13: On a scale of 1-5, how difficult do you consider it to be to collect and analyse the following Operational Performance Data at your site?



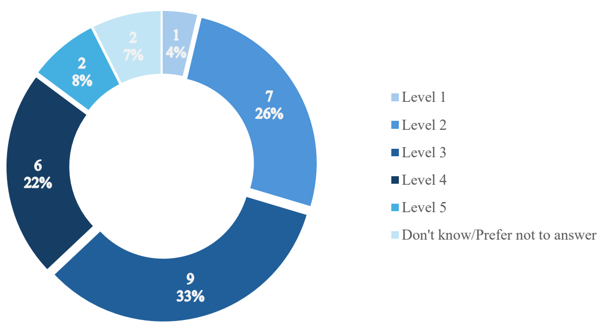
Q14: On a scale of 1-5, how difficult do you consider it to be to collect and analyse the following Energy & Environmental Impact Data at your site?



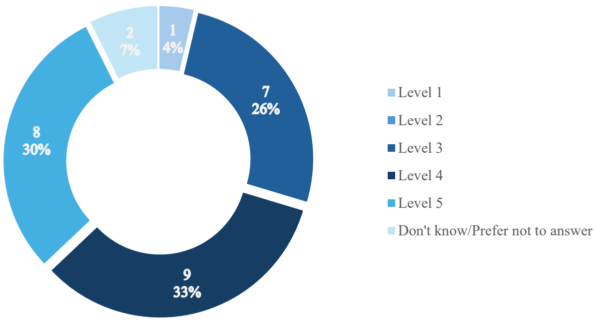
Q15: On a scale of 1-5, how difficult do you consider it to be to collect and analyse the following Material & Resource Efficiency Data at your site?



Q16: Based on the model shown in the picture, which level best represents the current maturity level of professional maintenance at your site? (Select one option)



Q17: Based on the model shown in the picture, which level do you expect to best represent the maturity level of professional maintenance at your site in 3 years? (Select one option)



Q18: What main factors do you think will influence your site's maintenance maturity level in the next 3 years?

“I think we will improve. But it goes slowly. We must focus more on standardize way of working. Stronger leadership to follow decided routines”

“I think that the maturity level will be the same. There are some new initiatives but the speed is low. Think a big problem is that there is no time in production to test new ideas.”

“Assignment of dedicated and skilled resources.”

“Management commitment when it comes to investing in new technology and solution. Generally an organization that is more aware of the importance of data and how it can help maintenance improve.”

“I expect it to improve. Great measures are taken regarding data driven maintenance. Data quality is important, and with that also education. A lot of data used for KPIs regarding all maintenance tasks is manually entered, the maintenance personnel needs education to understand the importance of their reports in our maintenance system. We also have to continue improving data collection from machines/sensors etc to be able to make more data driven decisions. We are somewhat "stuck" in the proactive replacements of parts based on historical breakdowns. For eg. one sensor breaks after 2.5years in a machine. We have 15 sensors like this in 4 more machines so we start to replace all sensors every two years to prevent breakdowns.”

“Maturity level will increase over the next few years, mainly due to restart of XPS Fa´s including PM during end of 2024 and 2025.”

“Vi måste sätta grundspelet och få alla att jobba mot samma uppsatta mål innan vi kan ta ett steg uppåt.”

”Reactive problem-solving with the ability to get to the root cause at the component level. The ability to prioritize and classify equipment, as we have over 8,000 pieces of equipment on site. Leveraging digitalization and automating our analysis, which will eventually provide the opportunity for suggestions on countermeasures."”

“Smart data collection, Condition based from different type sensors, time counter, AI analys of parameters ect”

“data collection, technology, data analysis”

“Thanks to the management commitment the level will increase”

“Small improvement from already high maturity. Finance Risk deployment as important driver. Implementation of new products and machines.”

“Resource constraints, we have a vast amount of equipment which to raise the level of maintenance maturity requires extensive efforts, which is often digested by other prioritized activities.”

“The main problem would be to have a stronger commitment to the need to develop maintenance from the plant top management. At the moment, the focus is clearly not on maintenance. We how and what to do but we don't have enough resources to develop it.”

“Management buy in, to get resouces freed up to learn and work with it.”

“We need to align the maintenance process with the general XPS methods. PM is a strong and solid pillar in XPS, but it still feels like maintenance is outside the system. This makes it difficult to set clear goals and define directions. The greatest impact comes from management work, directives, and demand.”

“One key factor i our ability to change our cultural mindset, to go from fix problem to make sure they don't happen again. Another key factors is our resources and knowledge, where the challenge is to keep current personal and train new personal, since we have a lot of people retiring within the coming 10 years.”

“We are currently working on all levels, but to increase the avarage levels within all areas take time and that´s what we are working on right now.”

“Implementing the 10 Rs concept

The 10 Rs concept is a step-by-step process that helps us make decisions about whether or not to use a new product or process, especially maintenance.The lower the “R” number (0 - 9), the more circular the strategy. Refuse, Rethink, Reduce,Reuse, Repair, Recondition, Remanufacture, Resignify, Recycle, Recover”

“From my point of view, the main factors are as follows:

*Share competence within the maintenance organization about current situation (based on the data we have) to draw conclusions of what type of maintenance strategy is preferable.

*Start working more with the actual maintenance data (from our CMMS), that will hopefully provide us with additional insights into where we should put our focus, to increase the efficiency of our maintenance activities.

*Train people within the maintenance organization to understand the transition from traditional way of working, to more preventive-/condition based maintenance strategies.

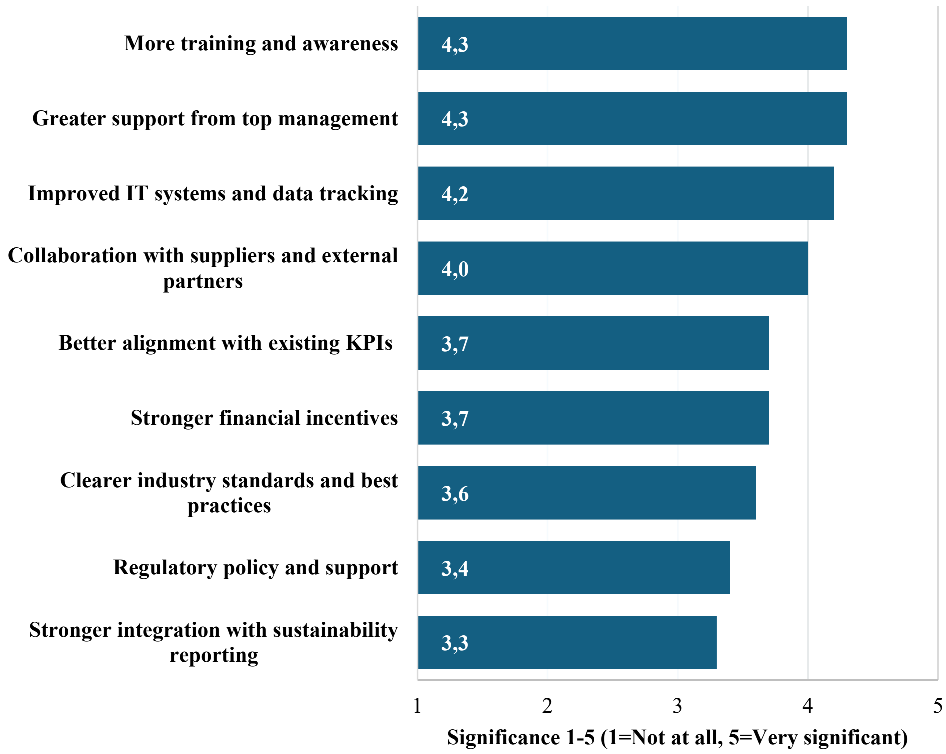
*As the development of AI/machine learning is progressing rapidly, it is crucial for the organization to enhance its competence in order to better understand what basis on which decisions are made. (It feels like there is a gap between, AI/machine-learning and the traditional way of working within maintenance, AM, PM).

*More collaboration between maintenance-teams/departments to share competence.”

“The main factor is ensuring that we can focus on improving the maturity level of our prioritized machines by developing competences, monitoring key indicators, improving standardization of our processes and way of working, and working cross-functionally with AM, PD, CD, EEM, Digital & IT, while connecting to XPS.”

“Increase, Introduction of AI tools for maintenance”

Q19: On a scale of 1-5, how significant do you consider these enablers to be in integrating Circular Economy principles and KPI's into the company's maintenance practices?



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