Diplomarbeit

Assessing Circular Economy oriented Maintenance: Development of a Performance Indicator Set

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines

Diplom-Ingenieurs

unter der Leitung von

Univ. -Prof. Dr. -Ing. Fazel Ansari

(E330 Institut für Managementwissenschaften, Forschungsbereich Produktions- und Instandhaltungsmanagement)

Dipl. -Ing. Lisa Greimel

(Fraunhofer Austria Research GmbH)

eingereicht an der Technischen Universität Wien

Fakultät für Maschinenwesen und Betriebswissenschaften

von

Philipp Stricker

[redacted]

Wien, im Jänner 2025

[redacted]

Philipp Stricker BSc

TECHNISCHE UNIVERSITÄT WIEN

Ich habe zur Kenntnis genommen, dass ich zur Drucklegung meiner Arbeit unter der Bezeichnung

Diplomarbeit

nur mit Bewilligung der Prüfungskommission berechtigt bin.

Ich erkläre weiters an Eides statt, dass ich meine Diplomarbeit nach den anerkannten Grundsätzen für wissenschaftliche Abhandlungen selbstständig ausgeführt habe und alle verwendeten Hilfsmittel, insbesondere die zugrunde gelegte Literatur, genannt habe.

Weiters erkläre ich, dass ich dieses Diplomarbeitsthema bisher weder im In- noch Ausland (einer Beurteilerin/einem Beurteiler zur Begutachtung) in irgendeiner Form als Prüfungsarbeit vorgelegt habe und dass diese Arbeit mit der vom Begutachter beurteilten Arbeit übereinstimmt.

Wien, im Jänner 2025

Philipp Stricker BSc

Danksagung

Mein Dank geht an alle Personen, die mich bei der Umsetzung der vorliegenden Diplomarbeit und den Weg dorthin unterstützt haben.

Ich möchte mich bei Herrn Dr.-Ing. Fazel Ansari vom Institut für Managementwissenschaften und Leiter des Forschungsbereich Produktions- und Instandhaltungsmanagement bedanken, der mir die Möglichkeit gegeben hat, meine Arbeit in diesem spannenden Thema zu verfassen. Hierbei gilt auch ein besonderer Dank Frau Dipl.-Ing. Lisa Greimel und Frau Dipl.-Ing. Tanja Nemeth vom Fraunhofer Institut, die mich mit ihrer Fachexpertise und ihrer Betreuung unterstützt haben und jederzeit für eine fachliche Diskussion und Fragen zur Verfügung gestanden sind.

Ein weiterer Dank gilt Herrn Dipl.-Ing. Linus Kohl, der mir nicht nur als Mentor mit seinem hilfreichen und reichhaltigen Feedback bei der Weiterentwicklung meiner Arbeit zur Seite gestanden ist, sondern mir auch bei außeruniversitären Fragen stets ein offenes Ohr geschenkt hat.

Weiters möchte ich meinen Eltern dafür danken, mir den Grundstein für meine Ausbildung gelegt zu haben und noch viel mehr meine Begeisterung für das Studieren geweckt zu haben und es mir dabei immer ermöglicht haben, das Studium in dieser Form ausüben zu können.

Ein ganz besonderer Dank gilt meiner Freundin, die mir immer mit Rat und Tat zur Seite gestanden ist und mir dabei immer wieder neue Denkanstöße gegeben hat. Dabei ist sie nicht zuletzt bei der Diplomarbeit, sondern auch in all den Jahren mit ihrer Geduld und Unterstützung ein wichtiger Halt gewesen und hat mich dabei durch alle Höhen und Tiefen begleitet. Dabei hat sie mich stets motiviert, das Beste aus mir rauszuholen.

Kurzfassung

Durch den zunehmenden Fokus auf Nachhaltigkeit und Ressourceneffizienz von Seiten der Industrie, Gesellschaft und Gesetzesgeber hat die Bedeutung der Prinzipien der Kreislaufwirtschaft (KLW) zugenommen. Dadurch wurde auch die Rolle der Instandhaltung zur Erreichung der KLW-Ziele gesteigert, da diese Lebensdauer von Produkten verlängert, Ressourceneffizienz erhöht und auch die Abfallmenge vermindert (Morseletto, 2020). Daher untersucht diese Arbeit die Schnittstelle zwischen der KLW und der Instandhaltung mit dem Ziel, eine umfassende Auswahl von Key Performance Indicators (KPIs) zu entwickeln, mit denen KLW-orientierte Instandhaltungsstrategien effektiv gemessen und verbessert werden können.

Die Studie beginnt mit einer Literaturübersicht und analysiert bestehende Leistungsmesssysteme und Instandhaltungsstrategien, insbesondere solche, die auf die Prinzipien der KLW ausgerichtet sind, da die Haupttreiber und Modi der kreislaufwirtschaftsorientierten Instandhaltung bisher nicht spezifiziert sind. Diese Übersicht identifiziert eine Reihe bestehender KPIs, hebt aber auch das Fehlen einer standardisierten KPI-Sammlung hervor, die sich speziell mit KLW in der Instandhaltung befasst. Um diese Lücke zu schließen, wird in der Arbeit ein neuartiges Indikatorenset entwickelt, bei dem die Indikatoren als Circular Maintenance Indicators (CMIs) bezeichnet werden, um erstmals die Indikatoren in diesem Bereich in einer einheitlichen und systematischen Visualisierung darzustellen.

Dies wird durch einen iterativen Prozess erreicht, der auf der Design Science Research-Methodik von Alan R.; Hevner (2007) basiert. Mit der Literaturrecherche können die KPIs für ein vorläufiges Indikatorenset eruiert werden. Nach einer Umfrage bezüglich der Bedeutung der Indikatoren mit Industrievertretern wird das CMI-Set verfeinert und ein Bewertungssystem erstellt, das Unternehmen die Messung des KLW-grades ihrer Wartungsstrategien ermöglicht. Dieses wurde dann auch in einem industriellen Anwendungsbeispiel getestet. In Kombination mit dem 9R-Framework von Kirchherr, Reike, and Hekkert (2017) trägt es dazu bei, die Implementierung und Kommunikation von Wartungen innerhalb von Organisationen zu erleichtern und Unternehmen die Möglichkeit zu geben, einen KLW-orientierten Wartungsansatz basierend auf ihrem spezifischen Anwendungsfall sicherzustellen.

Letztlich leistet diese Arbeit einen bedeutenden Beitrag sowohl zur akademischen Forschung als auch zu praktischen Industrieanwendungen. Das entwickelte Indikatorenset misst nicht nur aktuelle Vorgehensweisen, sondern dient auch als Orientierung für zukünftige Verbesserungen und unterstützt die Industrie beim Übergang zu nachhaltigeren, zirkulären Betriebsmodellen.

Abstract

The increasing focus on sustainability and resource efficiency in industrial sectors has expanded the popularity and importance of the principles of Circular Economy (CE). Furthermore, it has highlighted the crucial role of maintenance in a company to achieve CE related goals, by extending products' lifespan, increasing resource efficiency and reducing waste (Morseletto, 2020). Therefore, this thesis investigates the intersection of CE and maintenance, aiming to develop a comprehensive framework of Key Performance Indicators (KPIs) that can effectively measure and enhance CE oriented maintenance strategies.

The thesis begins with a literature review, analyzing existing performance measurement systems and maintenance strategies, particularly those aligned with the principles of the CE, as the main drivers and modes of CE oriented maintenance are not specified. This review identifies a range of existing KPIs but also highlights the absence of a cohesive and standardized set that specifically addresses CE in maintenance. To bridge the gap, this work develops a novel indicator set, where the indicators are termed Circular Maintenance Indicators (CMIs), to give the indicators a first organized and systematic visualization for this matter.

This is achieved through an iterative process, based on the Design Science Research methodology by Alan R.; Hevner (2007). It includes the synthesis of KPIs through insights from the literature to gain an overview and a set of possible indicators. After a rigorous selection process, a draft CMI set is reviewed in a survey of industry practitioners, who provide first-hand perspectives on the applicability and relevance of various CMIs in real-world scenarios. The survey results are crucial in refining the initial draft set of indicators, ensuring they are both practical and reflective of industry needs.

Based on the results of the survey and literature review, not only a final CMI set is created but also the importance review of each CMI is used to create a grading system for companies to measure their circularity level of their specific maintenance strategies. In combination with the 9R framework by Kirchherr et al. (2017) it assists in facilitating easier implementation and communication of maintenance measurements within organizations and give companies the possibility to ensure a CE oriented maintenance approach based on their specific use case.

Ultimately, this thesis offers a significant contribution to both academic research and practical industry applications. It provides a structured approach for companies seeking to enhance their sustainability efforts by embedding CE principles into their maintenance operations. The developed performance indicator set not only measures current practices but also guides future improvements, helping industries transition towards more sustainable, circular models of operation.

Table of Content

1 Introduction

Chapter 1 shows the initial motivation and problem definition and outlines the research questions and objectives. Furthermore, the research methodology and the systematic approach used to develop and validate an indicator set is explained. An explanation of the structure of the thesis is offering a guideline for the subsequent chapters.

1.1 Motivation and Problem Definition

Already in the year 2015 the United Nations (UN) established 17 Sustainable Development Goals (SDGs), which aim to address and counteract a broad range of global challenges, including poverty, inequality, environmental sustainability and climate change (UN, 2015). In the context of the ongoing industrial development, a conservative and efficient use of natural resources should be ensured as the industrial sector has a share of 37% on consuming resources and is responsible for 25% of the worldwide CO_2 emission (IEA, 2023). Whereas in the European Union (EU), the industrial sector is responsible for approximately 25-30% of resource use and contributes about 20% of the region's total CO_2 emissions (EEA, 2023). The EU meets the requirements of SDGs through different reporting systems and frameworks built on the European Green Deal to become the first climate neutral continent (Commission, 2019). As part of the shift countries, Europe is characterized by high levels of consumption and affluent lifestyles (Commission, 2019).

In recent years, the concept of the circular economy (CE) has increasingly come into focus in the EU, as the European Commission (2020) introduced legislative and non-legislative measures with the new CE action plan as one of the main building blocks of the European Green Deal. However, it needs to be said, that the term CE originally appeared in 1990, when the connection between the environment and the economy was highlighted (Pearce & Turner, 1990). But the approach gained significant popularity when the MacArthur Foundation positioned itself as a strong proponent of the CE (E. M. Foundation, 2023; Kara, Hauschild, Sutherland, & McAloone, 2022). The global circular report 2024 shows that the CE reached a megatrend status, but the global circularity is still declining by over 21% over the last five years and in the same period the consumption increased by 28% (C. E. Foundation & Deloitte, 2024).

Therefore, the CE action plan in the EU introduces initiatives that address every stage of a product's life cycle and environmental obstacles. It focuses on optimizing product design, promoting CE practices, fostering sustainable consumption habits, and ensuring that waste is minimized. Additionally, it seeks to keep resources within the EU economy for as long as possible, maximizing their utility and reducing environmental impact. CE strategies, including maintenance-driven approaches, could save EU businesses up to € 600 billion annually and reduce CO_2 emissions by 50%

says the European Commission (2020). Furthermore, the E. M. Foundation (2023) reports that CE strategies can reduce material consumption by 32% and cut greenhouse gas emissions by 72% in key industrial sectors. In this matter, maintenance is considered to be one of the key functions to achieving the goals of CE, by extending products' lifespan, increasing resource efficiency and reducing waste (E. M. Foundation, 2023; Sobral & Ferreira, 2018). Especially for the industrial sector, effective maintenance strategies can reduce equipment downtime by 30-50% and reduce overall maintenance costs by 10-15% (McKinsey, 2022). Figure 1 shows the framework by the Ellen MacArthur Foundation regarding the concept of CE and indicates the connection to maintenance approaches, which will be discussed in more detail in cf. Chapter 2.1.

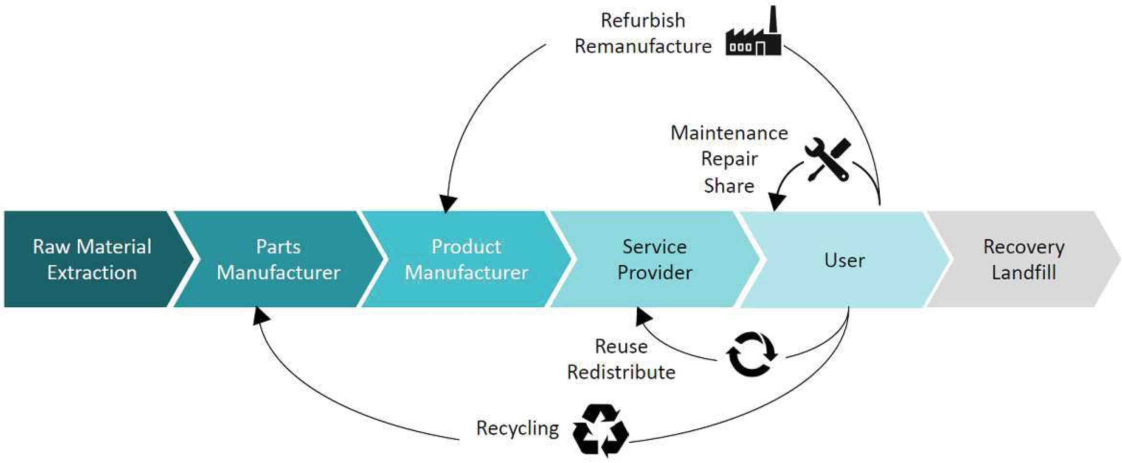


Figure 1: Circular Economy framework based on the EEA (2023); E. M. Foundation (2023)

While maintenance management is the systematic process of planning, organizing, and controlling maintenance related activities and the upkeep of physical assets, a transformation in maintenance engineering is necessitated to meet the goals of CE. On the one hand, there is the digital transition by the application of engineering skills, digital tools and technologies to improve the effectiveness of maintenance operations, such as optimized resource allocation, real-time machine monitoring and prediction of equipment failures (Brumby, 2023). On the other hand, there is the green transition, which implies waste minimization and reduction of resource consumption. By implementing specific methods, techniques, and tools for optimizing equipment, procedures, and departmental budgets, companies can significantly enhance the maintainability, reliability, and availability of their equipment (Brumby, 2023). These improvements actively support both the green and digital transitions and CE oriented maintenance plays a crucial role in this dual transformation by promoting sustainable resource use and integrating digital technologies (Brumby, 2023; DIN, 2022). Therefore, the new DIN EN 17666 tries to close the gap by including the tasks of modernization and modification in the maintenance engineering tasks with the aim of extending the Remaining Useful Life (RUL) and enhancing resource efficiency (Brumby, 2023).

New CE production and maintenance business models are also developing based on the CE concepts seen in Figure 1, such as remanufacturing (e.g. plant manufacturer takes back old plants, reuses parts of the old plant in new products and resells them) and refurbishment (e.g. plant manufacturer takes back old plants, repairs or replaces defective components and resells them). However, it is not specified yet, what the main drivers and modes of circularity in maintenance management systems (P1), and what the possible measurements to see the change towards CE in maintenance (P2) are. Furthermore, there is a lack of tangible and transparent methods for measuring CE oriented maintenance performance (P3).

Considering this pathway of research, this work aims to provide a sufficient answer to the following problems:

- P1: The main drivers and modes of circular oriented maintenance are not specified.
- P2: It is not evaluated what KPIs are needed and used in industrial use-cases for circular oriented maintenance.
- P3: These KPIs have not been organized and depicted in a systematic and visual manner yet.

1.2 Research Questions and Objectives

This thesis investigates the even more needed CE oriented maintenance challenges, as there are very few insights from the industry and research reports on this topic to date. Fontana et al. (2021) give an overview of equipment lifetime extension as a CE strategy, while Connolly (2023) developed a risk based CE framework to rank maintenance activities. Ibrahim, Hami, and Othman (2019) integrate sustainable maintenance to achieve and support sustainable manufacturing practices and Karki, Basnet, Xiang, Montoya, and Porras (2022) work on digital and sustainable asset maintenance services to prolong asset life cycles. Ghaleb and Taghipour (2022) show with their study the impact of maintenance practices on sustainable organizations. By analyzing these findings among others and conducting a literature review of state of the art (SOTA) CE oriented maintenance approaches, which is elaborated in more detail in cf. Chapter 3, (P1) is answered and (O1) is accomplished.

Furthermore, in the case of the environmental challenges such as the climate change and governmental and legal guidelines in the form of reporting goals and regulations of the EU, there is a need to take a closer look at maintenance engineering, paving the way for a comprehensive understanding of evolving maintenance paradigms and how they assist in supporting companies in fulfilling the given EU regulations and CE approaches (Brumby, 2023). The envisaged impact of maintenance can be measured by Key Performance Indicators (KPIs), which are explored by a literature review on existing maintenance approaches, Cf. Chapter 3, coupled with a survey to gather first-hand industry perspectives, Cf. Chapter 4. The explanation to assess the effectiveness and efficiency of maintenance activities in the form of KPIs support to answer (P2) and (O2) is attained. With the help of a comprehensive examination and representation of current maintenance strategies, their drivers to CE oriented maintenance and their KPIs, (P3) are identified and (O3) is fulfilled.

The main objective of this master thesis is the identification and creation of a maintenance performance indicator set under the premise of CE. This is supported by a literature review on existing KPIs, coupled with a survey to gather first-hand industry perspectives. Special attention is given to which drivers for CE oriented maintenance strategies exist, how maintenance can be a key enabler in fulfilling CE and how this can be measured.

On this basis, the main research question develops: “How can the impact of maintenance in the circular economy be evaluated in manufacturing companies?”

Sub research questions for P1, P2, and P3:

- RQ1: What are the drivers and modes of circularity in maintenance (management) systems?
- RQ2: What are significant KPIs of circular oriented maintenance in literature and today's practical industrial applications?
- RQ3: How can these KPIs represent a transparent CE oriented maintenance measurement?

The objective of this research is therefore summarized as:

- O1: Identification of CE oriented maintenance related drivers and modes by carrying out literature research.
- O2: Determination of CE enabling maintenance KPIs by carrying out a literature review and conducting a survey on industrial representatives.
- O3: Creation of an indicator set for CE oriented maintenance management model and evaluation by expert interviews.

1.3 Research Methodology

1.3.1 The Design Science Research Method

As seen in Figure 2, this thesis's work process is carried out according to the Design Science Research Cycles, which is based on the Design Science Research (DSR) method by Alan R.; Hevner (2007). The design science method aims to create an artifact (A. R. Hevner, Salvatore, Jinsoo, & Sudha, 2004). This artifact can be constructs, models, methods or instantiations to address formerly unsolved problems. In this case, the creation is an indicator set for CE oriented maintenance. DSR supports the creating process and can be classified into three phases, extended by three cycles.

The relevance cycle connects the real-world problem space with the building phase of the indicator set. Within the environment, general awareness of climate change, the regularities of the EU, the scarcity of resources and the drivers for CE oriented maintenance (all environment) create the requirements. An artifact (the indicator set) arises from these requirements. After the artifact has been created by going through the design cycle, it is evaluated with a maintenance use case from the environment.

As mentioned, the second phase, namely DSR, describes the artifact's development with the iteration of the core activities of building and evaluations and is symbolized by the design cycle.

The rigor cycle represents the majority of the thesis, as an artifact is built with the knowledge base expertise, seen in Figure 2. Therefore, research methods were used to assist in creating the indicator set. For the knowledge base, a holistic overview of all areas needed for maintenance in CE approaches is given at cf. Chapter 2. In the form of literature research, today's maintenance approaches are summarized, CE goals and frameworks are described and the existing KPIs are discussed. Furthermore, a survey with companies was conducted and the result was analyzed to enable the creation of a realistic and industry-oriented indicator set, cf. Chapter 4. The finished indicator set for CE oriented maintenance represents the contribution to the knowledge base and closes the rigor cycle (Alan R.; Hevner, 2007).

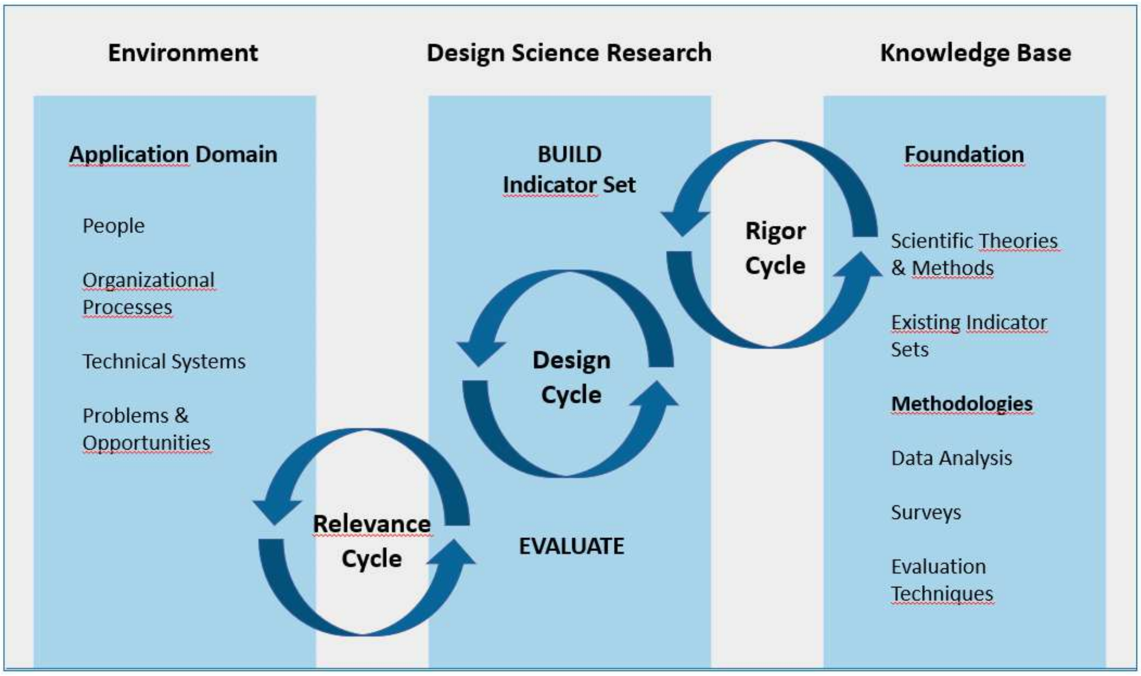


Figure 2: Three Cycle View recreated based on Alan R.; Hevner (2007)

Besides the framework, A. R. Hevner et al. (2004) provide seven guidelines to help the researcher apply the methodology, which can be seen in Table 1. They ensure that research is both innovative and practically relevant, emphasizing artifact creation, problem relevance, rigorous evaluation, and effective communication.

Table 1: Seven Guidelines by Hevner et al. (2004)

Guideline	Description
Guideline 1: Design as an Artifact	DSR produces a viable artifact in the form of a CE oriented maintenance indicator set.
Guideline 2: Problem Relevance	DSR develops a indicator set, that meets and challenges the environmental and governmental obstacles regarding CE.
Guideline 3: Design Evaluation	The design artifact's utility, quality, and efficacy is evaluated with a real-world industrial use case.
Guideline 4: Research Contributions	The DSR provide transparent and verifiable contributions to design artifacts, foundations, or methodologies.
Guideline 5: Research Rigor	The rigor cycle has a comprehensive literature review, feedback from industry practitioners, ensuring it is both scientifically grounded and practically applicable.
Guideline 6: Design as a Search Process	The search involves the use of existing knowledge from both the academic knowledge base and industry feedback and uses available tools and methods, including surveys and expert interviews.
Guideline 7: Communication of Research	The result of DSR can be presented effectively both to technology- and management-oriented audiences.

There are some limitations to this approach as well. The DSR process can be time-consuming and resource-intensive, as it often involves multiple iterations of artifact design, testing, and refinement, especially when engaging with practitioners or applying the research in real-world settings (A. R. Hevner et al., 2004). To address this, the focus in the survey is on industry practitioners with extensive knowledge of maintenance, which increases the quality of feedback and improvements made to the indicator set. Furthermore, Hevner's framework places significant emphasis on the creation and evaluation of IT artifacts, which can be restrictive in broader contexts where the creation of non-IT artifacts or the focus on processes and theories might be more important (Iivari, 2007). Therefore, the framework is adapted to accommodate non-IT artifacts by focusing on the application of processes and KPIs rather than technology-driven artifacts. Also, the evaluation of artifacts can be problematic. Since the evaluation process is context-dependent, it can be difficult to generalize findings or compare results across different studies. This context-dependence can also lead to issues with reproducibility and the robustness of the findings (Venable, Pries-Heje, & Baskerville, 2017). To mitigate this, the survey and literature review include multiple case studies from different production sectors to ensure a broader application of the indicator set.

1.3.2 Literature Analysis

As a starting point, an exploratory literature search was conducted using Google Scholar, focusing on papers that explicitly used the term CE oriented maintenance. From this search, 16 papers were identified as foundational papers due to their direct relevance to the topic. Following this, a systematic literature research was carried out to provide high quality results and a solid knowledge base, inspired by the literature research strategy by Zonta et al. (2020) and Peres et al. (2020). Therefore, a search

((“maintenance” OR “maintain”) AND (“repair” OR “reparation” AND (“refurbish” OR “refurbishment”) AND ”remanufacture” AND ”reuse” AND (“KPI” OR “performance” OR “indicator”))

Figure 3: Google Scholar search

string, screening criteria and databases were defined. The constructed search string, seen in Figure 3, was adapted to Google Scholar as a starting database, continuing with IEEE and ScienceDirect from Elsevier. To stay inside the scope and obtain the most important papers out of an enormous data pool, exclusion criteria were defined in Table 2. Criteria 1 was established, as CE became more prominent after 2013, with key publications like the Ellen MacArthur Foundation’s reports driving much of the conversation and innovation around sustainability, resource efficiency, and CE in industries. Some types of publications were excluded by criteria 2, to ensure a focus on peer-reviewed journal articles and conference papers, which typically provide more standardized, rigorously vetted, and concise findings. This allows a standardized research methodology and better comparability.

Table 2: Screening criteria

Criteria 1	Filter looking for a period of 10 years, 2014 to 2024
Criteria 2	Remove books, technical reports, dissertations and theses
Criteria 3	Publication must include the search terms “Circular Economy”, “reuse”, “remanufacture”, “repair” or “refurbish”
Criteria 4	Publications must be in an industrial and production context
Criteria 5	Publications must address maintenance as a model, method, architecture, approach or methodology for CE

Due to the limitations of bool's operators on the other databases, the search string got slightly adjusted. The updated search string, which has been proven the best out of several tries, for IEEE can be seen in Figure 4 and for ScienceDirect in Figure 5.

("Circular Economy" AND ("maintenance" OR "maintain") AND "remanufacture" AND "reuse" AND ("KPI" OR "performance" OR "indicator"))

Figure 4: IEEE Xplore search string

("maintenance" AND "repair" AND ("refurbish" OR "refurbishment") AND "remanufacture" AND "reuse" AND ("KPI" OR "performance" OR "indicator"))

Figure 5: ScienceDirect search string

The selection process, seen in Figure 6, can be described as different stages within the various databases. With an algorithm by Wittmann (2017), the most relevant papers on Google Scholar as the starting database were set. The time span was defined from 2014-2024 and a cut-off by 100 articles was done. Within these 100 papers, 1 was removed due to the second and six were removed due to the fourth criterion and 27 more based on text analysis. Then the search string was applied to IEEE and ScienceDirect with the same procedure. Duplicates, which were already analyzed in Google Scholar, were removed. At the end of the selection process, 75 articles were selected based on analysis of the abstract, keywords and conclusion, and section content checking. In addition, the 16 foundational papers from the exploratory literature search were also analyzed for existing indicators. The evaluation and the results can be seen in Chapter 3.2.

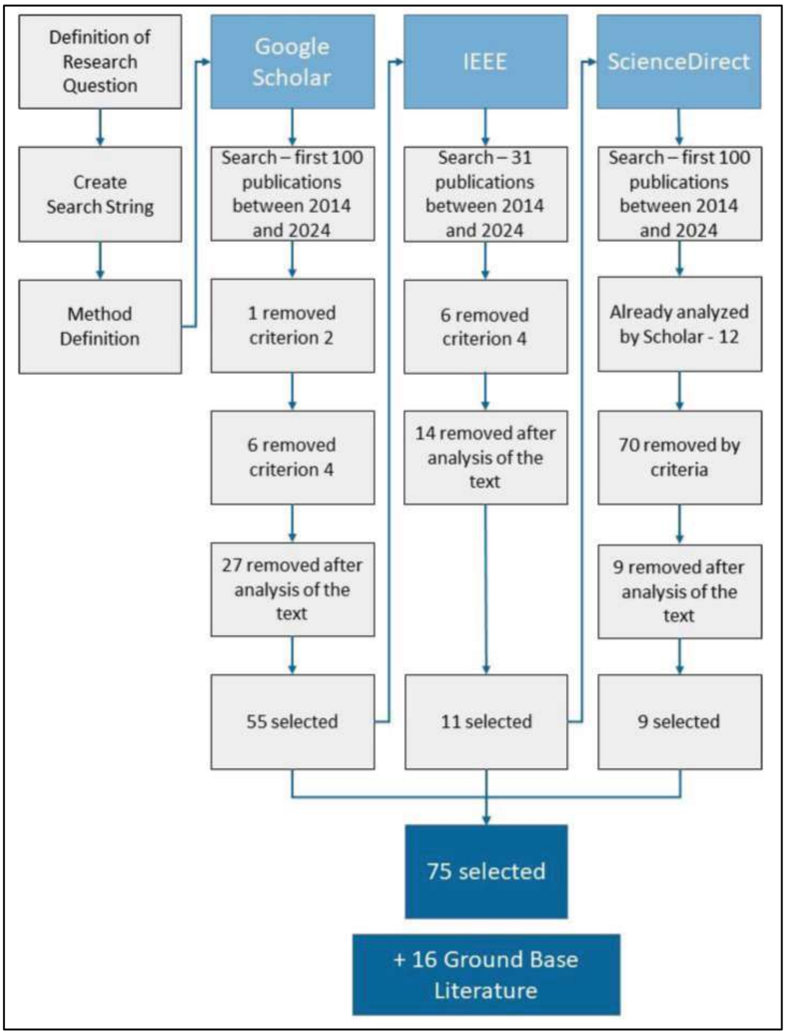


Figure 6: Screening of research

1.4 Structure of the thesis

This master thesis is divided into six chapters, seen in Figure 7. After this chapter, chapter two provides a theoretical background of the key areas CE, maintenance and performance measurement systems. In the third chapter, the findings of the literature analysis on existing indicators are presented. Based on this, chapter four validates this set with a survey and the findings of chapter three and four come together in the creation of an indicator set in chapter five. Chapter six gives a conclusion and outlook of this work and describes possible follow-up work regarding this topic.

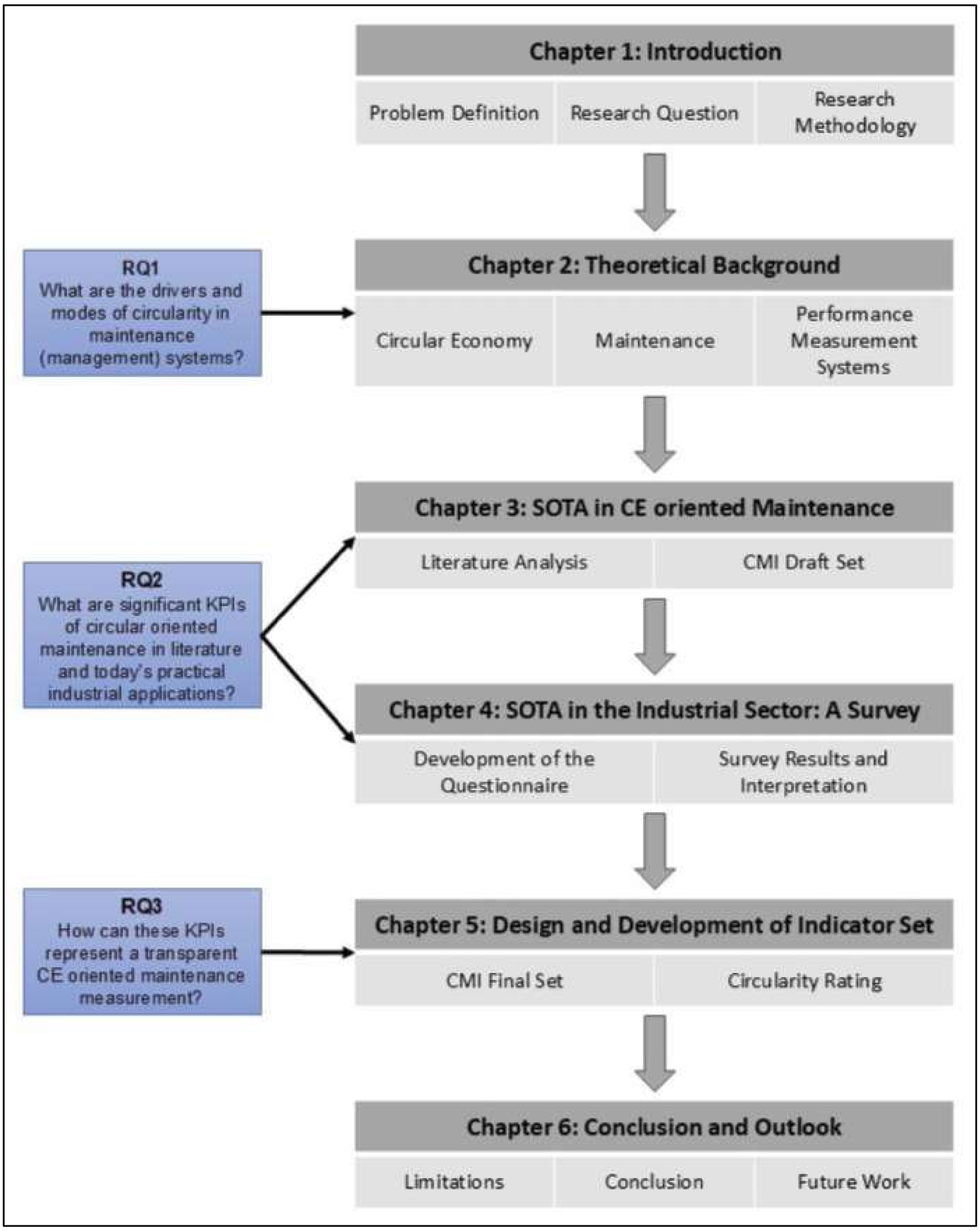


Figure 7: Structure of the Thesis

2 Theoretical Background

This chapter presents the needed fundamental knowledge for the development of the indicator set and discusses related terminologies.

2.1 Circular Economy

The term CE originally appeared in 1990, introduced by Pearce and Turner (1990), describing the need to decouple resource consumption from economic growth and value creation by focusing on sustainable practices that minimize waste and promote resource efficiency. The goal of CE is to challenge the traditional linear economic model, which relies on extracting raw materials, producing goods, and disposing of them after use (Grüning et al., 2021).

Therefore, the 9R principles build a guideline for the CE approaches, as seen in Figure 8. The original term used for these actions was the 3R concept (reduce, reuse, recycle). Next, the idea has been broadened to include the 6R (including recover, redesign, and remanufacture), and later developed into the 9R concept (adding refurbish, repair, and refuse). The CE, which relies on these 9Rs, goes beyond just minimizing waste (Khaw-ngern, Peuchthonglang, & Klomkul, 2021). The Rs can be categorized into three main groups based on their approach to resource efficiency and waste reduction, i.e. prevention, extension, and recovery (Kirchherr et al., 2017).

Prevention aims to minimize waste and resource use at the source. It encompasses actions like refusing unnecessary products and reducing material and energy use (Khaw-ngern et al., 2021). This approach is considered the most effective and desirable in CE terms because it addresses environmental impacts before they occur and is targeted by the three Rs refuse, rethink and reduce (Khaw-ngern et al., 2021). The measurement group of extension focuses on prolonging the life cycle of products and materials. Through reuse, repair, refurbishing, remanufacturing and repurposing, this category helps in reducing the demand for new resources and lowers the environmental footprint associated with production and disposal (Khaw-ngern et al., 2021). Recovery involves reclaiming value from waste through recycling and energy recovery (Grüning et al., 2021). It's a less preferred option compared to prevention and extension because it deals with materials after they've become waste, but it's still crucial for minimizing landfill use and extracting value from waste (Grüning et al., 2021).

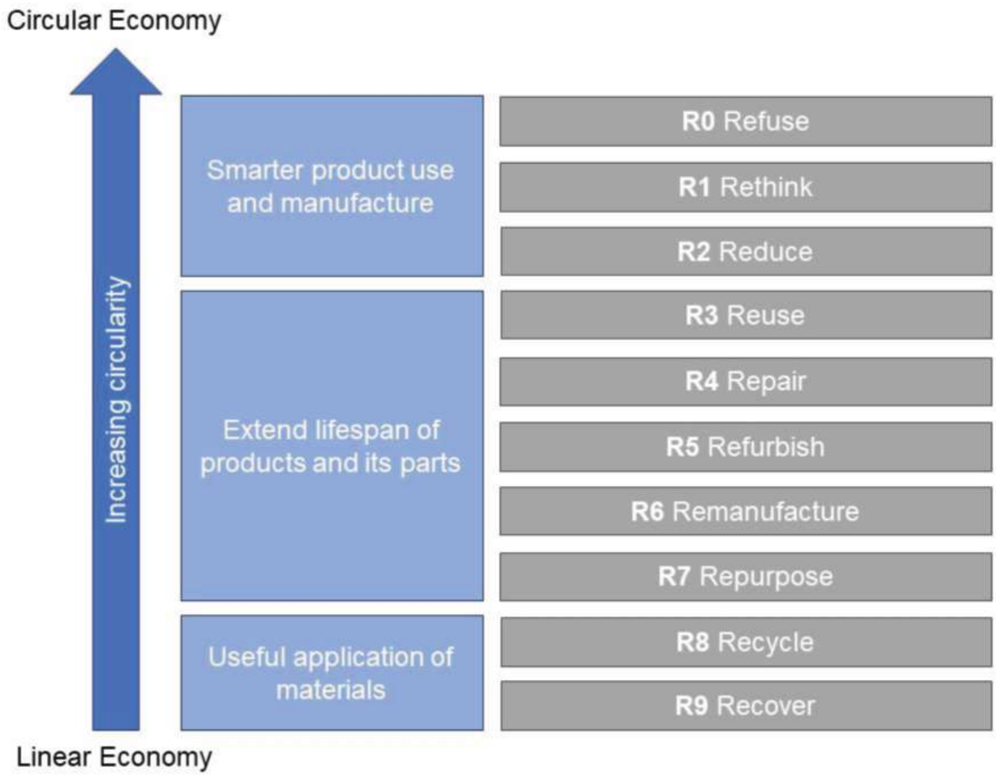


Figure 8: The 9R framework adopted from Kirchherr et al. (2017)

The following explains the 9Rs in detail (Khaw-ngern et al., 2021; Kirchherr et al., 2017):

- **Refuse:** Avoiding the use of products or materials that generate waste. This can involve rejecting products with excessive packaging or opting out of products that are not necessary.
- **Rethink:** Re-evaluating how products are used and exploring ways to use them more efficiently. This can include designing products for longer lifespans or finding new ways to use products to extend their usefulness.
- **Reduce:** Minimizing the amount of materials and energy used in the production and consumption of goods. This can be achieved through more efficient processes, reducing material use, and designing products that require fewer resources.
- **Reuse:** Using products or components again, either for their original purpose or for a different function. This involves repairing, refurbishing, or repurposing items instead of discarding them.
- **Repair:** Fixing products that are broken or malfunctioning so they can be used again. This helps extend the life of products and reduces the need for new items.
- **Refurbish:** Restoring old or used products to a good working condition by cleaning, repairing, or updating parts. This makes them suitable for resale or reuse.

- **Remanufacture:** Rebuilding products to their original specifications using a combination of reused, repaired, and new parts. This can offer the performance and warranty of new products but with a reduced environmental impact.
- **Repurpose:** Using an item for a different purpose than it was originally intended. This creative approach can prevent waste by finding new uses for products that are no longer needed for their original function.
- **Recycle:** Processing used materials into new products to prevent waste of potentially useful materials. This is the last resort after other options have been exhausted and involves converting waste into reusable materials.
- **Recover:** Extracting useful energy or materials from waste that cannot be recycled. This can include recovering energy through incineration or capturing valuable materials through advanced recovery processes.

The 9R have been used by various organizations and researchers to create their frameworks. Especially in recent years, the MacArthur Foundation positioned itself as a strong proponent of the CE. It describes CE as "an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models" (E. M. Foundation, 2023). The concept of the MacArthur Foundation with the derived objectives can be outlined using three key principles, which can be seen in Figure 9. The first principle is to conserve and augment natural capital by managing limited stocks and managing the flow of renewable resources to regenerate natural systems (Kara et al., 2022). The second one is to maximize resource efficiency by maintaining the circulation of products, components, and materials at their highest utility at all times, within both biological and technical cycles and the last one is to enhance system efficiency by identifying and eliminating negative externalities through thoughtful design and planning, such as waste and pollution (Kara et al., 2022).

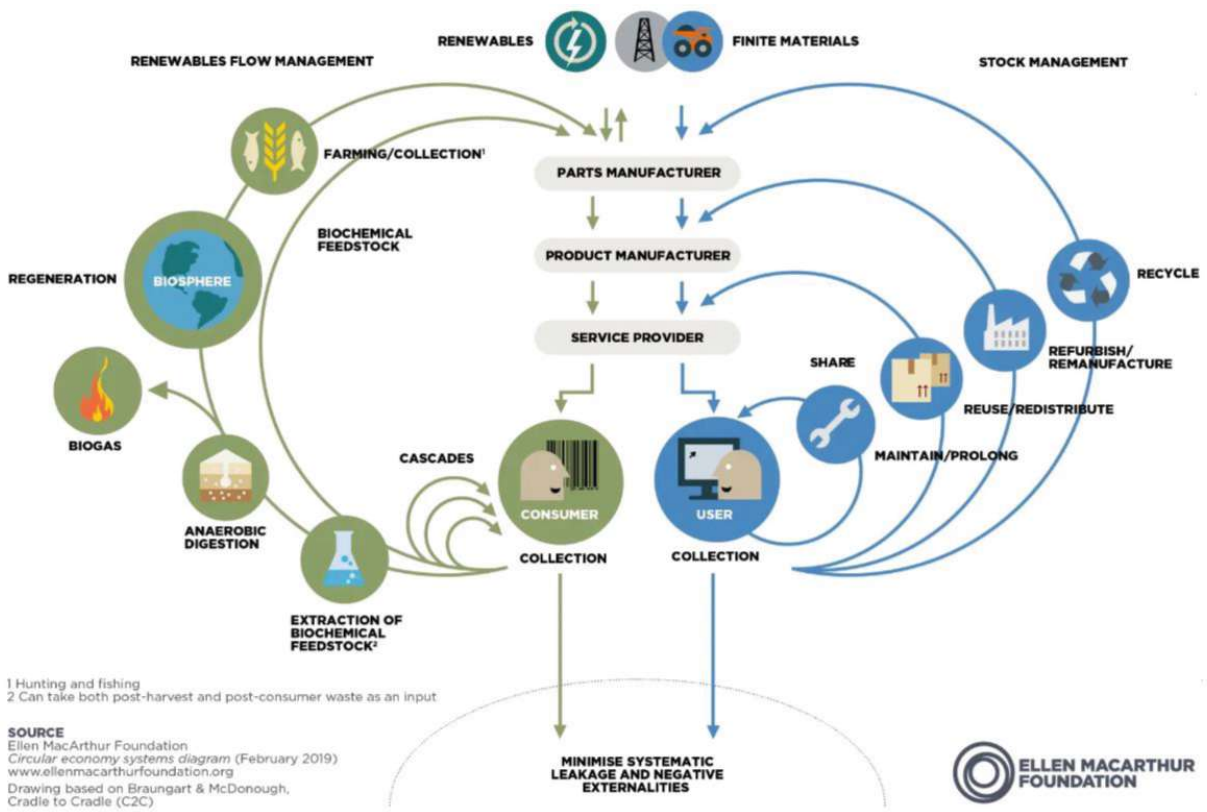


Figure 9: Circular economy butterfly diagram by E. M. Foundation (2023)

Doughnut economic model is connected to CE through their shared goal of creating a sustainable economy that operates within planetary boundaries while meeting human needs (Raworth, 2024). CE provides the practical strategies that help economies remain within the environmental limits defined by the doughnut-shaped diagram, as seen in Figure 10. The inner ring of the doughnut represents the social foundation as the essentials for a good life, such as access to food, water, health care, education, income, and political voice (Raworth, 2017). These elements are derived from the UNs SDGs. The outer ring of the doughnut represents the ecological ceiling, which consists of the nine planetary boundaries identified by Earth-system scientists. These include climate change, biodiversity loss, land conversion, and nitrogen and phosphorus loading (Raworth, 2017). The space between the two rings, the "safe and just space for humanity," is where social and planetary boundaries are respected. The goal is to ensure humanity does not exceed these ecological limits, which would lead to environmental degradation (Raworth, 2017, 2024).

The area between the social foundation and the ecological ceiling is where humanity can flourish as this space represents an economy that provides a decent standard of living for all people without depleting the planet's resources and Raworth (2017) emphasizes the importance of regenerative and distributive economic practices to achieve this balance. Companies are increasingly using the doughnut model to align their operations with both social and environmental sustainability goals.

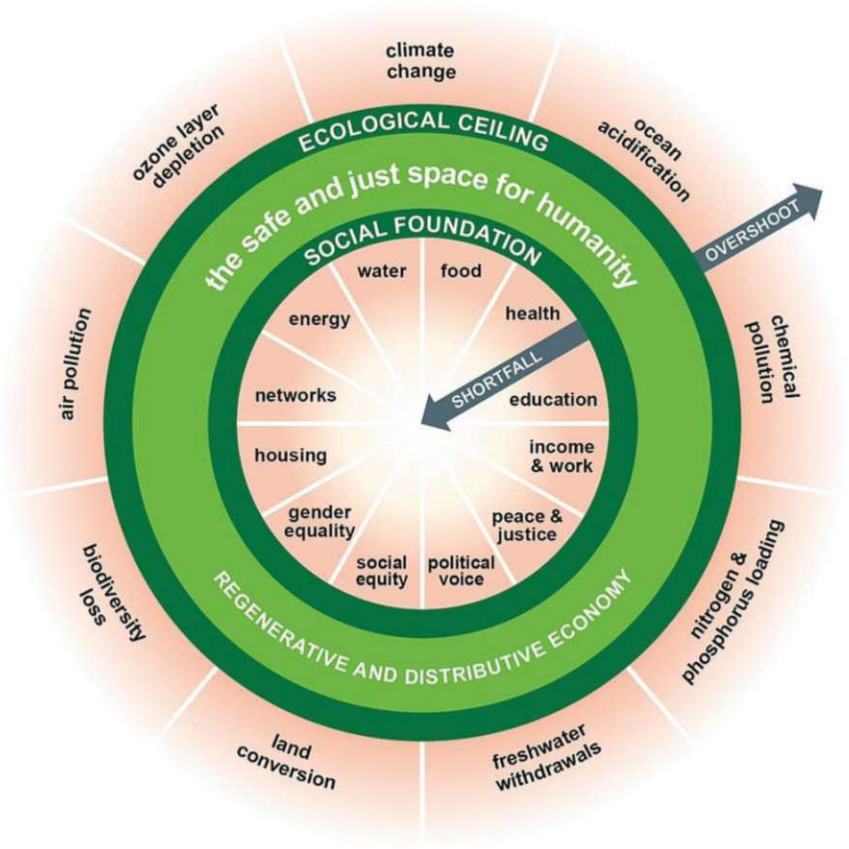


Figure 10: The doughnut of social and planetary boundaries based on Raworth (2017)

The **Triple Bottom Line** (TBL) is a well-known sustainability frameworks which was coined by Elkington (1994) and provides the overarching framework for sustainable development described in the interaction between people (social), the environment and the company (economic). CE offers concrete strategies to manage these interactions by closing the loop on material use and ensuring that economic activity benefits society and the environment. The matching Venn diagram, seen in Figure 11, emphasizing that true sustainability requires a balance of all three aspects. The following sections briefly describe the three individual categories.

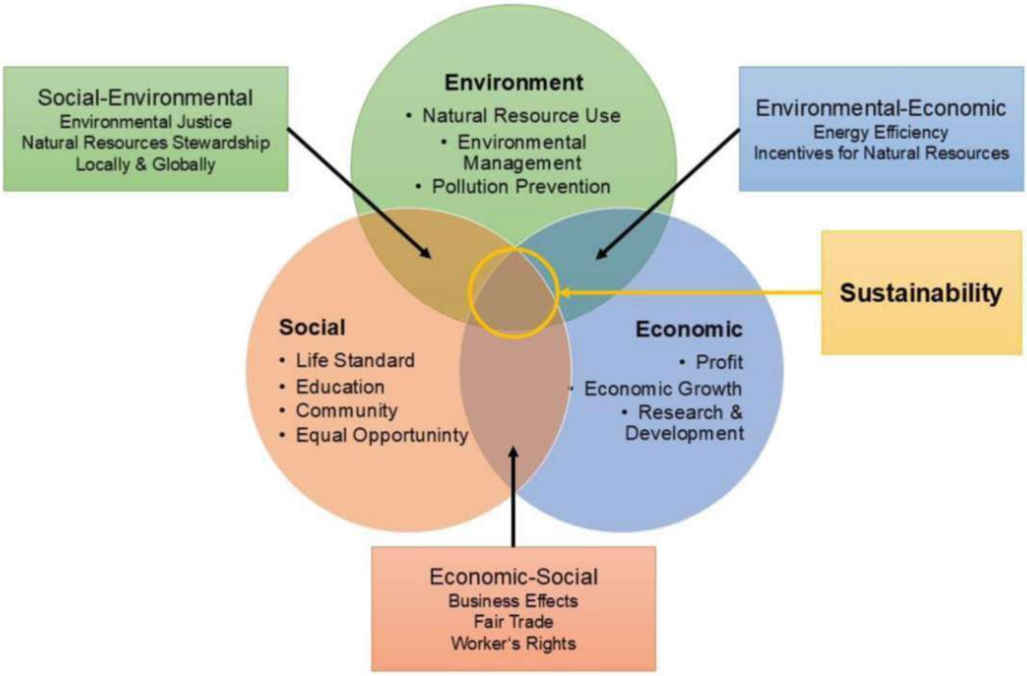


Figure 11: Triple Bottom Line based on Elkington (1994)

The economic line of the TBL focuses on how an organization's growth contributes to the economy and its support for future generations. This aspect emphasizes the economic value the organization provides to the overall system by promoting prosperity and ensuring sustainability for the future (Alhaddi, 2015).

TBL's social line refers to the implementation of fair and beneficial business practices for workers, human capital and the community (Elkington, 1997). These practices, such as offering fair wages and health care, provide value to society and "give back" to the community. Neglecting social responsibility can have a negative impact on a company's performance and sustainability (Alhaddi, 2015).

TBL's environmental policy includes practices that conserve environmental resources for future generations (Elkington, 1997).These include the efficient use of energy, reducing greenhouse gas emissions and providing a proper waste management (Alhaddi, 2015). A study has revealed that companies with environmentally and socially responsible practices outperformed their competitors financially during an economic downturn (Alhaddi, 2015). This financial advantage resulted from lower operating costs (e.g. energy and water consumption) and higher revenues from sustainably friendly innovative products (Alhaddi, 2015).

Velenturf and Purnell (2021) suggest a transformative framework of the TBL for a sustainable circular society with certain principles. They describe sustainable circular society which keeps environmental quality and economic prosperity for the following generations intact. It consists of the social and individual well-being, which create circumstances that guarantee fair chances for attaining a standard of living that matches or surpasses human rights norms for all (Velenturf & Purnell, 2021). The environmental quality as second value is understood as using resources in a way that is sustainable within the limits of the planet, while also improving natural assets for current and future generations (Velenturf & Purnell, 2021). To the third value consists of promoting a collective organization of resources to ensure fair access for all generations, enhance social and individual well-being, as well as environmental quality (Velenturf & Purnell, 2021).

In sum, the TBL should come to a viewpoint where the economy is seen as a structure within society that depends on the environment, Figure 12 (b). Finally, it is now viewed that the economy serves as a tool for organizing resources to maintain or enhance social well-being, environmental quality, and economic prosperity, Figure 12 (c) (Velenturf & Purnell, 2021).

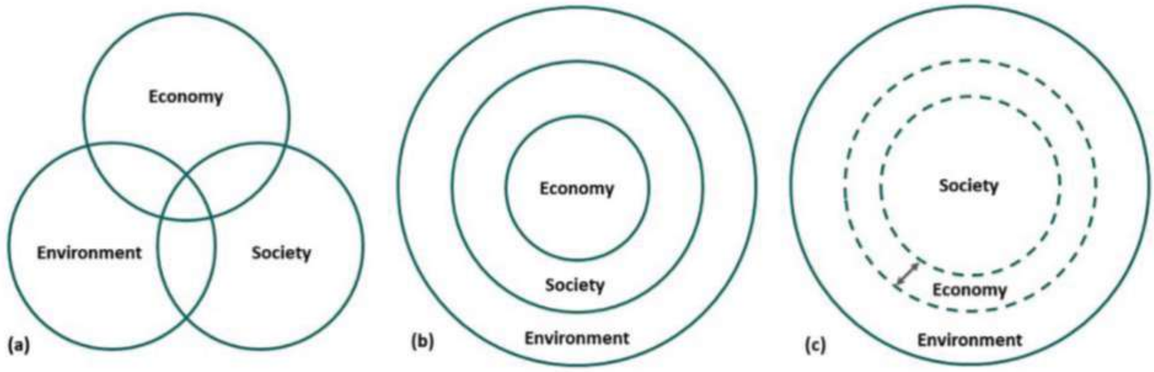


Figure 12: The evolution of the TBL by Velenturf and Purnell (2021)

There are numerous examples for companies in the EU and worldwide, who already implemented CE strategies. The following describes some examples and best practices in the industry.

Wienerberger, a leading company in the production of bricks and pipes, manufactures pipes from recycled content, which can achieve a service life of over 100 years. Notably, the pipes are designed to be fully recyclable, enabling them to be reused in the creation of new pipes, thus effectively extending their service life to 300 years or more over multiple recycling cycles (Wienerberger, 2024).

The automotive producer Renault focused on the CE integration by launching the "Re-Factory," Europe's first dedicated CE hub for vehicles. The Re-Factory aims to develop mobility solutions with a negative CO_2 balance by 2030, while creating 3,000 jobs. The four key areas are Re-trofit, where the life of vehicles is prolonged by reconditioning and converting them to lower-carbon alternatives, Re-energy, which is optimizing battery life, repurposing used batteries, and exploring new energy sources like hydrogen, Re-cycle, by dismantling end-of-life vehicles, remanufacturing parts, and recycling materials and Re-start, which is promoting innovation and knowledge sharing on circular economy practices (E. M. Foundation, 2021).

Der Mietpark is an Austrian company specializing in the rental of construction equipment. It operates as a subsidiary of Eisenwagen Baumaschinen and offers a broad range of construction machinery, covering key areas such as demolition, earthworks, forestry, asphalt and road construction, lifting operations, and load transport. Customers can rent this equipment per day, providing flexible solutions for various construction needs (DerMietpark, 2024).

Komatsu, a Japanese industrial conglomerate, operates a used equipment retrofitting and resale program for mining and construction machinery. In this program, distributors perform a comprehensive 100-point inspection, assessing both the interior and exterior of the used equipment. After identifying necessary repairs and retrofits, the machinery is restored to optimal performance levels. Once the equipment meets these standards, it is certified and resold at a significantly lower price compared to new products, offering a cost-effective solution for buyers while maintaining high quality (Komatsu, 2024).

SKF’s remanufacturing approach supports the CE by extending the lifespan of industrial bearings, reducing costs, energy use, and CO_2 emissions by up to 90% compared to new production. SKF inspects, cleans, and repairs bearings to like-new condition. By using AI-driven condition monitoring, SKF identifies the optimal remanufacturing time, enhancing sustainability. Their CE centers in Sweden and Austria further expand remanufacturing capabilities to meet growing industry demand (SKF, 2020).

Lenzing AG, an Austrian company specializing in the production of fibers from wood, offers ECOVERO™, a sustainable and fully biodegradable viscose fiber brand designed for clothing. These fibers are made from renewable sources of cellulose and wood, with the raw materials provided exclusively from certified sustainable sources. With a transparent supply chain, the fibers can be traced back to their origin, ensuring accountability and sustainability throughout the process (Lenzing, 2022).

In conclusion, CE is a strategically relevant topic in Europe and the business location Austria and is also present for manufacturing companies. In addition, a CE survey by Kolar, Holly, Fließer, and Berger (2023) with a total of 229 participants from the Austrian industry gives a valuable insight into the direction of CE in Austria. Almost 90% of the study participants attribute relevance to high relevance to the CE for the long-term success of the company (Kolar et al., 2023). Around half of these companies have already implemented circular initiatives, which focus on the use of sustainable/recyclable raw materials, sustainable packaging and increasing efficiency in the use of energy and materials (Kolar et al., 2023). But the authors also stated that reuse, refurbish, remanufacture, repurpose are at the top of the hierarchy of R-strategies that are important in the CE and should also be considered (Kolar et al., 2023). Based on the survey findings and the industry examples, it is important to continuously develop solutions for the successful realization of circular business models and focus on its essential such as repair and maintenance to recognize and exploit the economic potential of the CE.

2.2 Maintenance

In the ever-changing business environment, maintenance serves as a vigilant protector, preventing decay and obsolescence. This section delves into maintenance, examining its various methods and the different reasons why it is needed.

2.2.1 Maintenance Strategies

Maintenance management is the systematic process of planning, organizing, and controlling maintenance-related activities and the upkeep of physical assets (DIN, 2022). The maintenance management of production facilities, as well as the integration of the functions that support them, is a very complex and multifaceted task as it affects all employees of a company, but has a tendency towards fewer personnel who operate and maintain increasingly complex systems (Matyas, 2018). Indirect maintenance costs, in particular the follow-up costs of breakdowns, are often caused by a lack of transparency in processes and costs as well as inadequate planning of maintenance measures (Matyas, 2018). Therefore, maintenance management systems are needed, which consist of three major functions: planning, organization and control (Duffuaa & Raouf, 2015).

Figure 13 illustrates that planning activities encompass forming strategic maintenance alliances, where the maintenance department's strategic plans should align with the company's strategic goals, including aspects such as outsourcing, organization, and support. Additionally, planning involves forecasting the maintenance load; the outcomes of which serve as inputs for maintenance scheduling, control, and capacity planning. This includes determining the necessary resources for maintenance tasks, like labor, materials, spare parts, tools, and equipment. Planning for the maintenance organization also involves considering factors that influence the maintenance process, such as plant size, maintenance load, organizational structure, and the skills of the craftsmen. The final aspect of maintenance planning is the scheduling of maintenance, where resources, including labor, are allocated to specific tasks within a set timeframe. Likewise, organizational activities entail the creation of job and task designs, standards, and project management to enhance oversight. Feedback and control are crucial components of management aimed at regulating work, materials, and inventories, which include spare parts, costs, quality, and the overall efficiency of the manufacturing system (Duffuaa & Raouf, 2015; Shaheen & Németh, 2022).

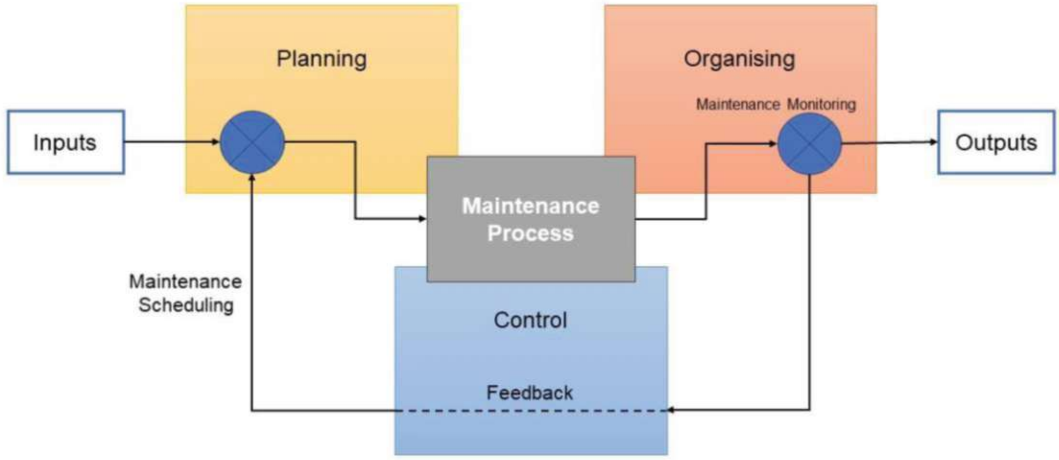


Figure 13: Maintenance Management System according to Duffuaa and Raouf (2015)

These maintenance systems help to clarify which actions are carried out at a specific time on which aggregates or components. It is crucial to make the right decisions in the area of conflict between economy, security and availability to minimize costs and maximize the availability of the systems (Matyas, 2018). To attain this objective, it is necessary to evaluate and choose appropriate maintenance strategies. Therefore, the primary maintenance approaches, seen in Figure 14, in any contemporary manufacturing system encompass but are not limited to the following list (Matyas, 2018).

Fault Elimination: With this method, the machines are operated without significant effort for inspection and maintenance until damage occurs. The machine failure is entirely beyond the control of the operator. Every standstill occurs unexpectedly, making operational planning in production difficult or impossible. Therefore, it often leads to the machine's destruction, enabling a maximum maintenance interval. The concept of damage or failure-related repairs in a modern industrial company only makes sense in exceptional cases, namely when the machines are redundant or of subordinate importance for the production process.

Time-controlled Periodic Maintenance: A standard maintenance method is to "preventively" overhaul or replace specific assemblies after a particular service life has been reached, regardless of their actual condition. This planned overhaul or replacement makes sense if either effect on safety and the environment are to be feared, or the approximate service life is known and the majority of the other system components remain functional up to this point in time.

Condition Oriented Maintenance: In condition oriented maintenance, the maintenance measures are based as precisely as possible on the specific degree of wear of the maintenance object. Suitable monitoring and diagnostic systems make it possible to inform about deviations from the required performance of the system. This maintenance strategy assumes that most malfunctions do not occur suddenly. Instead, they develop over a specific time and are announced by typical warning signals, called potential interference, before they occur. The main effort is to predict failures as early as possible and condition monitoring is an excellent way to prevent unexpected malfunctions. However, it does not allow precise scheduled maintenance due to missing knowledge about the future state of machines or components.

Predictive and Prescriptive Maintenance: The three maintenance strategies fault elimination, time-controlled periodic maintenance and condition oriented maintenance are often no longer sufficient to guarantee the required system reliability due to the increasing complexity of production processes. Improved system availability is usually associated with increased maintenance expenditure, resulting in a waste of resources since the maintenance measures are initiated at the wrong, unfavorable times (Matyas, 2018).

From the point of view of mass production, the standard strategies can still be used efficiently due to the constant machine load. However, in flexible manufacturing systems with a high variation in the production program and without fixed load collectives, there is a need for a predictive, anticipatory and holistic maintenance strategy (Matyas, 2018). This strategy, known as predictive maintenance, takes sensor signals from the condition monitoring systems into account as well as quality data and machine and historical knowledge of failure events. Prescriptive maintenance enhances predictive maintenance by incorporating additional decision-making capabilities. It not only assesses the equipment requiring maintenance but also examines the surrounding environment and the interactions between them, thereby offering a more comprehensive approach to maintenance planning (Ansari, Glawar, & Nemeth, 2019).

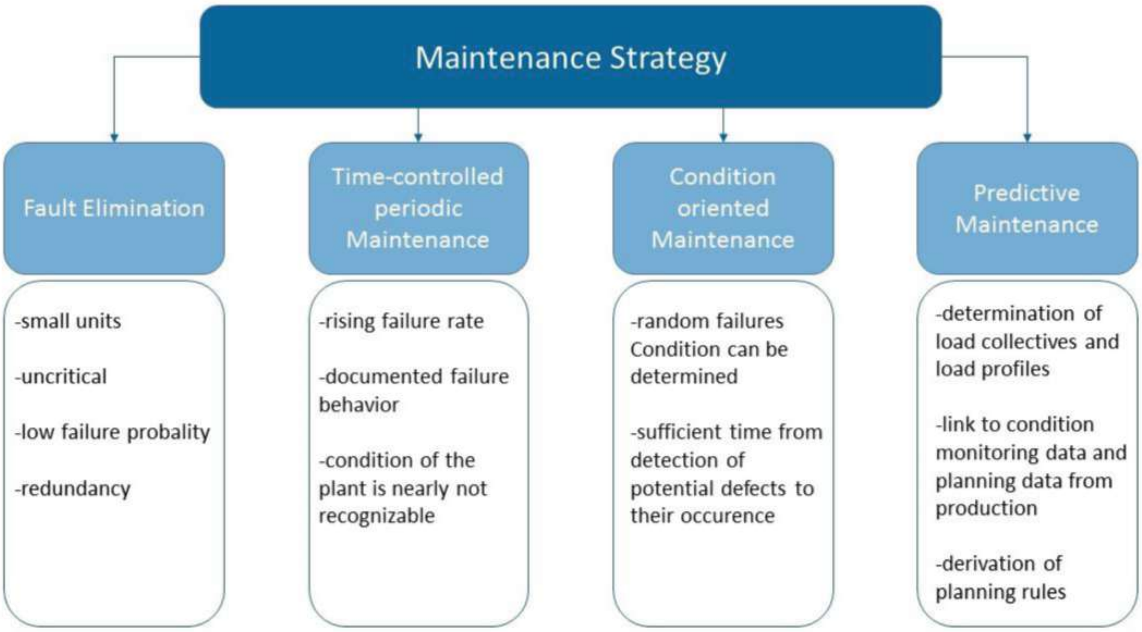


Figure 14: Maintenance Strategies according to Matyas (2018, p. 120)

From the technical perspective, a transformation in maintenance engineering is necessitated which describes the application of engineering skills, methods, techniques and tools to the optimization of equipment, procedures, and departmental budgets to achieve better maintainability, reliability, and availability of equipment (Brumby, 2023; DIN, 2022). With its entirety of strategies, technical applications and systems, maintenance is considered to be one of the key functions, with strategic, tactical and operative impacts, to achieving the goals of CE (E. M. Foundation, 2023; Sobral & Ferreira, 2018)

2.2.2 Trigger and Driver

Maintenance productivity seeks to reduce maintenance costs by measuring overall maintenance performance and optimizing maintenance execution (Ben-Daya, Raouf, Knezevic, & Ait-Kadi, 2009). Therefore, it is crucial to apply the correct maintenance strategy to the right triggers and drivers. The previous chapter focuses on the strategies and not explicitly on triggers and drivers. Table 3 shows the strategies, triggers and drivers and how they belong to each other.

Triggers are defined as events that are happening, subsequently causing a reaction. In the maintenance context, triggers are different for each strategy. Fault elimination is usually initiated by a failure or breakdown (Matyas, 2018). Time-Controlled Periodic Maintenance is based on time intervals or usage metrics (e.g., hours of operation) and condition oriented maintenance is defined by data from condition monitoring systems (Matyas, 2018). Triggers for the predictive maintenance approach are delivered by advanced data analysis and predictive models (Matyas, 2018).

In addition, the individual strategies for maintenance should be implemented under the following aspects: total cost minimization, reliability maximization, safety maximization and minimization of overall risk with the premise to do “as much maintenance as necessary” and “as little maintenance as possible” (Matyas, 2018).

Furthermore, online research on existing maintenance strategies and possible drivers has been conducted. Instandhaltung.de (2024) describes the importance of maintenance for efficiency, reliability and safety issues. Also PWC describe safety and compliance as one of the attributes to be competitive in an international environment (PWC, 2024). Safety is considered as one of the biggest selling points for maintenance actions as well as efficiency and prolonging of lifetime (Lübke, 2024; WestFA, 2024). IBM (2024) talks about the reliability, cost efficiency and performance optimization of and Rockwell (2024) increases equipment availability, reduces maintenance and resource costs and lower the injury risks. NonStopGroup (2024) describe maintenance audit and the decision for the right maintenance strategy as advantageous for the improvement of asset reliability, availability, decision-making and regulatory compliance as well as reducing maintenance cost and risk of accidents and injuries. MaintWiz (2024) focuses on preventive maintenance scheduling and list the advantages of improved equipment reliability and performance, minimized unplanned downtime and production losses, increased safety for personnel, extended equipment lifetime and general cost savings due to resource allocation. These named advantages are also supported by PNNL (2022) which describe the different maintenance strategies and their implementations. Sensemore (2024) argues that maintenance maximizes a company’s efficiency and ClickMaint (2024) describe how the right maintenance approach reduces costs.

Scientific papers support the findings of desktop research. The importance of reliability is highlighted in various documents as a key element in maintenance and operational effectiveness. Agustiady and Cudney (2018) emphasize the importance of reliability-based maintenance systems as crucial for maximizing equipment effectiveness, with proactive, predictive, and preventative maintenance serving as essential strategies to achieve this goal. Moreover, the move towards digitalization and Industry 4.0 is considered a crucial moment that will augment the image and function of maintenance in manufacturing, leading to greater reliability (Birtel, 2018; Freund, 2010). This digital change enables immediate access to data and quicker organizational adaptations, which are essential for upholding high dependability in agile manufacturing settings (Birtel, 2018; Heller & Schroll, 2021). Also Schenk (2009) sees increasing the reliability of complex production systems as one of the main features of maintenance.

The importance of cost efficiency from effective maintenance practices is also highlighted within the framework of Lean Smart Maintenance (Biedermann & Kinz, 2019; Brumby, 2017). The idea of Total Productive Maintenance (TPM) involves strategies to cut costs too, by reducing errors at the beginning of the process (Agustiady & Cudney, 2018; Brumby, 2017). Güntner, Eckhoff, Isopp, Loidl, and Markus (2014) further discusses how the effective management of maintenance costs can be a strategic advantage, particularly when integrated with digital technologies to improve decision-making and operational efficiency. Maintenance activities should not just seen as cost centers but as strategic functions that contribute to overall efficiency (Heller & Schroll, 2021).

In relation to Customer Health and Safety maintenance can be focused on ensuring that the equipment meets the expected quality level for production and safety (Pires, Sénéchal, Loures, & Jimenez, 2016). Safety is a crucial priority, especially in settings where dependable performance and reliability are vital (Schenk, 2009). The main goal of the TPM framework is to create an accident-free work environment by implementing strict maintenance procedures and empowering operators to take care of their equipment. It is extremely important to prioritize safety to make sure that maintenance tasks do not jeopardize the safety of workers and that equipment functions without posing a risk (Agustiady & Cudney, 2018; Dhillon, 2002; Güntner et al., 2014).

Regulatory compliance is always present, even if not explicitly stated, in the maintenance frameworks being discussed. Quality monitoring and logging during the entire construction phase by the installer himself or by external certified monitoring bodies are crucial and regulated by industrial safety standards (Freund, 2010). Also Biedermann and Kinz (2019) discuss the importance of adhering to regulatory standards and optimizing performance in maintenance practices as well. Güntner et al. (2014) and Heller and Schroll (2021) highlight the importance of data transparency and consistency in maintaining regulatory compliance in a digitalized maintenance setting.

Optimizing performance is a major focus in all documents, emphasizing the significance of enhancing and sustaining equipment efficiency. The central role of maintenance in the agile manufacturing company of the future is eminent (Birtel, 2018). This is due to the fact that it has many advantageous influence reaching from increasing availability to the increase in production revenue and modernization (Dhillon, 2002). Furthermore, the importance of setting clear goals and metrics for the continuous improvement of maintenance performance is discussed (Heller & Schroll, 2020).

Out of these online findings and the substantiation with the findings in the literature, the defined drivers are reliability, cost efficiency, safety, regulatory compliance and performance optimization. These drivers also implicate the goals within a specific maintenance strategy.

Table 3: Maintenance strategies and their triggers and drivers

Maintenance Strategy	Trigger	Driver	Characteristics
Fault Elimination	*Failure or Breakdown*	Reliability	Immediate response to restore function
		Cost Efficiency	Unplanned, reactive, corrective
		Safety	Ensures safety post-failure
		Regulatory Compliance	Corrective actions to meet standards
		Performance Optimization	Addresses performance loss due to failure
Time-Controlled Periodic Maintenance	*Scheduled Inspections*	Reliability	Routine, planned, preventive
		Cost Efficiency	Scheduled to minimize unexpected costs
		Safety	Regular checks to ensure safe operation
	Usage or Time-Based	Regulatory Compliance	Adherence to mandated maintenance cycles
		Performance Optimization	Ensures consistent performance
Condition-Oriented Maintenance	*Condition Monitoring*	Reliability	Data-driven, based on actual condition
		Cost Efficiency	Reduces unnecessary maintenance
		Safety	Prevents failures by monitoring conditions
		Regulatory Compliance	Meets standards through condition checks
		Performance Optimization	Maintains optimal performance
Predictive Maintenance	*Condition Monitoring*	Reliability	Prevents failures before they occur
		Cost Efficiency	Anticipatory, data-driven
		Safety	Enhances safety by preventing incidents
		Regulatory Compliance	Proactive compliance through predictions
		Performance Optimization	Predicts and prevents performance drops

Table 3 clearly illustrates how different maintenance strategies are driven by various strategic, operational, financial, safety, and regulatory factors and how they are triggered by specific events or conditions. Each strategy has distinct characteristics and is selected based on the specific maintenance needs and objectives of an organization. This structured approach helps in selecting the most appropriate maintenance strategy to achieve desired outcomes.

2.3 Performance Measurement Systems

Performance Measurement and Management (PMM) plays a pivotal role in the operational efficiency and strategic execution within organizations, however, in literature, there is no agreement on performance management and performance measurement (Bourne, Melnyk, & Bititci, 2018; Melnyk, Bititci, Platts, Tobias, & Andersen, 2014). This chapter explains PMM with a focus on performance measures and its indicators in the business context of industry and maintenance, as a general definition of performance for all contexts is infeasible (de Wilde, 2018).

2.3.1 Definition of Performance and Indicators

The term performance can be described as the efficiency and/or effectiveness of an action, whilst the performance measure is the qualitative and quantitative assessment of these (Bititci, Bourne, Cross, Nudurupati, & Sang, 2018). Furthermore, Bititci et al. (2018) describe performance measurement (system) as a process (or processes) of establishing objectives, creating a suite of performance metrics, gathering, analyzing, presenting, interpreting, evaluating, and responding to performance information while the performance management uses this acquired information to define cultural and behavioral procedures in order to manage the performance of an organization. The goal of this thesis is to develop a performance measurement system that can measure CE oriented maintenance performance in industry.

As performance measurement systems consist of performance indicators, the terms of measures, metrics and indicators are introduced and clarified as there is no consistent definition (Ahmad, Wong, & Rajoo, 2019). An indicator is a parameter that provides insights into or characterizes a condition, which typically encompasses a wider scope (Ahmad et al., 2019). Conversely, a metric represents a quantifiable measure used to monitor an indicator (Ahmad et al., 2019). Additionally, a metric can consist of a combination of two or more measures, with these measures representing the actual data values collected (Ahmad et al., 2019). An example, based on Ahmad et al. (2019), is the working time used (2 hours of work time is used to repair one machine) in a maintenance process. In this example, “working time used” is an indicator, “2” is a measure and “hours of work time used to repair one machine” is a metric for the measure.

Parmenter (2019) considers four different types of indicators measuring performance, namely (key) result indicators and (key) performance indicators. The term “key” describes the ability to be a more overall and important summary of the indicator. Key result indicators (KRIs) help to measure the result of a working team over a period and give an overview of how the organization is performing (Parmenter, 2019). They are always past-focused and are therefore not useful for management, because the handling of a process cannot be changed at a proper time and they do not show how to improve these results (Parmenter, 2019). An example of KRI is the net profit of a company before tax or employee satisfaction over 10 months. If a CEO of a firm is completely responsible for the measure, it is a KRI. The result indicators (RIs) give management an insight into the working of teams to get results (Parmenter, 2019). Performance indicators (PIs) on the other side show the management what teams are contributing to the company (Parmenter, 2019). Key performance indicators (KPIs) are critical indicators that emphasize the aspects most vital to an organization's present and future success. In comparison to other indicators, KPIs can be indicators of close past (e.g. one week), current or close future performance (Parmenter, 2019). They provide continuous, daily, or weekly insights into how the organization is performing concerning its critical success factors. By utilizing these insights for action, management can significantly enhance organizational performance (Parmenter, 2019).

In this thesis, the focus is on the development of a measurement system of CE oriented maintenance indicators (CMIs), which can be in the form of KRIs as well as KPIs interchangeably. But the following rules and characteristics for excellent KPIs also count for the CMIs.

2.3.2 Features of KPIs

In the literature, there are numerous different attributes for high-quality KPIs. The most important described by different authors are depicted in the following (Bishop, 2018a; Eckerson, 2012; Gray, Micheli, & Pavlov, 2012; Parmenter, 2019).

Table 4: Characteristics for a proper indicator

Attribute	Description	References
Concise and Descriptive Names	KPIs should have clear names that minimize ambiguity regarding their intended purpose.	Gray et al., 2012
Clearly Defined Purpose	The purpose of each KPI should be explicitly defined to ensure it serves a specific, relevant function and provides valuable information.	Bishop, 2018a; Gray et al., 2012
Relevance to Organizational Goals	Indicators should align with organizational goals and be related to other indicators to contribute meaningfully to strategic objectives.	Bishop, 2018a; Eckerson, 2012; Gray et al., 2012; Parmenter, 2019
Precise Calculation Method	The method for calculating the KPI should be clear and precise, avoiding ambiguity to ensure consistent application.	Eckerson, 2012; Gray et al., 2012
Frequency of Measurement	The frequency at which the KPI is measured and reviewed should ensure that the data is timely and accurately reflects current performance.	Eckerson, 2012; Gray et al., 2012; Parmenter, 2019
Data Source Clarity	The source of data for the KPI should be clearly identified to ensure reliability and consistency in measurement.	Gray et al., 2012
Defined Responsibility and Actions	It should be explicitly stated who is responsible for measuring the KPI, who will act on the results, and what specific actions are expected.	Bishop, 2018a; Gray et al., 2012; Parmenter, 2019
Connection Efforts and Outcomes	KPIs should allow a clear connection between team efforts and performance outcomes.	Parmenter, 2019
Resistance to Manipulation	KPIs should be designed so they cannot be easily manipulated or gamed by employees, ensuring they genuinely reflect performance.	Eckerson, 2012
Grounded in Research	The development of KPIs should be grounded in research to ensure their validity, accuracy, and relevance, especially for complex KPIs.	Bishop, 2018a
Actionable Components or Controls	Effective KPIs should be actionable, enabling users to identify specific areas for improvement and facilitate decision-making.	Bishop, 2018a

In general, it should be considered that previous research indicates that a performance measurement framework should be practical and straightforward, aiding companies in improving performance and adopting a more systematic method for CE initiatives (Negri, Neri, Cagno, & Monfardini, 2021). Companies that have limited awareness, resources, and skills might benefit from a simplified set of indicators that allows for an effective and efficient assessment of performance (Negri et al., 2021). As companies grow and their resources and maturity increase, the framework can be broadened to incorporate additional indicators (Negri et al., 2021). Ideally, these frameworks ought to be adaptable, providing support to a company throughout all phases of its CE transition, regardless of its stage of resource availability, awareness, or competency levels (Negri et al., 2021).

2.3.3 Types of Indicators: Leading or Lagging, Hard or Soft and Top-down or Bottom-up

Leading indicators are proactive and predictive metrics that provide early warnings about potential issues before they occur (Kumar et al., 2013). These indicators help in identifying trends and conditions that could lead to equipment failures or maintenance problems (Kumar et al., 2013). They track the completion of tasks that will potentially lead to desired results (Muchiri, Pintelon, Gelders, & Martin, 2011). Maintenance backlog and mean time to repair (MTTR) are maintenance related leading indicators. Muchiri et al. (2011) even state, that leading indicators are more important than lagging indicators, as they can assist in avoiding unfavorable situations from arising. On the other hand, lagging indicators are reactive metrics that reflect the outcomes of past maintenance activities. They provide insights into the effectiveness of maintenance programs and their impact on equipment performance (Kumar et al., 2013). Prevailing maintenance lagging indicators are mean time between failure (MTBF) and overall equipment effectiveness (OEE) (Muchiri et al., 2011).

Furthermore, indicators can be divided into hard and soft (Kumar et al., 2013). Hard indicators are easily measurable through the extraction and analysis of data from databases, e.g. computer maintenance management system (Kumar et al., 2013). Examples include downtime of machines or MTBF (Kumar et al., 2013). While soft indicators are subjective and qualitative, providing insights that are not easily measured but are important for understanding the context and effectiveness of maintenance practices (Kumar et al., 2013). They include indicators like training and skill level of employees or employee satisfaction (Kumar et al., 2013).

Top-down indicators describe the development of performance indicators by the (senior) management and bottom-up are developed from the ground up by involving employees at all levels of the organization (Kumar et al., 2013).

Bishop (2018b) suggests that KPIs should be applied in a top-down approach, as he states that the organization's overall performance will only improve if employees at all levels enhance their performance. Therefore, a top-down approach is more suitable to ensure that everyone is working towards the overall strategic plan. On the other side, Parmenter (2019) says that it is essential to empower employees to achieve successful performance improvement, especially those on the operational front lines. Fostering effective and transparent top-down, but even more importantly honest bottom-up communication is crucial for performance improvement.

2.3.4 Indicator Sets

A group of indicators combined to analyze a broader topic is called an indicator set. Different indicators are combined to offer a comprehensive view of the overall progress of a process (Australia, 2024). Creating a reliable set of indicators requires a precise definition of the specific concept and its various components. Quality indicator developers need to clarify why they are measuring something and should take into account the potential drawbacks of using certain indicators, such as decreased content validity due to factors like measurement costs (Schang, Blotenberg, & Boywitt, 2021). Several performance measurement researchers claim that companies frequently engage in excessive and careless measurement, which can sometimes impede success by providing misleading performance information (Bishop, 2018b; Gray et al., 2012; Parmenter, 2019). Even though this thesis focusses on creating a completely new form of indicator sets just for CE maintenance, issues with existing performance measurement systems are an important basis for the definition of an own indicator set.

2.3.5 Existing Performance Measurement Systems

Performance measurement roots have undergone significant evolution from the late nineteenth to the twentieth century. This transformation has two stages: The initial one starting in the late 1880s, concentrating on fundamental financial indicators, and the subsequent one rising in the late 1980s, propelled by globalization and the demand for more thorough performance evaluation methods (Khurram, 2011).

During the 1940s and 1950s, manufacturing companies focused on financial metrics such as sales, return on investment, and efficiency, which were crucial for cost and management control systems (Kaplan & Norton, 1992). But in the late 1980s it became clear that these metrics had limitations as the global economy required a more comprehensive approach encompassing quality, time, cost, flexibility, and customer satisfaction (Kaplan & Norton, 1992). This change resulted in the creation of more extensive frameworks for measuring performance (Khurram, 2011). The shortcomings of conventional financial metrics resulted in a crisis and subsequent transformation in performance evaluation (Khurram, 2011). The idea of "balance" in measurement frameworks is now essential and includes both financial and non-financial metrics. The frameworks must be timely, measurable, precise, and in line with organizational goals (Kaplan & Norton, 1992). Therefore, the 1990s witnessed the emergence of several impactful frameworks, which will be shortly named in the following paragraphs.

As the most popular performance measurement framework, depicted in Figure 15, the balanced scorecard by Kaplan and Norton (1992) has the goal of covering all performance aspects from a top-down perspective (de Wilde, 2018; Khurram, 2011). This well-known model addresses performance comprehensively by focusing on four key strategic viewpoints: financial, customer, internal processes, and learning and innovation. It acts to measure, manage strategically, and communicate, although there are concerns about its susceptibility to manipulation (Neely, Kennerley, & Adams, 2007; Parmenter, 2019).

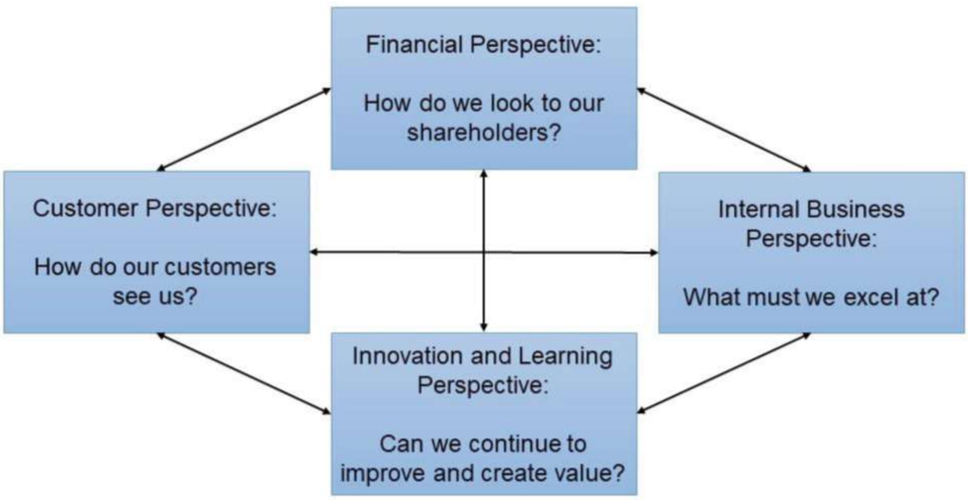


Figure 15: Balanced Scorecard according to Kaplan and Norton (1992)

The Performance Pyramid, also known as the Strategic Measurement Analysis and Reporting Technique by Lynch and Cross (1991) is an organized structure that connects the overall goal of a company to its daily activities by using a series of financial and non-financial indicators and can be seen in Figure 16. It aligns strategic objectives with operational effectiveness throughout different levels of the organization (Striteska & Spickova, 2012). Figure 16 shows this framework.

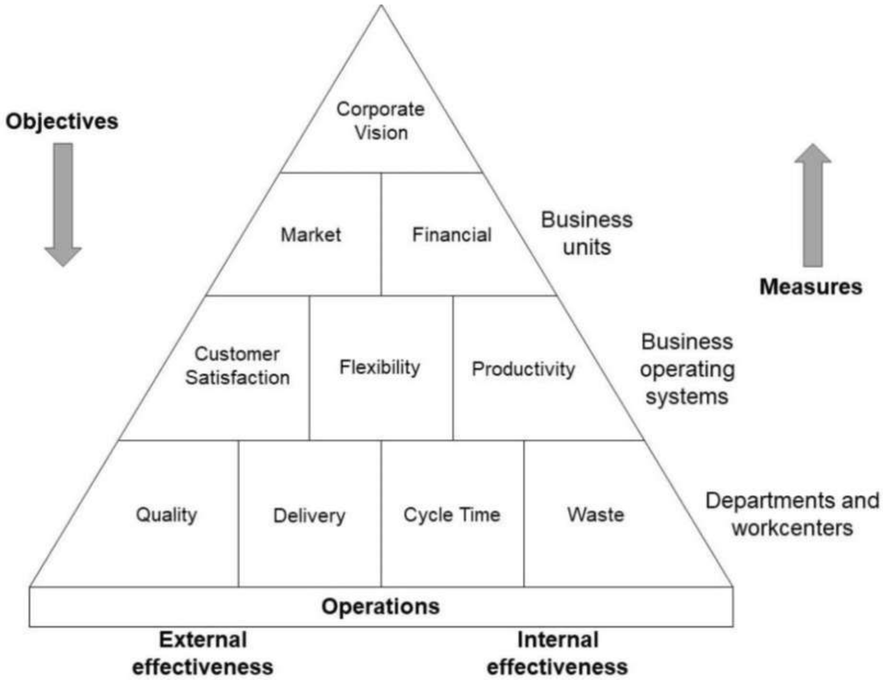


Figure 16: Performance pyramid according to Lynch and Cross (1991)

The Performance Prism (Neely, Kennerley, & Adams, 2002) emphasizes providing value to important stakeholders by considering five aspects: stakeholder satisfaction, strategies, processes, capabilities, and stakeholder contribution. It ensures that strategies and processes are in line with the requirements of stakeholders (Neely et al., 2007). Keegan, Eiler, and Jones (1989) Performance Measurement Matrix classifies metrics based on financial/non-financial and internal/external factors, prioritizing well-rounded and flexible assessment techniques (Neely et al., 2007). The conceptual framework of Results and Determinants by Fitzgerald, Brignall, Johnston, and Silvestro (1991) is modified from the Performance Measurement Matrix. It connects present results to previous performance measures, aiding in the recognition of crucial factors for achievement (Khurram, 2011; Neely et al., 2007).

Besides the briefly mentioned performance measurement systems there are numerous other frameworks such as the European Foundation for Quality Management model by the European Commission but these are among all the most important to focus on while building an own measurement system (Striteska & Spickova, 2012). Besides the figures of the frameworks, the linked literature can be used for gaining a deeper insight into each framework.

Challenges of Measurement Frameworks: In today's business environment with increasing complexity, the frameworks need to be less theoretical and fit into these ever changing surroundings (Bourne et al., 2018). Melnyk et al. (2014) state that literature and tools are deemed inadequate to address the challenges faced in dynamic environments. This inadequacy necessitates a co-evolutionary approach between organizational settings, business strategy and PMM system. Furthermore, there is often a misalignment between measurement systems and business strategies, which requires the manager to adjust them to the new business environments.

2.3.6 Maintenance Performance Measurement System

The maintenance strategy needs to be based on and incorporated into the overall corporate strategy, as already seen in the performance pyramid. To achieve the main goals of the stated objectives, to implement the maintenance strategy effectively, these goals must be passed down to the team and the team members' individual goals (Lynch & Cross, 1991). Successfully adopting fair processes is crucial in the alignment of these objectives (Ben-Daya et al., 2009). In a process industry or production system, the hierarchy consists of the factory, process unit and component levels (Ben-Daya et al., 2009). The ranking structure correlates with the conventional tiers within an organization, which include top, middle, and shop floor levels (Ben-Daya et al., 2009). Nevertheless, certain organizations may necessitate additional levels of hierarchy to accommodate their intricate organizational structure (Ben-Daya et al., 2009). The maintenance performance measurement (MPM) system must be connected to both the operational and hierarchical tiers to function effectively (Ben-Daya et al., 2009). Monitoring and controlling become highly intricate when dealing with large-scale operations (Ben-Daya et al., 2009). MPM becomes even more complex when considering multiple goals, as depicted in Figure 17 (Ben-Daya et al., 2009).

From a hierarchical point of view, the highest tier focuses on corporate or strategic matters using stakeholders' qualitative or perceptual evaluations. This strategic level may be seen as subjective, as it is linked to the organization's vision and long-term goals (depicted as S1 and S2 in Figure 17). Nonetheless, this subjectivity decreases as you descend through the levels, with the most objective level being at the functional level. The second level addresses tactical issues (labeled T1–T4 in Figure 17) concerning both financial and non-financial aspects from the perspectives of effectiveness and efficiency. This layer is typically composed of senior or middle management, depending on the organizational hierarchy. In an organization with four hierarchical levels, the second level corresponds to the senior managerial level, while the third level corresponds to the managerial/supervisory level. The lowest level is comprised of operational personnel, including shop floor engineers and operators (shown as F1–F3 in Figure 17). The corporate or business objectives at the strategic level must be effectively communicated down through the organization, translating these objectives into terms that are meaningful at the tactical or functional level. Maintenance objectives and strategies, derived from stakeholders' requirements and corporate goals, must consider overall effectiveness, front-end and back-end processes, and involve employees at all levels in an integrated top-down and bottom-up approach. At the functional level, these objectives are translated into specific measurement criteria (Ben-Daya et al., 2009; Parida & Chattopadhyay, 2007).

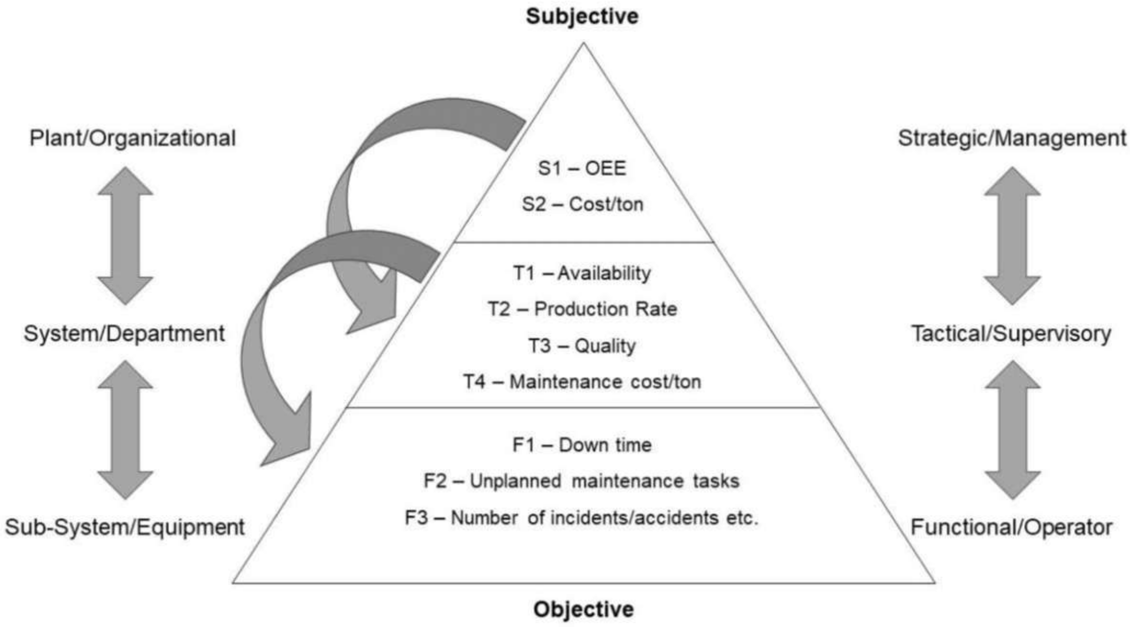
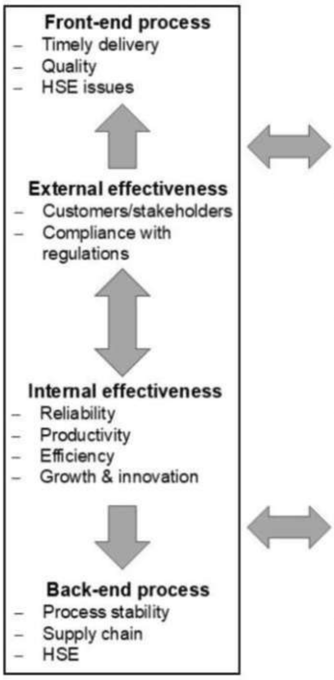


Figure 17: Hierarchical levels of an organization according to Ben-Daya et al. (2009)

The MPM system must facilitate and support management leadership in making timely and accurate decisions (Ben-Daya et al., 2009). It should offer performance measurements that directly link to the organizational strategy, incorporating both financial and non-financial indicators. Additionally, the system must be flexible to adapt over time as needed (Ben-Daya et al., 2009). Transparency and accountability across all hierarchical levels are essential features of the MPM system (Ben-Daya et al., 2009). In terms of application and usage, the system should be user-friendly and supported by appropriate training for relevant personnel (Ben-Daya et al., 2009).

Parida and Chattopadhyay (2007) say that maintenance indicators can be classified into seven categories and are interconnected to ensure total maintenance effectiveness, namely: customer satisfaction indicators, cost-related indicators, equipment-related indicators, maintenance task-related indicators, learning and growth indicators, health, safety, and environment (HSE) indicators and employee satisfaction indicators. Table 5 shows the connection between hierarchies and these criteria.

Table 5: Multi-criteria framework for maintenance performance measurement according to Parida and Chattopadhyay (2007)



Multi-criteria / Hierarchical level	Level 1 Strategic Top Management	Level 2 Tactical Middle Management	Level 3 Functional Operator
Equipment/ Process related	– OEE – Downtime	– Availability – Production Rate – Quality – Number of stops	– Production rate – Quality – Number of stops – Downtime
Cost/finance related	– Maintenance/ production cost per ton	– Maintenance/ production cost per ton	– Maintenance cost per ton
Maintenance task related	– Costly maintenance task	– Change over time – Planned/unplanned maintenance task	– Change over time – Planned/unplanned maintenance task
Learning growth & innovation	– Generation of a number of new ideas – Skill improvement training	– Generation of number of new ideas – Skill improvement training	– Generation of number of new ideas – Skill improvement training
Customer satisfaction related	– Quality complaint numbers – Quality return – Customer satisfaction – New customer addition	– Quality complaint numbers – Quality return – Customer satisfaction – New customer addition	– Quality complaint numbers – Quality return – Customer satisfaction
Health safety & environment	– Number of accidents – Number of legal cases – Compensation paid – HSE complaints	– Number of accidents – Number of legal cases – Compensation paid – HSE complaints	– Number of accidents – HSE complaints
Employee satisfaction	– Employee retention – Employee complaints	– Employee retention – Employee complaints	– Employee complaints

The framework takes a comprehensive view of the organization, considering both internal and external factors. It links the indicators from the subsystem/component level up to the corporate level, ensuring alignment with organizational goals and operating across different hierarchical levels – operational, tactical, and strategic – it ensures that performance measures are relevant and actionable at all levels of the organization Parida and Chattopadhyay (2007). Validated through case studies in different industries, such as mining and energy, the framework demonstrates its applicability and effectiveness in real-world settings (Parida & Chattopadhyay, 2007).

The following chapters show the selection of indicators based on a whole company level involving maintenance framework but also tackle the CE challenges with the help of literature based indicators.

3 State of the Art in CE oriented Maintenance

As the theoretical background of maintenance, CE and KPIs have been elaborated, chapter 3 focuses on the findings of a CE oriented maintenance indicator in today's literature. In the followings, some findings are mentioned in more detail, as they help to get a deeper understanding of the topic.

3.1 Models and Approaches in CE oriented Maintenance

From a theoretical perspective, Fontana et al. (2021) aim at bridging the knowledge gap for Small and Medium Enterprises regarding CE and Life Cycle Extension Strategies (LCES), especially within the equipment and machinery sector. They introduced a Strategy Characterization Framework to guide the application of production equipment LCES across various industrial use cases. They specifically address indicators for lifespan extension and RUL. In addition, the work shows the relevance of the different lifecycle extension approaches in the form of new patents for their identified relevant sustainable maintenance strategies, as depicted in Figure 18. Strategies relevant for this thesis, namely predictive and preventive maintenance are under the top three most relevant once with a share over 65%.

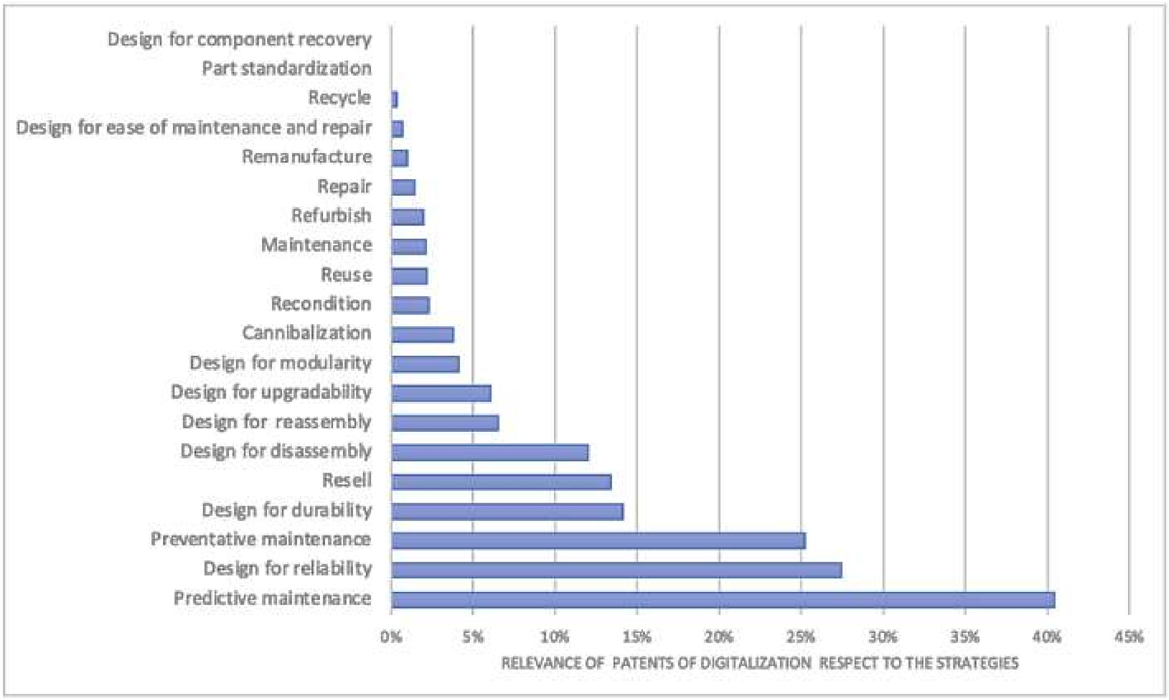


Figure 18: Relevance digitalization patents and maintenance strategies by Fontana et al. (2021)

Ghaleb and Taghipour (2022) demonstrate the positive impacts of maintenance on sustainability and identify the sustainability-related indicators such as energy consumption, CO_2 emission rate on a system level as well as availability, and failure rate of components. Other indicators are also significantly influenced by maintenance actions and the authors categorize these indicators even further into the environmental, social and economic dimensions of the TBL framework.

To improve maintenance KPIs, Karki et al. (2022) promote a digital and sustainable maintenance service and bring up the indicator of system intelligence level. Working together with a firm, which already has the infrastructure for a digitalized maintenance service and is in an asset-intensive surrounding, they developed the framework consisting of automated monitoring, predictive maintenance solutions and execution and optimization, which can be seen in Figure 19.

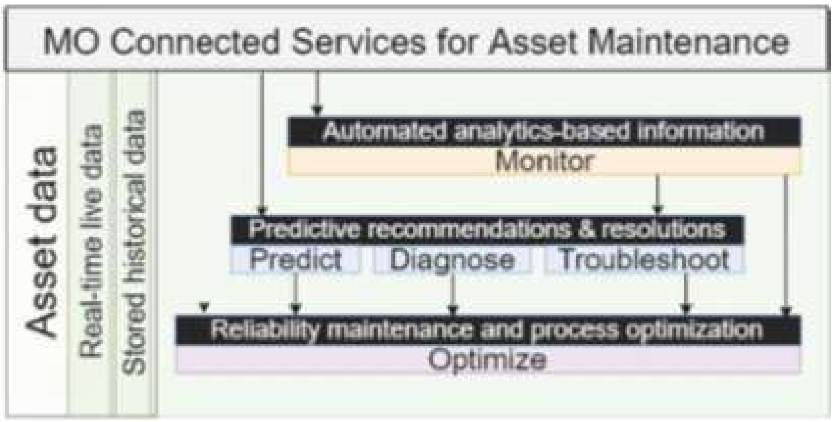


Figure 19: Functional model for digitalized services by Karki et al. (2022)

Also Turner, Okorie, Emmanoulidis, and Oyekan (2020) give a framework for digital maintenance for the circular production of automotive parts and mention the level of system intelligence. Sidahmed Alamin et al. (2022) proposes the comprehensive model, entitled as SMART-IC, that integrates smart monitoring, predictive maintenance, and production optimization to significantly reduce waste and defects in semiconductor production. This can be achieved by diagnosis and prognosis algorithms and an advanced manufacturing execution system (MES), working as simulation and advanced scheduling tool, depicted in Figure 20.

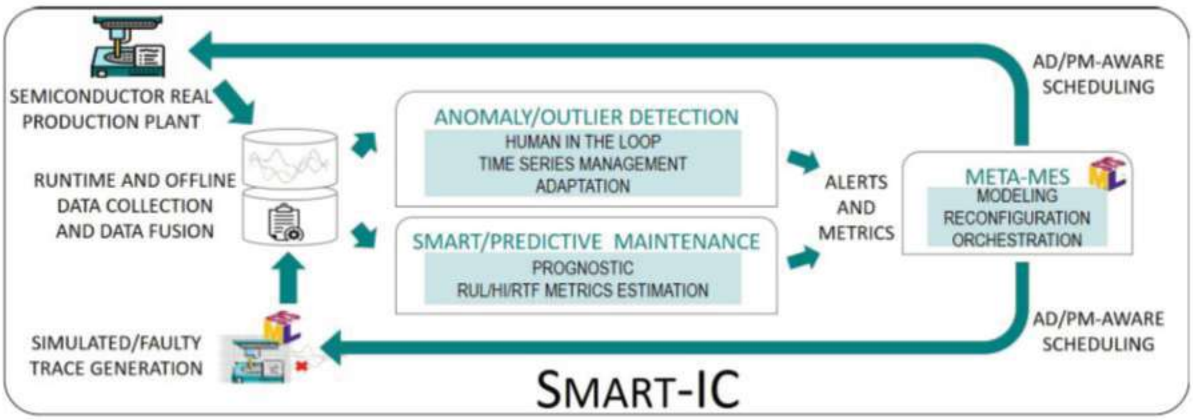


Figure 20: SMART-IC flow for semiconductor manufacturing based on prediction and detection by Sidahmed Alamin et al. (2022)

Furthermore, sustainable concepts based on maintenance-centered circular manufacturing are presented to achieve a balance between economic, environmental, and social sustainability (Ibrahim et al., 2019; Takata, 2013). They also focus on the humanistic part of safety and health for employees and workforce satisfaction. Moreover, Ibrahim et al. (2019) argues, that maintenance is a crucial addition to manufacturing to achieve a sustainable performance, mentioned in Figure 21.

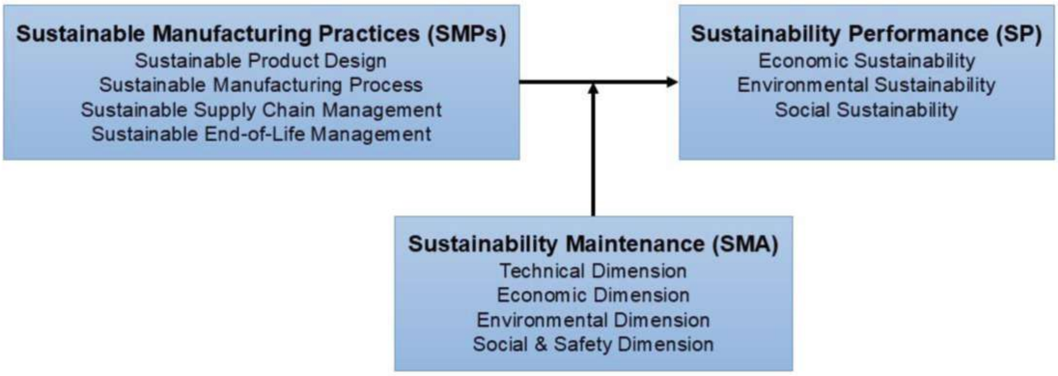


Figure 21: A conceptual framework for sustainability performance by Ibrahim et al. (2019)

Takata (2013) argues the importance of maintenance for facility conditions, depicted in Figure 22. Effective maintenance ensures that facilities remain functional, preventing deterioration that can lead to higher life cycle costs (LCC). Without proper maintenance, the condition of facilities can degrade faster, which not only shortens their operational life but also leads to reduced productivity and lower output quality (Takata, 2013). This degradation can result in increased operational costs, as the facility might require more frequent repairs or replacements to maintain production levels (Takata, 2013). Furthermore, if maintenance is not carefully balanced with operational needs, there could be a conflict between scheduling production and necessary maintenance (Takata, 2013). For instance, prioritizing operations over maintenance can lead to insufficient upkeep, accelerating the facility's deterioration (Takata, 2013). On the other hand, prioritizing maintenance excessively could reduce production capacity, causing opportunity losses due to downtime (Takata, 2013).

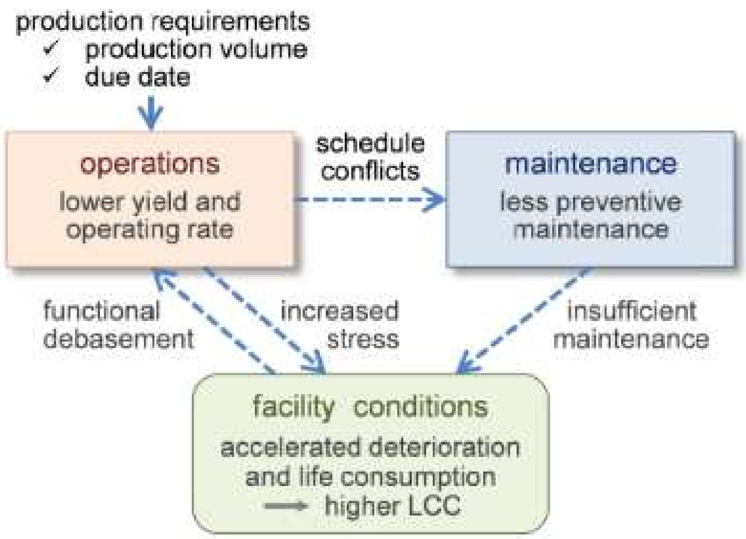


Figure 22: Relationships between operations and maintenance in production by Takata (2013)

To address the dynamic nature of equipment reliability and maintainability, which can change due to several factors, Abdi and Taghipour (2019) focus on improving the sustainability of asset management through a repair-replacement decision model. It comes with a user-friendly interface and has features such as a Green House Gas calculator. Su, Weng, Yang, and Hsu (2023) present a production inventory system that aims to minimize cost by optimizing among other things the number of maintenance times. By implementing a computational algorithm, they achieved the optimal solution.

In the energy sector, Ayu and Yunusa-Kaltungo (2020) created a framework for supporting maintenance and asset management life cycle decisions for power systems. Crespo Marquez, Gomez Fernandez, Martínez-Galán Fernández, and Guillen Lopez (2020) highlight Intelligent Assets Management Platforms (IAMP), which leverages digital technologies to collect, analyze, and use data effectively for maintenance decision-making.

In the construction sector, Connolly (2023) addresses a risk-based framework that employs a weighted sum incorporating risk, cost, and various KPIs to evaluate and rank road construction and maintenance. The aim is to identify and evaluate new circular and bio-based maintenance approaches.

Sobral and Ferreira (2018) emphasize the transformation of the traditional linear consumption model into a circular one, where the life cycle of products is extended through repair, reuse, and recycling, reducing waste and maximizing resource efficiency. The paper shows the importance of maintenance for the success and the reliability of systems and equipment. It also takes the recovery delay time after a maintenance process into account.

Naughton and Repko (2023) create instruments for the effective and efficient implementation of circular maintenance within the process industry. Therefore, measurement models have been created to quantify the circularity and CO_2 emissions of maintenance processes but only focusing on the waste and emissions reduction during the cleaning of shell-tube heat exchangers. They introduce the six-stage model for maintenance with the adaptation of a Plan-Do-Check-Act cycle and input of sustainability goals, the R strategies and environmental goals. In addition, a company value matrix is considered as an important part of the input, which shows the consequences and the influences of a failure to the company, seen in Figure 23.

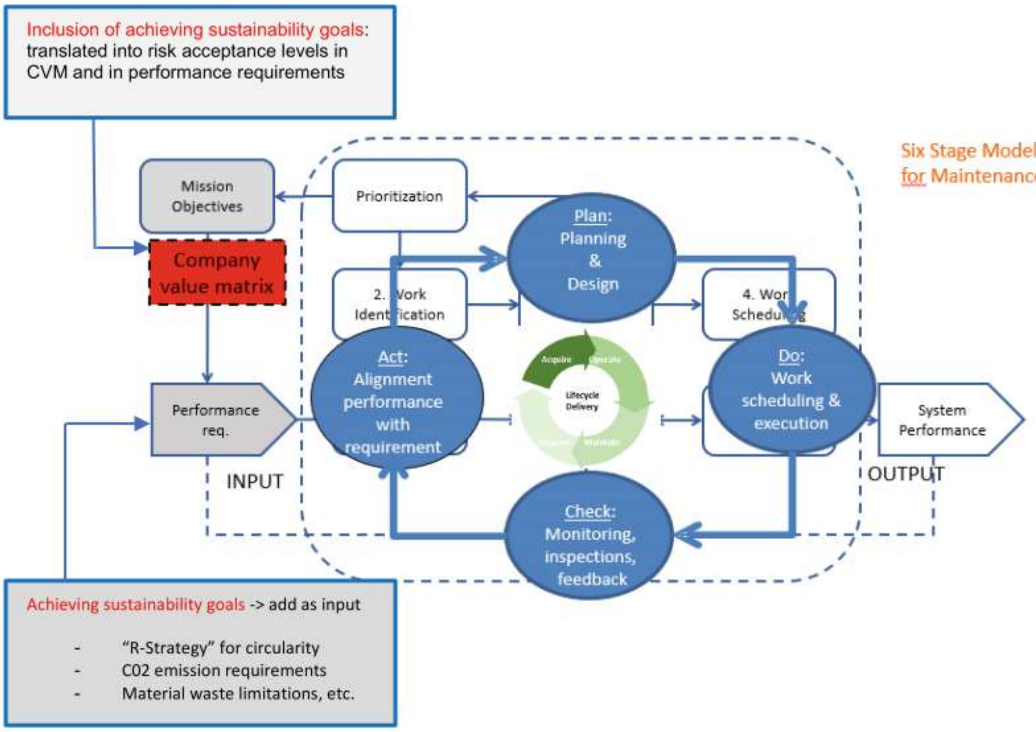


Figure 23: Six Stage Model for Maintenance a circular process by Naughton and Repko (2023)

The described findings can be used as an orientation point to apply CE oriented maintenance but are lacking regarding an all-encompassing and generally valid measurement model for problem domains. There are also several KPIs, filtered out from those findings, which can be used as a starting point and fundament for proposing new KPIs.

Furthermore, the above-discussed papers reveal that there is an enormous amount of KPIs discussed in the literature. Therefore it is important to filter out, which of these are important for defining the CE oriented maintenance indicators (CMIs), and how they can be categorized. As a categorization, the already presented sustainability framework TBL has been chosen.

Table 6 shows the foundational papers with their industrial sector and the number of extracted KPIs, categorized in the categories.

Table 6: Categorization of the foundational papers

Reference authors and year	Type of publication or journal's name	Outcome of work (model, review…)	Number and type of indicators		
			Environment	Social	Economic
Abdi & Taghipour (2019)	Computer & Industrial Engineer	model creation	2	3	12
Ayu & Yunusa-Kaltungo (2020)	MDPI Energies	Framework creation	1	0	3
Connolly et al. (2023)	Transportation Research Procedia	Risk-based analysis framework	1	0	3
Crespo et al. (2020)	MDPI Energies	Review of a software platform	0	3	0
Fontana et al. (2023)	MDPI Sustainability	Literature review	2	0	2
Ghaleb & Taghipour (2022)	International Journal of Production Research	Literature review	2	1	8
Ibrahim et al. (2018)	International Journal of Energy Economics and Policy	Framework creation	2	2	3
James et al. (2023)	Journal of Cleaner Production	Framework creation	0	0	0
Karki et al. (2022)	Digital Business	Model creation	0	0	6
Mahpour (2023)	Sustainable Materials and Technologies	Transformation model	2	0	3
Naughton & Repko (2023)	Asset Management Research	Framework creation	2	0	1
Sidahmed et al. (2022)	Conference paper	Monitoring model	0	0	7
Sobral & Ferreira (2018)	Conference paper	Literature review	0	0	4
Su et al. (2023)	MDPI Mathematics	System description	0	0	6
Takata (2013)	Conference paper	System description	1	0	6
Turner et al. (2020)	Conference paper	Framework creation	3	0	3

3.2 Literature Analysis on existing KPIs

This section shows how the selected papers for the indicator findings brought out the indicators and which role the foundational literature plays. Section 1.3.2 shows further information on the selection process of the papers and how the literature research has been conducted.

The selected foundational papers show methods and approaches of CE oriented maintenance, define the SOTA and are used as the basis for identifying further CMIs. They give a solid understanding of how the indicators might look like and how they can be categorized. As already mentioned, the main categories are grounded on the TBL sustainability system, namely, environment, economic and social. For an even better distinction, these three categories can be divided into subgroups. These subgroups are based on the findings of the foundational literature and papers on measuring maintenance impact on sustainability of manufacturing industries, which can be seen on Figure 24 (Franciosi, Voisin, Miranda, Riemma, & Iung, 2020; Ghaleb & Taghipour, 2022). In addition, the economic side is further divided into maintenance subgroups, to get an insight into specific maintenance indicators, depicted in Figure 25. The aim was to create a final CMI draft set with an indicator amount between 45 and 50. In the final CMI set there should be only between 35 and 40 indicators.

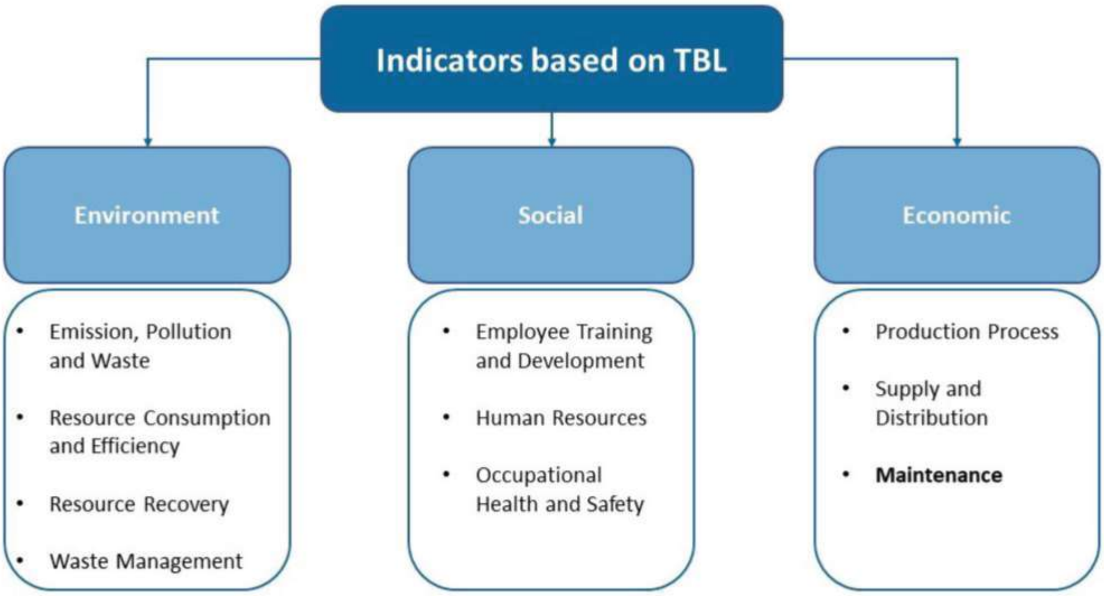


Figure 24: Indicator subgroups based on TBL and literature based on (Franciosi et al., 2020; Ghaleb & Taghipour, 2022)

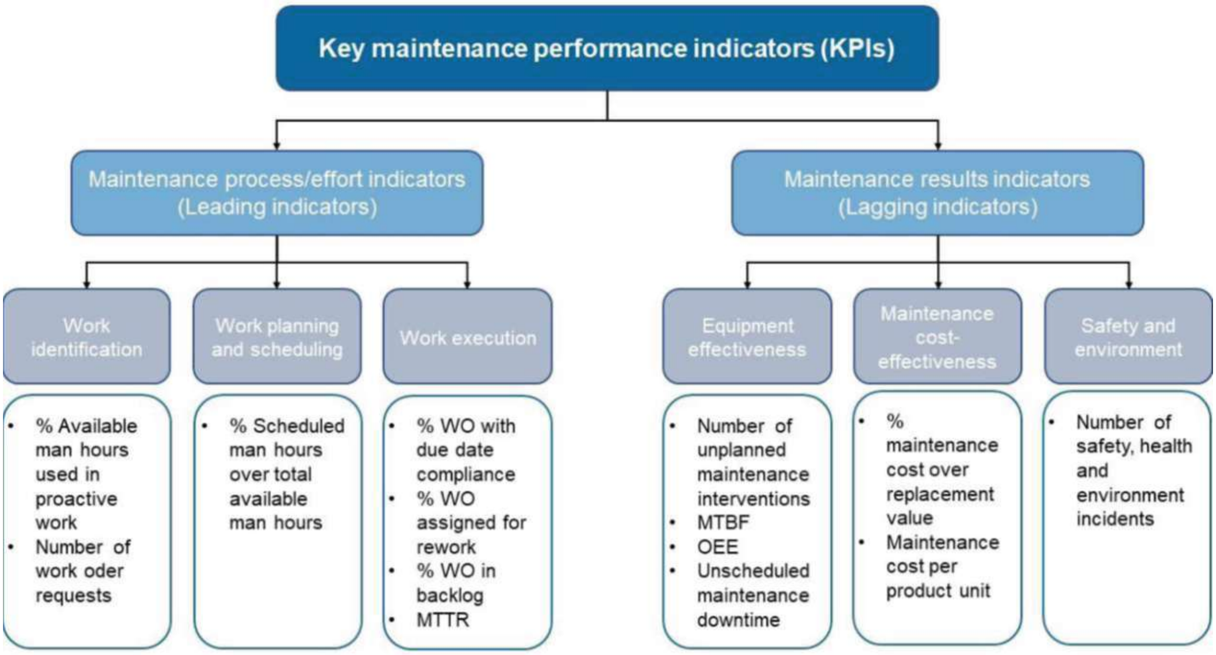


Figure 25: Category of maintenance indicators according to Kumar et al. (2013)

Out of the total of 91 paper findings from the databases and the foundational literature from the exploratory literature search, extraction and identification of KPIs has been done. A total of 104 KPIs were filtered out based on their relevance and frequency of appearance across the literature. These KPIs were then subjected to a rigorous sorting process: subsequently, they were marked as directly related or might be related to the three TBL dimensions. This classification was crucial for understanding the broader context and impact areas of each KPI. In the next step, each KPI was assigned to its main dimension based on the principles of the TBL approach, by considering the major impact on either social, economic or environment. After that, each KPI was furthermore assigned to the subgroups and the specific maintenance attribute, which was especially a crucial step in the economic category. The categorization process yielded the following distribution of KPIs across the main dimensions as follows: 12 social KPIs, 18 environmental and 74 economical, where the specific maintenance related indicators are also included. The whole list of indicators and classification can be seen in Appendix A.

After the development of a pool of 104 KPIs, every identified KPI was reviewed to determine its uniqueness and relevance. KPIs that did not significantly contribute to the framework were either consolidated or discarded. The consolidation resulted in a preliminary total of 84 KPIs across all dimensions. Further analysis and the removal of duplicates and the final refinement, conducted through collaborative workshops involving subject matter experts, led to the establishment of a final draft set of 48 KPIs, now considered as CMIs. The term was defined from this moment on because the iterative process ensured that the KPIs were not only relevant and non-redundant but also practically applicable and aligned with the objectives of CE oriented maintenance. The 48 CMIs consist of eight environmental, seven social, and eight purely economical and 25 economical but specific maintenance related indicators. The path to gain these CMIs is displayed in Figure 26. Table 7 shows the CMIs, including their assigned main and subcategory and their measurement unit. All together they describe the final CMI draft set.

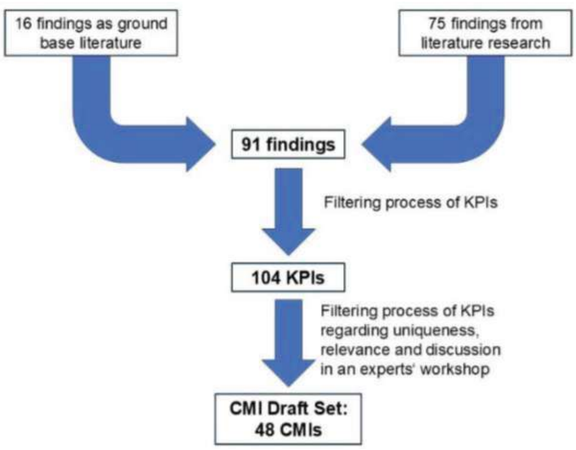


Figure 26: Workflow of the creation of the CMI draft set

Table 7: List of the CMI draft set

Main	Sub Category	KPI	unit
Environment	emission, pollution and waste	Environmental Impact	kg CO2 eq.
	resource consumption and efficiency	Energy Consumption Rate	kWh
		Material Consumption Rate	kg
		Resource Utilization Efficiency	%
	resource recovery	Product Reuse Potential	%
		Resource Recovery Rate	%
	waste management	Net Waste Management Cost	€
		Waste Management Efficiency	kg/%
Social	employee development and training	Employee Skill Proficiency	integer
		Workforce Efficiency Ratio	%
	human resources	Employee Satisfaction Index	integer
		Workforce Allocation for Maintenance	integer
		Overtime Workload	h
	Occupational Health and Safety	Workplace Safety and Health Assessment	integer
		Employee Stress Assessment	integer
Economic	production process	System Knowledge and Intelligence Level	integer
		Manufacturing Efficiency Index	%
		Net Present Value	€
		Readiness for System Evolution and Upgradeability	%
		Refurbished Parts Cost Benefit	€
		Component Importance Index	%
	supply and distribution	Supply Chain Expenses	€
		Parts Delivery Frequency	h
Economic-Maintenance related	maintenance: work identification	Preventive Maintenance Intensity Index	%
		Work Order Compliance Rate	%
	maintenance: work planning and scheduling	Maintenance Time (inklusive assembly, disassembly, inspection, measurement repairment, refurbishment, remanufacturing, replacement)	h
		Scheduled Maintenance Compliance	%
		Recovery Delay Time	h
		Emergency Maintenance Ratio	%
		Expected Service Life Cycles	integer
	maintenance: work execution	Mean Time to Repair	h
		Inspection Frequency	integer
		Component Replacement and Refurbishment Rate	%
		Maintenance Backlog	integer
	maintenance: equipment effectiveness	Remaining Useful Life	h
		Downtime (planned and unplanned)	h
		Mean Time Between Failure	h
		Reliability Rate	%
		Overall Equipment Effectiveness	%
		Downtime Cost	€
		Maintenance Efficiency	%
	maintenance: cost effectiveness	Maintenance Cost (including disassembly, inspection, repairment, replacement, remanufacturing, refurbishment costs)	€
		Spare Parts Procurement Expenses	€
		Strategic Maintenance Investment	€
		Maintenance Budget	€
		Maintenance cost per unit production	€
		Spare Parts Repair Viability Assessment	€
	maintenance: safety and environment	Maintenance Risk Assessment	integer

3.3 Summarization of Key Findings

This section summarizes the findings of the literature, gives details on the creation of the final draft set and assesses the validity of each CMI.

3.3.1 Selection Process: Naming and Relevance

As already mentioned, the different selection procedures presented different challenges, also in the different categories of TBL.

The sub chapter customer was completely cut out of the social category, because the focus is solely on the industrial side and manufacturing. Furthermore, the KPI “human harmness potential”, “safety” and “health for employees” were summed up as “Workplace Safety and Health Assessment”.

In the category environment, emissions like CO_2 and SO_2 has been combined under “Environmental Impact”. In addition, “disposal cost”, “volume of waste”, “net recoverable value” and “mean dispose process” could be organized into the CMIs “Net Waste Management Cost” and “Waste Management Efficiency”.

The biggest changes were made, also due to the amount of KPIs, within the economical part. To explain the maturity of a maintenance system, the KPIs “level of system intelligence” and level of knowledge” were generalized as the CMI “System Knowledge and Intelligence Level”. Also, KPIs like “quality of components” and “backorder of cost rate” “production costs” and “cost of tools” were not considered as single KPIs and were considered as parts of other CMIs.

For the maintenance related part, several KPIs were considered as already implemented in bigger indicators, for example “availability” is already part of the “Overall Equipment Effectiveness”. Furthermore, a few indicators were put together as the overall CMI “Maintenance Time”, which includes assembly, disassembly, inspection, measurement repairment, refurbishment, remanufacturing and replacement. The same applies for “Maintenance Cost”, which includes disassembly, inspection, repairment, replacement, remanufacturing, refurbishment costs. For the sake of comprehension, with the aim that no additional explanation would be needed, already well-fitting CMIs were renamed without changing their meaning. This leads to the general characteristics of performance indicators.

3.3.2 Assessment of the Final Draft Set

In the theoretical section about indicators, several characteristics for proper defined performance indicators were mentioned, Section 2.3.2 can be referred to for a more specific description of these characteristics. To make sure that the CMIs were well-developed, the draft CMI set underwent a thorough evaluation by the author to assess their alignment with eight desired performance indicator traits, seen in Table 8. The “+” signals the characteristic is met, "~" and marked in green defines it as “in question” and "-" describes the fulfillment as “concerning”.

The environmental CMIs are considered as completely fulfilled regarding their characteristics. However, the social category has some CMIs, which are not fulfilling the characteristics of data source clarity. These indicators, namely “Employee Skill Proficiency,” “Employee Satisfaction Index” and “Employee Stress Assessment” are based on subjective and truthful statements from people and are therefore not so easy to assess regarding their quality. For instance, if the data sources used to gauge employee satisfaction are unclear, unreliable, or not comprehensive, it could result in a misrepresentation of actual employee sentiment. This could happen due to poorly designed surveys, low response rates, or an over-reliance on limited data points.

In economic, the CMI “Refurbished Part Cost Benefit” is marked as only partly fulfilled for precise calculation. It might happen, that the calculation does not consider all variables, such as the potential for increased maintenance costs or reduced part lifespan, the benefit may be overstated or understated. The same applies to “Supply Chain Expenses”, where external factors such as fluctuating prices of raw materials, unexpected shipping costs, or inefficiencies in the supply chain process can make it difficult to achieve accurate cost estimations. Also, the maintenance related CMI “Component Replacement and Refurbishment Rate” cannot be easily calculated, as there might be a lack of accurate data on component lifecycles, variability in component quality, or inconsistency in the application of refurbishment processes. Furthermore, it is difficult to compare the market prices of new products and parts with refurbished ones, that is why “Refurbished Parts Cost Benefit“ is also marked in green for the characteristic precise calculation.

Regarding understandability, the maintenance related CMIs “Preventive Maintenance Intensity Index“ and “Work Order Compliance Rate“ are marked as “in question” as these indicators might not be easily understood across the organization. This might lead to inconsistent application or misinterpretation of the necessary maintenance protocols for preventive actions or to issues with adhering to work orders. This could be due to unclear instructions, lack of training on compliance expectations, or the complexity of the work orders themselves.

The CMI “Spare Parts Repair Viability Assessment” is marked as green. There might be scenarios where the cost or effort involved in assessing repair viability does not justify the potential benefits, leading to the perception that the process is not always necessary or impactful. The assessment could be seen as adding complexity to the maintenance process without a clear return on investment in all cases, leading to it being considered less relevant for certain parts or under specific circumstances.

Table 8: Assessment on the desired characteristics of the draft CMI set

Main	Sub Category	CMI	Understandability	Goal	Relevance	Precise Calculation	Data Source Clarity	Actionable	Research Foundation	Connected Improvement
Environment	emission, pollution and waste	Environmental Impact	+	+	+	+	+	+	+	+
	resource consumption and efficiency	Energy Consumption Rate	+	+	+	+	+	+	+	+
		Material Consumption Rate	+	+	+	+	+	+	+	+
		Resource Utilization Efficiency	+	+	+	+	+	+	+	+
	resource recovery	Product Reuse Potential	+	+	+	+	+	+	+	+
		Resource Recovery Rate	+	+	+	+	+	+	+	+
	waste management	Net Waste Management Cost	+	+	+	+	+	+	+	+
		Waste Management Efficiency	+	+	+	+	+	+	+	+
Social	employee development and training	Employee Skill Proficiency	+	+	+	+	-	+	+	+
		Workforce Efficiency Ratio	+	+	+	+	+	+	+	+
	human resources	Employee Satisfaction Index	+	+	+	+	-	+	+	+
		Workforce Allocation for Maintenance	+	+	+	+	+	+	+	+
		Overtime Workload	+	+	+	+	+	+	+	+
	Occupational Health and Safety	Workplace Safety and Health Assessment	+	+	+	+	+	+	+	+
		Employee Stress Assessment	+	+	+	+	-	+	+	+
Economic	production process	System Knowledge and Intelligence Level	+	+	+	+	+	+	+	+
		Manufacturing Efficiency Index	+	+	+	+	+	+	+	+
		Net Present Value	+	+	+	+	+	+	+	+
		Readiness for System Evolution and Upgradeability	+	+	+	+	+	+	+	+
		Refurbished Parts Cost Benefit	+	+	+	~	+	+	+	+
		Component Importance Index	+	+	+	+	+	+	+	+
	supply and distribution	Supply Chain Expenses	+	+	+	+	~	+	+	+
		Parts Delivery Frequency	+	+	+	+	+	+	+	+
Economic-Maintenance related	maintenance: work identification	Preventive Maintenance Intensity Index	~	~	+	+	+	+	+	+
		Work Order Compliance Rate	~	+	+	+	+	+	+	+
	maintenance: work planning and scheduling	Maintenance Time (inklusive assembly, disassembly, inspection, measurement repairment, refurbishment, remanufacturing, replacement)	+	+	+	+	+	+	+	+
		Scheduled Maintenance Compliance	+	+	+	+	+	+	+	+
		Recovery Delay Time	+	+	+	+	+	+	+	+
		Emergency Maintenance Ratio	+	+	+	+	+	+	+	+
		Expected Service Life Cycles	+	+	+	+	+	+	+	+
	maintenance: work execution	Mean Time to Repair	+	+	+	+	+	+	+	+
		Inspection Frequency	+	+	+	+	+	+	+	+
		Component Replacement and Refurbishment Rate	+	+		~	+	+	+	+
		Maintenance Backlog	+	+	+	+	+	+	+	+
	maintenance: equipment effectiveness	Remaining Useful Life	+	+	+	+	+	+	+	+
		Downtime (planned and unplanned)	+	+	+	+	+	+	+	+
		Mean Time Between Failure	+	+	+	+	+	+	+	+
		Reliability Rate	+	+	+	+	+	+	+	+
		Overall Equipment Effectiveness	+	+	+	+	+	+	+	+
		Downtime Cost	+	+	+	+	+	+	+	+
		Maintenance Efficiency	+	+	+	+	+	+	+	+
	maintenance: cost effectiveness	Maintenance Cost (including disassembly, inspection, repairment, replacement, remanufacturing, refurbishment costs)	+	+	+	+	+	+	+	+
		Spare Parts Procurement Expenses	+	+	+	+	+	+	+	+
		Strategic Maintenance Investment	+	+	+	+	+	+	+	+
		Maintenance Budget	+	+	+	+	+	+	+	+
		Maintenance cost per unit production	+	+	+	+	+	+	+	+
		Spare Parts Repair Viability Assessment	+	+	~	+	+	+	+	+
	maintenance: safety and environment	Maintenance Risk Assessment	+	+	+	+	+	+	+	+

4 State of the Art in the Industrial Sector: A Survey

This chapter describes the creation of the questionnaire, gives an insight into the participants and the survey process and shows the outcome of the survey.

4.1 Development of the Questionnaire

To validate and refine the CMI draft set, a survey among experts in the industry with knowledge in the area of maintenance was conducted. Using a survey for obtaining feedback is considered highly effective, especially in social science research, due to its proven track record (Chan, 2014). In this survey, the industrial participants were asked to rate the importance of the CMIs in the CMI draft set. The survey's objective was twofold: The results were used to reduce the seemingly less important CMIs and it served to find out the importance of maintenance in the future of CE. Therefore, questions were based on the importance of each CMI and the assessment of the industry participants regarding their practical knowledge with today's maintenance.

In the aforementioned foundational papers which used a questionnaire Ayu and Yunusa-Kaltungo (2020) and Mahpour (2023) applied a five-point Likert scale while Connolly (2023) worked with open questions in his questionnaire. Furthermore, Melnyk et al. (2014) uses the Delphi method to conduct a survey.

Bidhan (2010) describes that there are approximately two types of questionnaires, namely structured and unstructured. Structured surveys contain predetermined questions with specific skip logic to ensure question order is maintained (Bidhan, 2010). These are frequently utilized in gathering quantitative data because of their benefits, including minimizing discrepancies, simplicity in administration, maintaining uniformity in responses, and aiding in data organization (Bidhan, 2010). Questionnaires that are unstructured typically contain questions that are open-ended and based on opinions (Bidhan, 2010). These inquiries might not be posed as questions, thus necessitating the moderator or enumerator to clarify their significance (Bidhan, 2010). Nevertheless, it is not always simple to pre-code all questions with every potential answer option. One useful strategy is to primarily utilize structured questions but also incorporate some unstructured questions for responses that are challenging to fully list. This kind of survey is referred to as a semi-structured questionnaire (Bidhan, 2010). These numerous approaches lead to deciding which type of questionnaire to use and what type of question should be asked in the survey.

4.1.1 Choice of Question Style

Parida and Chattopadhyay (2007) use open questions, but most of the analyzed literature works with a Likert scale, more precisely with a 5-point Likert scale (de Toni & Tonchia, 2001; Gunasekara, 2020; Samadhiya, Agrawal, Kumar, & Garza-Reyes, 2023). A Likert scale is generally suitable for any survey that involves the respondents' personal opinions. Likert scale questionnaires are particularly useful if a (complex) topic needs to be evaluated in detail. They allow for nuanced answer options and can still be completed and evaluated quickly (Bidhan, 2010). The answer on a question with scaling 1 to 5 can look like this: 1 is "strongly disagree", 2 is "disagree", 3 is "neutral", 4 is "agree" and 5 is "strongly agree" (Surajit, 2018). As the wording with neutral is not meaningful in this case as the survey aims to find out the importance of the CMIs, the wording for this survey with a 5-point scale was chosen to be "not important, slightly important, moderately important, important, very important". This scale also implied four answer possibilities of positive importance and therefore seemed to be more appropriate for this survey.

In addition, open questions regarding the positions of the survey participants and their role in the maintenance sector were implemented as well as general open questions regarding the company to gain information about different implementation strategies of maintenance in different businesses.

4.1.2 Questionnaire Design

The platform on which the survey was created and conducted is Google Forms. As an online survey tool, it of course has advantages over offline options as it is also possible to create a questionnaire in the mobile browser or web browser without any special software. Furthermore, it is possible to see incoming replies immediately and the results can be clearly presented in diagrams and graphics using Google Forms and can easily be exported for further analysis.

After a short introduction at the beginning, the survey is divided into three main sections. The first section gathers general information about the participant's company including the sector in which it operates, the type of business relationships it maintains (B2B, B2C, B2PA), the number of employees, the percentage of employees involved in maintenance activities, and the type of maintenance concepts the company primarily follows, such as preventive or predictive maintenance. Additionally, this section inquiries about the company's familiarity with and integration of circular economy principles and orientates on the whitepaper "Zukunft Kreislaufwirtschaft 2023" from EFS in cooperation with Fraunhofer Austria and TU Wien (Kolar et al., 2023). The second section is dedicated to evaluating the pre-selected indicators across three dimensions: environmental, social, and economic. Therefore, a brief introduction to the TBL model has been provided for the participants. The third section collects voluntarily personal information about the participant, specifically their current or past roles related to maintenance. It also provides optional fields for the participant to enter their company name and email address if they wish to receive the survey results or participate in follow-up interviews.

The questionnaire itself was developed in English and German, as most of the contacts have been German-speaking experts from Austria or Germany and can be found in Appendix B.

4.1.3 Pre-assessment of the Survey

Pretesting is considered as an unquestioned stage of the survey construction process as the absence of this can cause even veteran researchers to use unreliable tools, resulting in doubts about the research findings (Ikart, 2019). It can answer questions such as:

- Did the survey capture your interest?
- How much time did it take to finish?
- Was the logical flow of the question satisfactory?
- Were there any questions that caused confusion?
- Were there any aspects that caused frustration? (Ikart, 2019).

Three people with expert knowledge from Fraunhofer Austria and TU Wien were chosen to fill out the questionnaire and provided feedback on the comprehensibility and clarity of the survey. The test participants were able to fill out the questionnaire within seven to ten minutes. In addition, a psychologist without any expert knowledge worked on the questionnaire and the feedback from the technical as well as the psychological side have been implemented in the adjustment of the survey. These improvements ensured better understandability and clarity of the survey.

4.2 Execution of the Survey

For the questionnaire, participants from the industry have been chosen without any exceptions regarding the sector. The participants were contacted via email or personal messages on LinkedIn. Furthermore, the survey has been shared on the authors' personal LinkedIn profile to gain additional attention through the personal network. Another source was Fraunhofer Austria, who promoted the survey at a conference. The survey was able to be filled out from the 21st of May 2024 until the 21st of June 2024, but the timeframe got prolonged by 2 weeks, as there was still the possibility for a feedback from LinkedIn. However, it needed to be said that already two thirds of the participants filled out the survey within the first week after the release.

All-encompassing 39 experts participated in the survey, with the exclusion of the own pretests. Out of this, 38 answered every question and 28 gave an insight into their professions. Out of these 28, nine serve as CEOs or Managing Directors, and may have maintenance oversight within their larger duties. There are seven roles exclusively focused on maintenance, such as Head of Maintenance, Deputy Maintenance Manager, and Technical Director, who are all directly overseeing or participating in maintenance tasks. Furthermore, there are four roles connected to infrastructure, product management, and process management, with maintenance being a key aspect of their responsibilities, especially in guaranteeing operational efficiency and service continuity. Project Management, Division Management, and Service and Spare Parts Management are other positions that are connected to maintenance but in an indirect way, as they prioritize project completion and oversee divisions that might involve maintenance tasks, as well as handle essential parts for maintenance tasks. Figure 27 shows the geographical distribution of the responders. Even though only 18 companies could be located, there is the tendency towards a location in Upper Austria and Lower Austria, where a lot of manufacturing companies are located.

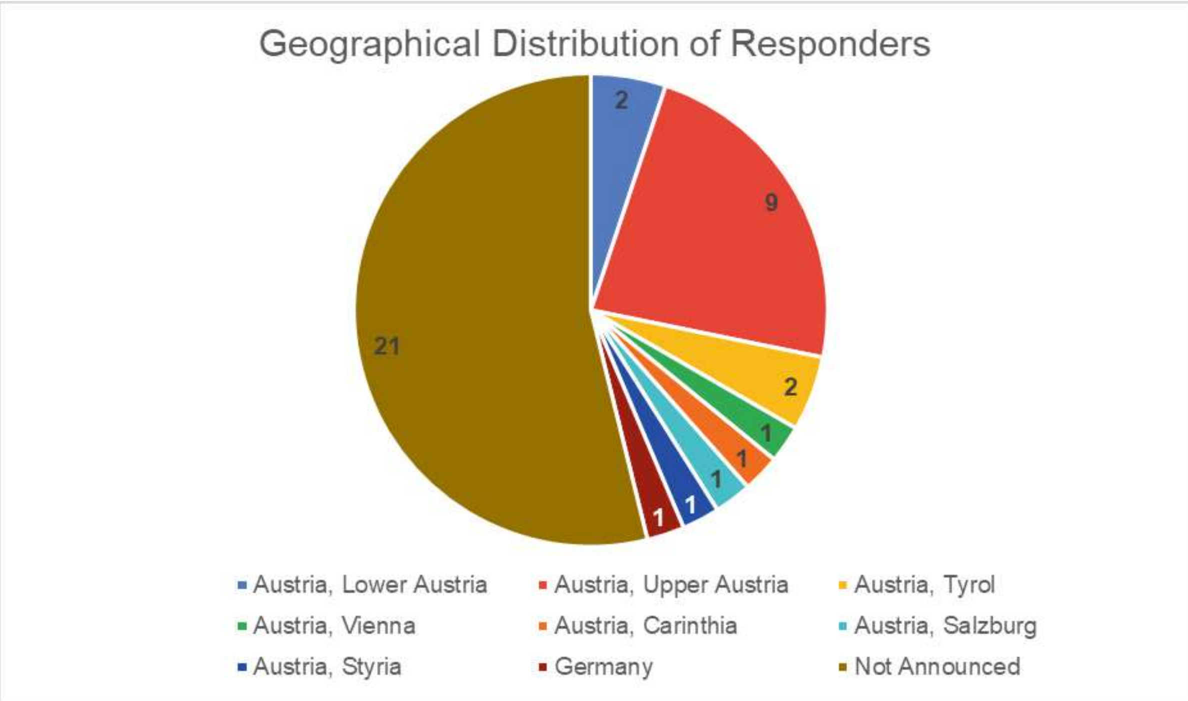


Figure 27: Geographical distribution of the responders

A third of the participants also want the results of the survey or at least the thesis, which shows the importance and interest in this topic. The following chapter shows the results of the questionnaire and discusses what knowledge can be derived from this for the indicator set. All results can be seen in Appendix C.

4.3 Results and Interpretation of the Survey

4.3.1 General Information regarding the participating Companies

As the focus of the survey and the indicators is on the industry and manufacturing sector, 56.4% of respondents stated that they work in the manufacturing sector, with six participants specifying their field as mechanical and plant engineers. Four indicated working in the field of professional, scientific and technical advice. The remaining participants are working in different fields from the energy sector to the construction sector, seen in Figure 28. Regarding their company's type of business relationship, 37 have answered that their company pursues business to business. Giving multiple answers was also possible. 17.9% pursue business to customer relationships and four works together with public administration.

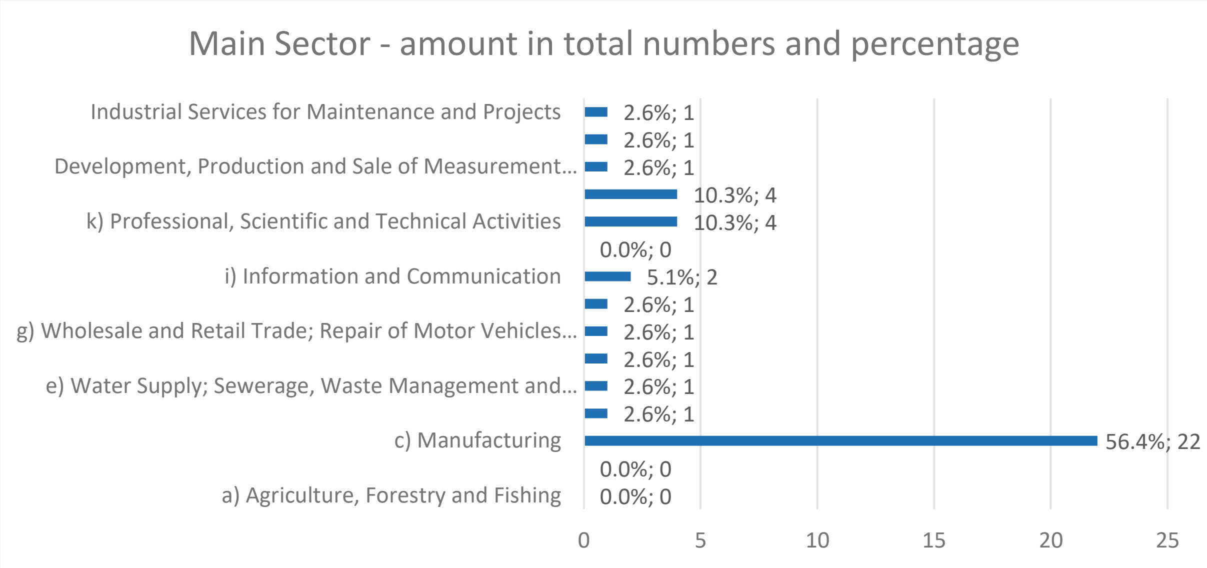


Figure 28: Question 1: Please specify the (main) sector of your company

48.7% of the companies are large enterprises with more than 250 employees, 41% are medium-sized and only two are small enterprises with up to 49 employees.Two are micro-enterprises with up to nine employees. This can lead to a common problem in such surveys, the high representation of bigger companies means that it is challenging to capture the experiences, challenges, and needs of these smaller businesses. Due to that, the next question regarding the maintenance employee in the firm, needed to be answered in percentages. Figure 29 shows the maintenance staff relative to the total number of employees in the company. However, small enterprises might not employ one person solely for maintenance, while bigger companies in manufacturing have their own maintenance department. Nevertheless, the figure shows that maintenance is a crucial part in industry: Nine participants answered that they have five percent of their staff working in a maintenance department and eleven even answered with a percentage of ten and higher. There were also two companies with zero percent but on the other side also companies with 50 and even 70 percent of their staff working in a maintenance related position. These findings can also be seen in the fact that 69.2% of the companies stated that they do their maintenance services on premise.

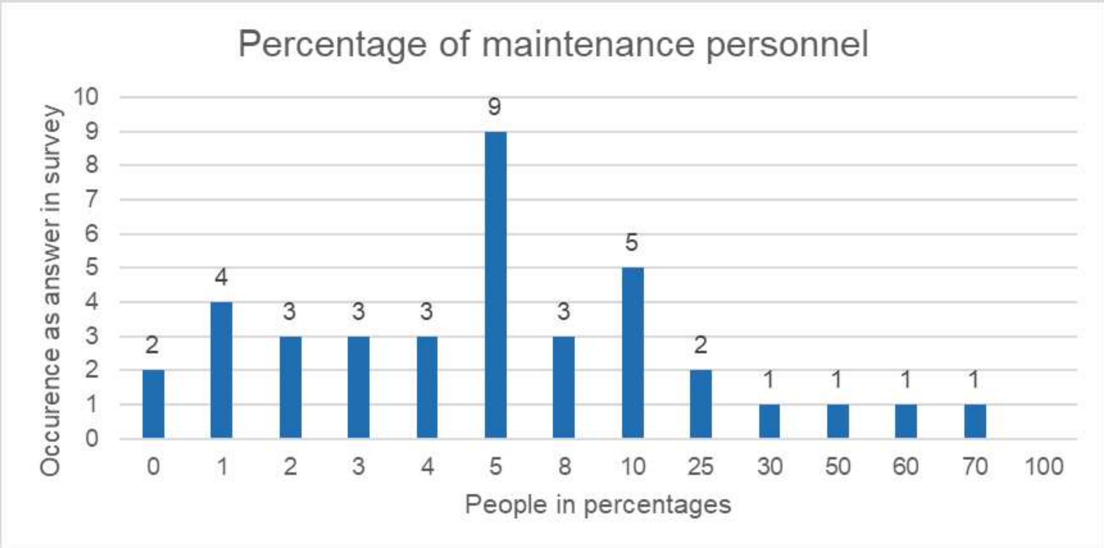


Figure 29: Question 4 - What percentage of your employees work in maintenance or carry out maintenance-related activities?

Regarding the already discussed maintenance strategies, Figure 30 gives insight into the companies' traditional maintenance approaches, depicted in. The biggest amount of maintenance services are still based on the concept of corrective maintenance and preventive maintenance. Data driven approaches such as condition based and predictive maintenance are only used by a third to 41% of the companies.

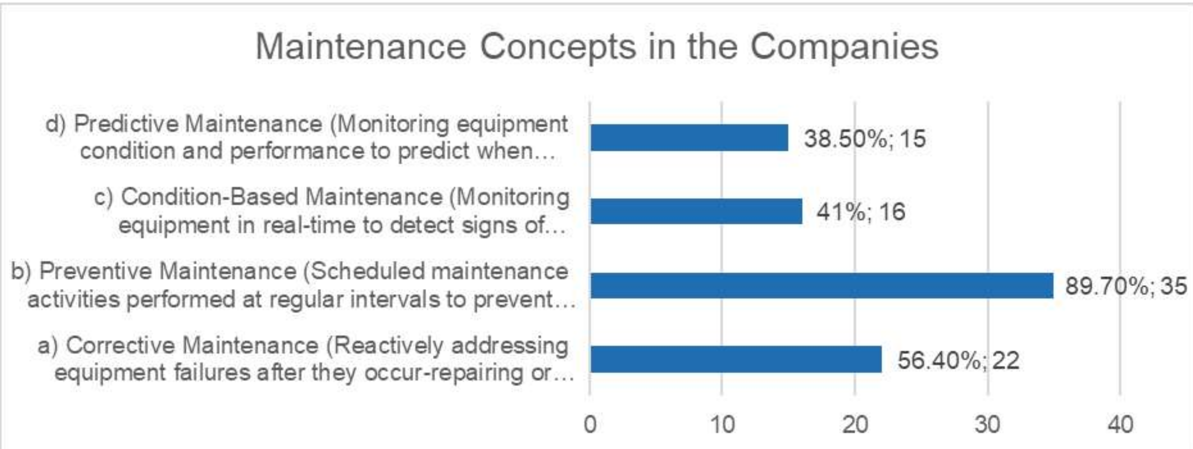


Figure 30: Question 5 - What type of maintenance concept does your company primarily follow?

This outcome fits in with other results on questions related to the CE, seen in Figure 31. Regarding the question, to what extent the company is familiar with the concept of the CE, 15.8% stated that the company and its employees are not familiar with CE and 10.5% indicated that only the top management and experts in the firm are familiar with the concept. On the other hand, 39.5% declared that management level, experts and some managers in the company know and understand the concept of CE and 21.1% claim that there is a company-wide understanding. Nevertheless, a mere 13.2% have CE already implemented as corporate culture, which is a sign that it is still not a very common and established practice. This limited implementation highlights the novel and emerging nature of the CE field, making it a particularly interesting area for growth and shows maintenance as an important enabler for that.

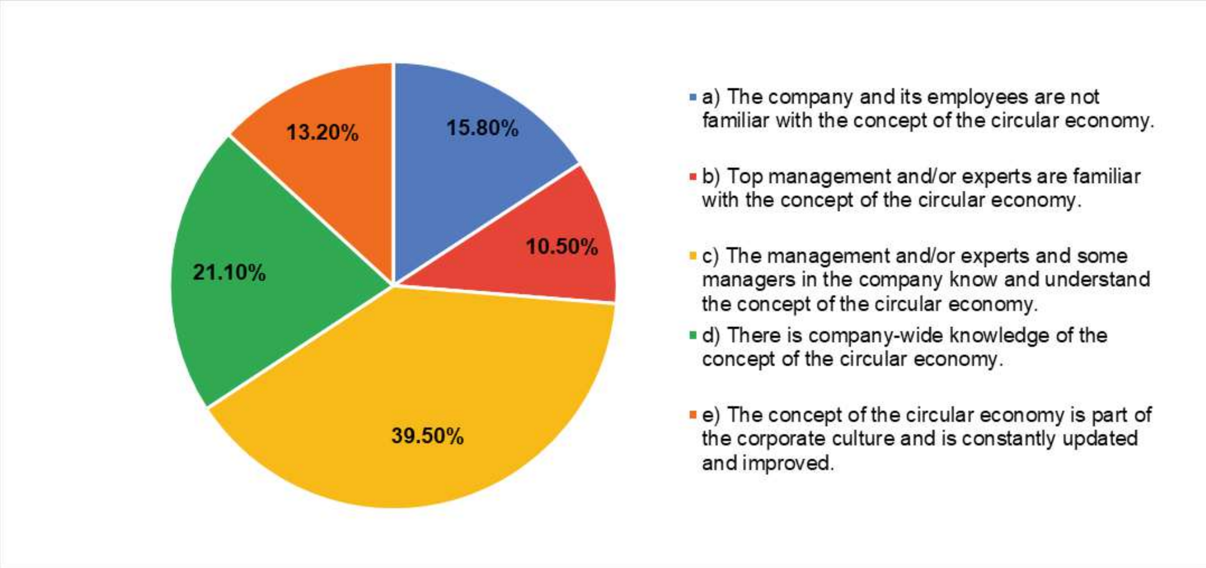


Figure 31: Question 7 - To what extent is your company familiar with the concept of the CE?

Interestingly, only 18.4% stated that CE is not part of the corporate strategy and does not even have a single project influenced by CE. The majority has at least projects related to CE or even CE established in the firms' vision. This shows the openness of the companies and the willingness to change towards CE, which is depicted in Figure 32.

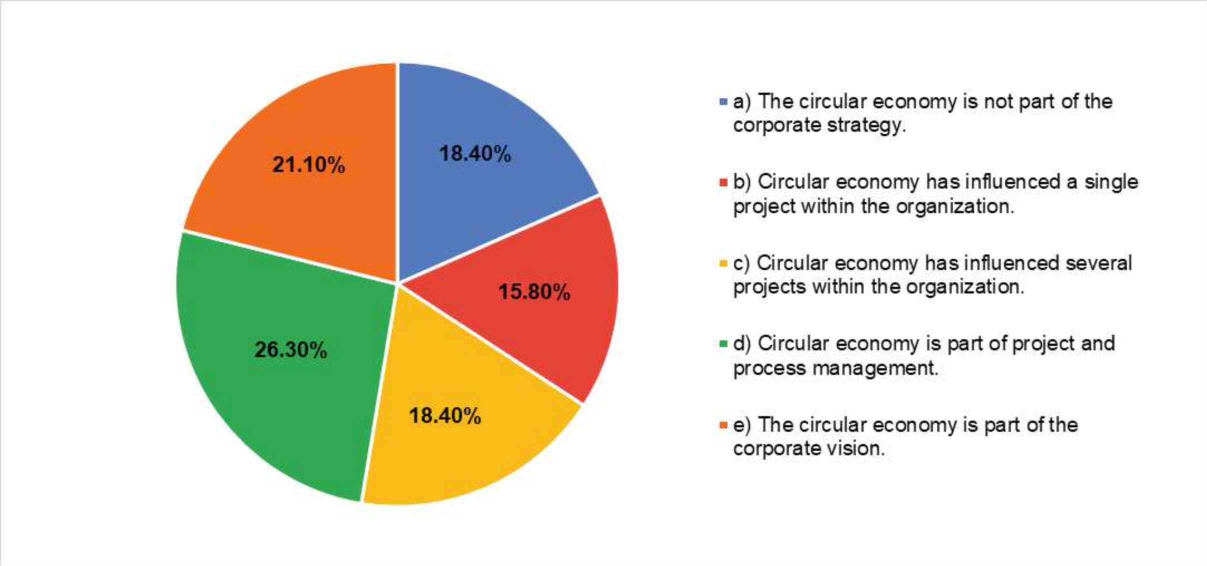


Figure 32: Question 8 - To what extent is the CE anchored in your corporate strategy?

In addition, the findings, as depicted in Figure 33, indicate that most survey participants acknowledge that maintenance plays a significant role in the circular economy. In particular, 30.8% of the respondents gave a rating of 5, showing a significant recognition of the role of maintenance in upholding CE principles. 28.2% of respondents rated the impact as a 6 or 7, indicating a firm conviction in the important role maintenance has. At the other extreme, only 28.2% of participants rated the impact as 1, 2, or 3, indicating that a smaller portion of industry members may view maintenance as less important within the CE. Based on the outcome of this question and the previous one it can be said that in general a significant number of participants acknowledge the powerful impact of maintenance, indicating a growing understanding and inclusion of maintenance tactics to promote CE goals.

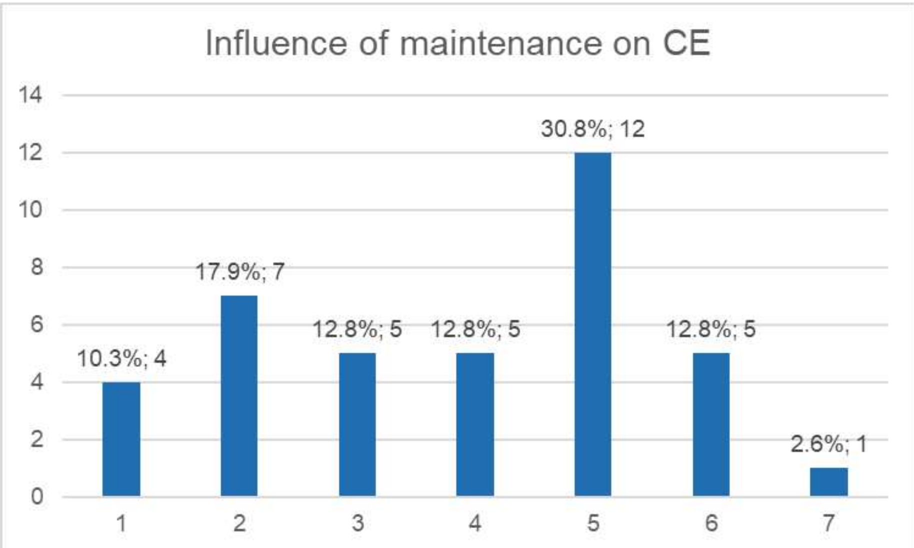


Figure 33: Question 9 - Rate the influence of maintenance on the CE

These findings support the importance of the chosen maintenance indicators, which are directly based on and derived from the experience and knowledge of the industry.

4.3.2 Importance of the CMIs in the Industry

As the validation and creation of a CMI set is the most important aim, the survey aims to not only validate the draft set but also to determine possible CMIs which are not relevant for the industry. Therefore, the least important CMIs might be removed from the final CMI set. Regarding the Likert-Scale, different analysis strategies exist to find out the sentiment for an indicator, based on the answers given.

First of all, the mean, median and mode were calculated for the CMIs. However, it turned out that there are only small differences in the results of the CMIs which might be among others possible reasons, attributed to the small margin within the five-point Likert scale. Therefore, the decision was made to conduct the top two box score as validation strategy. For this reason, the percentages of respondents who selected the top two categories “important” and “very important” were calculated. This rating is called importance ratio (IR) and a cut-off for the drop out of indicators being below has been made at the level of 55% for all three dimensions.

$$\mathrm{IR}_{CMI} = \frac{\text{Number of respondence "important" and "very important"}}{\text{Total number of respondence}} \times 100$$

Formula 1: CMI importance ratio

Applied as an example to the CMI “environmental impact”, which has 19 “very important” and 10 “important” answers and a total amount of 38 respondents, gives an IR of 76.32%.

$$\mathrm{IR}_{Environmental\ Impact} = \frac{29}{38} \times 100 = 76.32\ \%$$

It was also possible to answer with “unknown”, questions answered with this had to be looked at separately, because they can falsify the analysis of the Likert answers. However, they are not ignored, owing the fact that they control the very important characteristic “understandability” and “recognizable” of an indicator. Therefore, an analysis of a possible rename of the indicator was initiated, if there were at least three answers that the CMI is unknown. It might also be a sign that within the literature research indicators were found, that are important but might be not known by the industry at this point. These indicators are discussed separately to decide about future steps.

TBL dimensions

First, the importance of each TBL dimension was checked. The calculation of the IR was not needed here, as there was a clear difference between the three categories.

The environment and economic dimension were considered as important to very important whereas the social dimension was considered primarily as moderately important to important, as depicted in Figure 34 to Figure 36: Importance of the Economy CMI Dimension. This emphasis on the economic dimension aligns with the industry's traditional focus on economic performance. However, the significant importance given to environmental and social dimensions reflect an increasing awareness and integration of sustainability and social responsibility in industry practices.

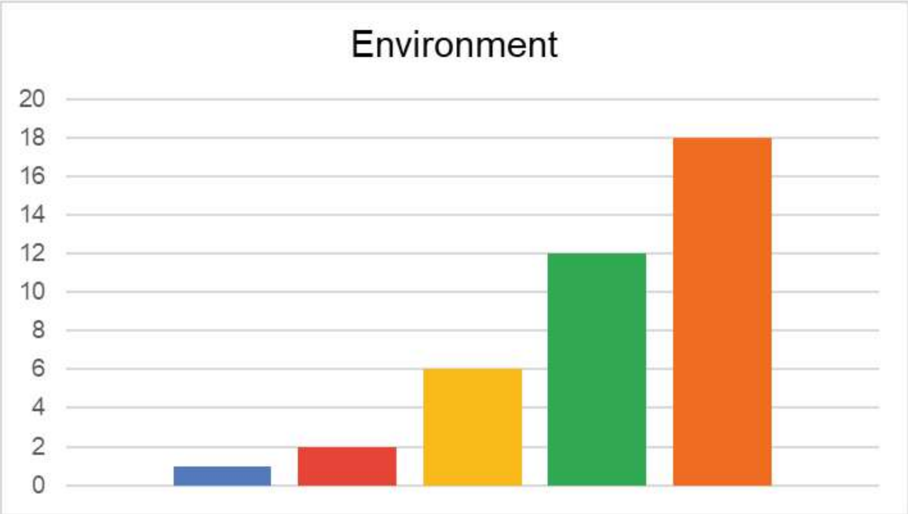


Figure 34: Importance of the Environment CMI Dimension

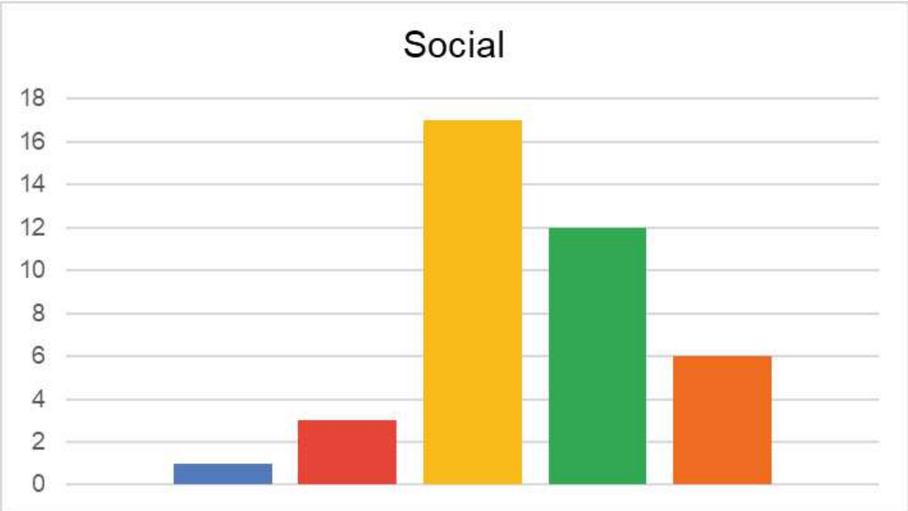


Figure 35: Importance of the Social CMI Dimension

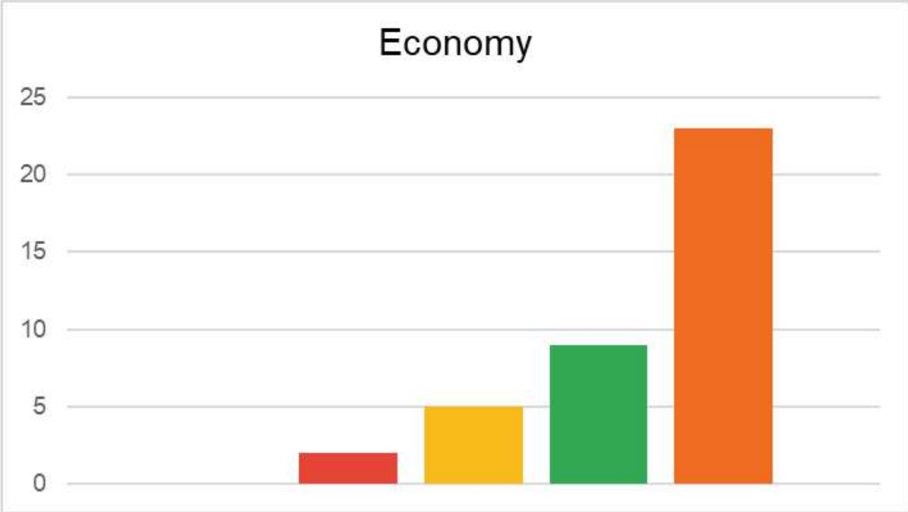


Figure 36: Importance of the Economy CMI Dimension

CMIs in the environment dimension

The survey shows that the industry prioritizes indicators like "Energy Consumption Rate," "Material Consumption Rate," and "Resource Utilization Efficiency." All three have an IR higher than 80%. These measures show a clear focus on maximizing resource utilization, minimizing usage, and improving effectiveness, all of which are crucial for both economic success and sustainability endeavors. The "Environmental Impact" IR of 76% suggests that environmental concerns are also important, possibly due to efficient resource usage. On the other hand, measures connected to "Product Reuse Potential" with an IR of 65%, "Resource Recovery Rate" and the waste management indicators, with IRs even below 58%, are seen as less important. This indicates the importance of prioritizing reducing resource use and waste generation at the beginning instead of focusing on recovery and management later. Nevertheless, as the cut-off for the environment dimension was set for 55%, none of the CMIs are influenced by the measure.

In general, the results indicate a prevalent industry shift towards emphasizing resource efficiency and reducing consumption, driven by economic and environmental reasons. The areas are deemed highly important, showing that although broader environmental effects and waste management still matter, they come after the more immediate advantages of efficiency and decreased consumption. This can be seen in Table 9, with the blue boxes indicating the highest answer occurrences.

Table 9: Importance Level of environment indicators by Stricker (2024)

Main	Sub Category	CMI	Importance Level: Not important	Slightly Important	Moderately Important	Important	Very Important	Unknown
Environment	emission, pollution and waste	Environmental Impact	1	3	5	10	19	1
	resource consumption and efficiency	Energy Consumption Rate	0	1	3	11	24	0
		Material Consumption Rate	0	1	6	11	20	1
		Resource Utilization Efficiency	0	1	4	16	15	3
	resource recovery	Product Reuse Potential	2	4	7	11	14	1
		Resource Recovery Rate	0	7	10	11	10	1
	waste management	Net Waste Management Cost	0	4	12	11	11	1
		Waste Management Efficiency	1	6	9	13	9	1

CMIs in the social dimension

The survey reveals that in the social aspect, the key indicators are "Employee Skill Proficiency," "Workforce Efficiency Ratio," and "Workplace Safety and Health Assessment". These performance indicators have the most significant IRs and consistently high mode, median, and mean scores. This shows a clear emphasis on employee talents, effectiveness, and workplace security, all crucial for sustaining a productive and secure work atmosphere. Factors such as "Employee Satisfaction Index" and "Employee Stress Assessment " are also deemed significant but to a slightly lower extent. The industry acknowledges the significance of employee well-being and satisfaction, but still prioritizes skill proficiency and efficiency over them, as the stress indicator has a significantly lower IR with 64%. Indicators concerning "Workforce Allocation for Maintenance" and "Overtime Workload" have much less significance and average scores, indicating that they are relevant but not as highly prioritized as other social indicators. “Overtime Workload” has an especially low IR of only 37%, making it the lowest of all 48 CMIs. Due to it falling below the cut-off at 55%, this CMI will not be part of the final set.

Summing up, the results show that the sector gives importance to CMIs that have a direct influence on productivity and safety, demonstrating a strategic emphasis on cultivating a qualified workforce and upholding streamlined operations, depicted in Table 10. Focusing on important indicators is consistent with the broader objectives of improving employee effectiveness and guaranteeing a secure workplace.

Table 10: Importance Level of social indicators by Stricker (2024)

Main	Sub Category	CMI	Importance Level: Not important	Slightly Important	Moderately Important	Important	Very Important	Unknown
Social	employee development and training	Employee Skill Proficiency	0	1	0	13	24	1
		Workforce Efficiency Ratio	0	0	2	12	24	1
	human resources	Employee Satisfaction Index	0	2	7	14	16	0
		Workforce Allocation for Maintenance	1	4	13	16	3	2
		Overtime Workload	2	4	17	9	5	2
	Occupational Health and Safety	Workplace Safety and Health Assessment	0	1	4	10	22	2
		Employee Stress Assessment	1	3	10	14	11	0

CMIs in the economic dimension

The study shows that the "Manufacturing Efficiency Index" and "Component Importance Index" are the most crucial indicators within the economic aspect. These key performance indicators hold the most significant IRs with over 94% and consistently high mode, median, and mean scores, indicating a clear industry emphasis on enhancing manufacturing efficiency and recognizing component significance.

The indicator "System Knowledge and Intelligence Level" seems to also be very relevant for the industry, as mean and mode are the highest and it has an IR of over 80%. Also "Net Present Value," and "Readiness for System Evolution and Upgradeability" are seen as significant. These CMIs showcase the industry's focus on improving system intelligence, assessing financial sustainability, and guaranteeing future system flexibility, which is an important aspect of a digital maintenance approach.

Some emphasis is given to "Refurbished Parts Cost Benefit" and "Parts Delivery Frequency," showing that benefits from refurbished parts and timely delivery in the supply chain are important but not the primary focus. The indicator pertaining to "Supply Chain Expenses" holds the lowest IR, indicating that while monitoring supply chain expenditures is important, it is not as crucial as other economic indicators. This could be because although maintenance is largely responsible for participation of the company in a supply chain, it has no direct interaction with the supply chain and its expenses.

In general, the results emphasize that the sector focuses on CMIs that have a direct influence on production efficiency, system expertise, and component significance. This focused strategy is in line with larger economic objectives like boosting productivity, financial strength, and flexibility; all necessary for long-term competitiveness and prosperity. The results are also shown in Table 11.

Table 11: Importance Level of economic indicators by Stricker (2024)

Main	Sub Category	CMI	Importance Level: Not important	Slightly Important	Moderately Important	Important	Very Important	Unknown
Economic	production process	System Knowledge and Intelligence Level	1	1	5	19	10	3
		Manufacturing Efficiency Index	0	0	1	12	22	4
		Net Present Value	0	0	8	11	20	0
		Readiness for System Evolution and Upgradeability	0	0	9	18	11	1
		Refurbished Parts Cost Benefit	1	2	7	20	9	0
		Component Importance Index	0	0	2	20	16	1
	supply and distribution	Supply Chain Expenses	0	1	17	15	6	0
		Parts Delivery Frequency	1	1	7	17	9	4

CMIs in the economic dimension, maintenance related

The survey indicates that within the maintenance-related economic dimension, the most critical indicators are "Downtime (planned and unplanned)," "Reliability Rate", "Downtime Cost", and "Maintenance Time". They are highlighting a strong industry focus on minimizing downtime, ensuring reliability, and maintaining high equipment effectiveness.

CMIs such as " Overall Equipment Effectiveness", "Maintenance Efficiency", and "Maintenance Cost" are also significant, emphasizing the importance of efficient and cost-effective maintenance practices to sustain operational performance. Moderate importance is placed on indicators like "Emergency Maintenance Ratio" and "Remaining Useful Life", indicating the relevance of strategic planning and predicting equipment life for long-term efficiency. “Spare Parts Procurement Expenses” fits into these ranking with a high mean of four and an IR of 68%. Crucial indicators such as MTBF and MTTR are also seen as important, whereas “Maintenance Backlog” seems to be less important, with its IR of 54%. This also applies to CMIs like “Spare Parts Repair Viability Assessment” and “Scheduled Maintenance Compliance” with the same statistic outcomes as “Maintenance Backlog”. Therefore, they are falling below the cut-off mark.

Overall, the results emphasize that the sector prioritizes maintenance indicators that directly impact operational efficiency, cost management, and equipment reliability. This strategic focus aligns with the broader economic goals of enhancing productivity and reducing costs, but could be considered too short-term oriented in some aspects of sustainability, thereby it could harm maintaining competitiveness and achieving long-term success in all dimensions. The tabular visualization of all indicators, which couldn't all be elaborated individually, can be found in Appendix D.

The "unknown" indicators

The "unknown" indicators, namely the indicators where three or more participants said the indicator is not familiar to them, are listed in the following Table 12. In addition, the table includes an explanation of the CMI, the IR and the ranking from the literature review. The first four can be easily recognized as important, for the industry as well as in scientific literature. However, the other three can be considered for a name change or even for a drop out of the final set. The "Scheduled Maintenance Compliance" falls within the higher ranking half of the literature findings, but on the IR scale it is on the high importance scale only for every second participant. The "Preventive Maintenance Intensity Index" also has a lower placing and IR, but this might be due to the bulky name of the CMI. Therefore, this CMI will be renamed for the final set. In conclusion, the "Work Order Compliance Rate" and "Scheduled Maintenance Compliance" will not be part of the final set, because they are both below the cut-off mark. Additionally, the CMI "Work Order Compliance Rate" ranks even lowest regarding the literature review.

Table 12: Indicators declared as "unknown" after the survey

"Unknown" indicators	Unit	Explanation	Importance Rate	Rank in Literature
Resource Utilization Efficiency	%	Output achieved (number of products)/total resource consumption (energy, materials)	86.11%	28
System Knowledge and Intelligence Level	integer	degree of intelligence embedded within a system, such as automation, monitoring capabilities, and decision-making algorithms; knowledge available within an organization or team, including expertise, experience, and access to information resources	80.56%	5
Manufacturing Efficiency Index	%	Cost of goods manufactured/cost of tools used	97.14%	19
Parts Delivery Frequency	h	average spare parts arrival rate	74.29%	28
Preventive Maintenance Intensity Index	%	involves scheduled inspections, tasks, or repairs aimed at preventing equipment failures and maximizing asset reliability	58.33%	34
Work Order Compliance Rate	%	extent to which maintenance activities are organized, tracked, and controlled through established procedures	44.44%	38-48
Scheduled Maintenance Compliance	%	number of scheduled maintenance action/number of maintenance action	51.43%	15

4.3.3 Biases in the Survey

Different biases can compromise the integrity of survey data, impacting the results in various ways. The identified biases are sample bias, social desirability bias, extreme response bias and response scale interpretation bias and they are all presented in section 6.2.

5 Design and Development of an Indicator Set

Chapter 5 shows the creation of a CE oriented maintenance indicator set, with an explanation of the CMIs and their formulas and the grading system for the circularity measurement. The final indicator set is evaluated on an industrial use case and the findings are summarized.

5.1 Creation of an Indicator Set for CE oriented Maintenance

5.1.1 Importance Survey vs. Literature

By combining the results of the industry survey and the SOTA literature analysis, the indicator set describes a practical reference and also the state of science. Table 13 shows the draft CMI set with the results of the importance survey and the literature review.

Table 13: Draft CMI set based on the survey and literature research

Main	Sub Category	KPI	Mode	Median	Mean	Importance Rate: "important" or "very important"	Marked as "Unknown"	Ranking by Frequency in the Literature
Environment	emission, pollution and waste	Environmental Impact	5	4.5	4.13	76.32%	1	3
	resource consumption and efficiency	Energy Consumption Rate	5	5	4.49	89.74%	0	6
		Material Consumption Rate	5	5	4.32	81.58%	1	24
		Resource Utilization Efficiency	4	4	4.25	86.11%	3	28
	resource recovery	Product Reuse Potential	5	4	3.82	65.79%	1	15
		Resource Recovery Rate	4	4	3.63	55.26%	1	34
	waste management	Net Waste Management Cost	3	4	3.76	57.89%	1	19
		Waste Management Efficiency	4	4	3.61	57.89%	1	19
Social	employee development and training	Employee Skill Proficiency	5	5	4.58	97.37%	1	13
		Workforce Efficiency Ratio	5	5	4.58	94.74%	1	28
	human resources	Employee Satisfaction Index	5	4	4.13	76.92%	0	38-48
		Workforce Allocation for Maintenance	4	4	3.43	51.35%	2	24
		Overtime Workload	3	3	3.30	37.84%	2	38-48
	Occupational Health and Safety	Workplace Safety and Health Assessment	5	5	4.43	86.49%	2	13
		Employee Stress Assessment	4	4	3.79	64.10%	0	38-48
Economic	production process	System Knowledge and Intelligence Level	4	4	4.00	80.56%	3	5
		Manufacturing Efficiency Index	5	5	4.60	97.14%	4	19
		Net Present Value	5	5	4.31	79.49%	0	28
		Readiness for System Evolution and Upgradeability	4	4	4.05	76.32%	1	38-48
		Refurbished Parts Cost Benefit	4	4	3.87	74.36%	0	38-48
		Component Importance Index	4	4	4.37	94.74%	1	38-48
	supply and distribution	Supply Chain Expenses	3	4	3.67	53.85%	0	24
		Parts Delivery Frequency	4	4	3.91	74.29%	4	28
Economic - Maintenance related	maintenance: work identification	Preventive Maintenance Intensity Index	4	4	3.56	58.33%	3	34
		Work Order Compliance Rate	3	3	3.33	44.44%	3	38-48
	maintenance: work planning and scheduling	Maintenance Time	5	4	4.26	84.21%	1	2
		Scheduled Maintenance Compliance	4	4	3.51	51.43%	4	15
		Recovery Delay Time	5	4	3.86	67.57%	2	34
		Emergency Maintenance Ratio	4	4	4.08	75.68%	2	22
		Expected Service Life Cycles	4	4	3.66	57.89%	1	7
	maintenance: work execution	Mean Time to Repair	5	4	3.89	63.16%	1	22
		Inspection Frequency	4	4	3.49	54.05%	2	12
		Component Replacement and Refurbishment Rate	4	4	3.59	54.05%	2	28
		Maintenance Backlog	3	4	3.70	54.05%	2	38-48
	maintenance: equipment effectiveness	Remaining Useful Life	4	4	3.86	70.27%	2	4
		Downtime (planned and unplanned)	5	5	4.39	86.84%	1	7
		Mean Time Between Failure	5	4	4.05	71.05%	1	15
		Reliability Rate	5	4	4.32	86.84%	1	10
		Overall Equipment Effectiveness	5	4	4.14	78.38%	2	9
		Downtime Cost	5	5	4.34	81.58%	1	15
		Maintenance Efficiency	4	4	3.95	67.57%	2	34
	maintenance: cost effectiveness	Maintenance Cost	4	4	4.05	76.32%	1	1
		Spare Parts Procurement Expenses	4	4	3.82	68.42%	1	10
		Strategic Maintenance Investment	4	4	3.92	65.79%	1	28
		Maintenance Budget	3	4	3.76	57.89%	1	38-48
		Maintenance Cost per Unit Production	4	4	3.76	63.16%	1	24
		Spare Parts Repair Viability Assessment	3	4	3.71	52.63%	1	38-48
	maintenance: safety and environment	Maintenance Risk Assessment	4	4	3.51	54.05%	2	38-48

The already mentioned cut-off, depicted in Table 14, was implemented for all categories at 55%. The red cells show the CMIs, which are excluded from the final set. In some cases they are additionally not of much relevance in the literature either, if that is the case they are depicted in blue. Namely, these are ”Overtime Workload”, “Work Order Compliance Rate”, “Maintenance Backlog”, “Spare Parts Repair Viability Assessment” and “Maintenance Risk Assessment”.

However, there are also others which fell below the industrial cut-off, such as “Supply Chain Expenses”, “Inspection Frequency” and “Component Replacement and Refurbishment Rate”. These indicators, although acknowledged as important from a research viewpoint, have not been extensively used in industry practice. It is crucial to recognize that these indicators could gain significance in the future as industry standards develop, see chapter 6. The other least frequent in literature are checked within the importance of the industry. “Readiness for System Evolution and Upgradeability,” “Refurbished Parts Cost Benefit” and “Component Importance Index” are directly named only once but are considered as very important by the survey participants. On the other hand, “Maintenance Backlog”, “Maintenance Budget”, “Spare Parts Repair Viability Assessment” and “Maintenance Risk Assessment” do not have such a high recognition in the industry. The indicator “Maintenance Budget” can be implemented in “Maintenance Cost”. Furthermore, there is the renaming of the “Preventive Maintenance Intensity Index” into “Preventive Maintenance Activity Index” for a better understanding. The other indicators are considered as important additions to the prevailing ones for a future maintenance strategy based on the current industry situation.

Table 14: Importance rate cut-off for the CMIs

IR cut-off:	environment	55%
	social	55%
	economic	55%
	Unknown	>=3
	Least frequent in literature	38-48

5.1.2 Formulas and Calculation of the Indicators

To effectively assess the circularity of maintenance practices, key indicators must be calculated using precise formulas. Below in Table 15, an in-depth look at four primary indicators is provided. Besides the specific calculation formula, each indicator is described by a definition. The full table of formulas can be seen in Appendix E.

Table 15: Formula and explanation of the indicators

Indicator	Environmental Impact
Formula	$Environmental\ Impact = \frac{Total\ CO_2\ Emissions\ (kg\ CO_2\ eq.)}{Total\ Operation\ Time\ (hours)}$
Definition	This indicator calculates the total CO_2 emissions generated by production activities over a specific operational period. By measuring CO_2 emissions, companies can understand their carbon footprint, identify high-impact processes, and implement strategies to reduce emissions. Lowering environmental impact aligns with regulatory requirements and supports broader CE goals, particularly in reducing waste and pollution.
Indicator	**Employee Satisfaction Index**
Formula	$\frac{Employees\ satisfaction\ score}{Total\ possible\ satisfaction\ score} \times 100$
Definition	This measurement provides a quantitative way to gauge employee morale and job satisfaction, which are directly linked to productivity, retention, and overall workplace harmony, which is important when we take a look at the social component of the holistic sustainability framework.
Indicator	**Maintenance Efficiency**
Formula	$\frac{Plannend\ maintenance\ hours}{Total\ maintenance\ hours} \times 100$
Definition	It reflects the effectiveness of planned maintenance activities compared to the total time spent on all maintenance. A higher percentage indicates that maintenance activities are well-planned and executed within expected timeframes, which reduces unscheduled downtimes and increases equipment reliability.
Indicator	**Downtime Cost**
Formula	$\frac{Lost\ Production\ (units)\ \times Unit\ Cost}{Total\ Downtime\ (hours)}$
Definition	Downtime costs assess the financial impact of equipment being out of operation due to maintenance or failure. This indicator is vital for understanding the economic implications of downtime, helping companies identify areas for improvement to minimize disruptions. Reducing downtime supports the CE by increasing the operational efficiency of equipment, thus conserving resources and reducing waste through better resource utilization.

5.1.3 CMI Final Set

After all the exclusion steps, the final CMI set has 37 indicators, depicted in Table 16.

Table 16: Final CMI set

Main	Sub Category	CMI	Unit
Environment	emission, pollution and waste	Environmental Impact	kg CO2 eq.
	resource consumption and efficiency	Energy Consumption Rate	kWh
		Material Consumption Rate	kg
		Resource Utilization Efficiency	%
	resource recovery	Product Reuse Potential	%
		Resource Recovery Rate	%
	waste management	Net Waste Management Cost	€/kg
		Waste Management Efficiency	%
Social	employee development and training	Employee Skill Proficiency	%
		Workforce Efficiency Ratio	%
	human resources	Employee Satisfaction Index	%
	Occupational Health and Safety	Workplace Safety and Health Assessment	%
		Employee Stress Assessment	%
Economic	production process	System Knowledge and Intelligence Level	integer
		Manufacturing Efficiency Index	%
		Net Present Value	€
		Readiness for System Evolution and Upgradeability	%
		Refurbished Parts Cost Benefit	€
		Component Importance Index	integer
	supply and distribution	Parts Delivery Frequency	h
Economic-Maintenance related	maintenance: work identification	Preventive Maintenance Activity Index	%
	maintenance: work planning and scheduling	Maintenance Time (including assembly, disassembly, replacement inspection, measurement repairment, refurbishment, remanufacturing)	h
		Recovery Delay Time	h
		Emergency Maintenance Ratio	%
		Expected Service Life Cycles	integer
	maintenance: work execution	Mean Time to Repair	h
	maintenance: equipment effectiveness	Remaining Useful Life	h
		Downtime (planned and unplanned)	h
		Mean Time Between Failure	h
		Reliability Rate	%
		Overall Equipment Effectiveness	%
		Downtime Cost	€
		Maintenance Efficiency	%
	maintenance: cost effectiveness	Maintenance Cost (including disassembly, inspection, repairment, replacement, remanufacturing, refurbishment costs)	€
		Spare Parts Procurement Expenses	€
		Strategic Maintenance Investment	€
		Maintenance Cost per Unit Production	€

The CMI set represents a comprehensive pool of relevant CMIs that can be used to assess the circularity and efficiency of maintenance operations across different industries. As companies have varying operational needs, data availability and approaches to measuring performance, the set includes some overlapping or interconnected indicators. This flexibility allows companies to select the most relevant metrics that best reflect their strategic goals and operational context. Businesses must customize the indicator set to match their specific needs and focus areas. Furthermore, too many indicators can harm the effectiveness of a set. 10 to 20 KPIs are sufficient to have a well working indicator set (Parmenter, 2019).

To guide this selection process, companies should use the main categories and the sub categories as a reference to ensure a balanced evaluation across different aspects of performance. As it guarantees an adaptable method, the set of indicators is not a "one-size-fits-all" solution, but instead a tailored framework that aligns with specific industry and company requirements. For instance, a company in the textile production sector might prioritize indicators related to water usage efficiency, resource recovery, and employee safety, as these are critical to addressing their environmental and social impacts. On the other hand, a firm in the heavy machinery manufacturing sector might focus on indicators such as equipment refurbishment rates, downtime costs, and preventive maintenance to ensure operational reliability and efficiency. Therefore, organizations should aim to select at least two to three indicators from each of the four main category. Furthermore, companies are encouraged to choose at least one to two indicators out of each sub category, that best reflect their operational goals and circularity objectives. However, not all sub categories need to be implemented. Companies can omit sub categories that are less important for their operations (e.g., a company might not need indicators in the "Waste Management" sub category if waste is not a significant issue for them).

In general, the selection will ensure that all areas are adequately covered, allowing for a well-rounded performance assessment. The following section shows the circularity rating in form of an illustrative example, which takes place after the selection of the CMIs.

5.1.4 Circularity Rating with the Indicator Set

To measure the circularity level of a maintenance approach, the CMI set is used. The 37 indicators are ideally suited to providing an all-encompassing statement on effectiveness in the environmental, social and economic dimensions, with a particular focus on maintenance, which shows the level of CE oriented maintenance. The following section shows how the five formulas are applied to an example and illustrates how the classification for the degree of circularity works.

Step 1, each CMI is weighted regarding two parameters. One parameter is the IR, described in section 4.3.2, which is based on the importance assessment of the survey participants. The second one is the ranking of the CMIs based on the frequency in the literature review. This score is fixed, regardless of the use case or company. The normalized weighted score can also be described as the maximum possible score of the specific CMI and is calculated by:

$$\text{Weighted Score}_{\text{normalized}_{\text{CMI}}} = \text{IR}_{\text{CMI}} \times \left(\frac{1}{\text{Ranking}_{\text{CMI}}}\right) \times 100$$

Formula 2: Normalized weighted score

For example, the CMI “Environmental Impact” has an IR of 76.32% and a literature ranking of 3:

$$\text{Weighted Score}_{\text{normalized}_{\text{Environmental Impact}}} = 0.7632 \times \left(\frac{1}{3}\right) \times 100 = 25.44$$

Step 2, the achieved score of the CMI is calculated by multiplying the Weighted $\text{Score}_{\text{normalized}}$ by the Fulfillment Rate of the CMI. The Fulfillment Rate needs to be assigned by the user of the circularity level tool. This should be someone who has the expertise and knowledge of maintenance in the company, to be able to provide a realistic value for the fulfillment of the respective CMI. The value is chosen between 0 and 1 in 0.1 increments, where 0 means the indicator is not measured or fulfilled at all and 1 marking the aim of the indicator as completely fulfilled. The Fulfillment Rate is determined by comparing the actual measured value in the company with the corresponding industry standard value, legally required value or internal company target value.

$$\text{Score}_{CMI} = \text{Weighted Score}_{\text{normalized}_{\text{CMI}}} \times \text{Fulfillment Rate}_{CMI}$$

Formula 3: Score of the CMI

For example, the CMI “Environmental Impact” has according to the maintenance expert and the company internal calculation a Fulfillment Rate of 0.7. The score is now calculated by the maximum possible score of “Environmental Impact” times 0.7.

$$\text{Score}_{Environmental\ Impact} = 25.44 \times 0.7 = 17.81$$

Step 3, the total score of the maintenance approach is calculated by summing up all the reached scores of each CMI.

$$\text{Total Score} = \sum \text{Score}_{CMI}$$

Formula 4: Total Score

Step 4, the maximum possible score which could be reached is calculated.

$$\text{Maximum Possible Score} = \sum \text{Weighted Score}_{\text{normalized}_{\text{CMI}}}$$

Formula 5: Maximum Possible Score

Step 5, the total circularity score of the maintenance approach in percentage can be calculated by dividing the total score by the maximum possible score.

$$\text{Grade} = \frac{\text{Total Score}}{Maximum\ Possible\ Score}$$

Formula 6: Total Grade

In the example, the maximum possible score of “Environmental Impact” is 25.44, and the summation after choosing nine additional CMIs is 100. Furthermore, the actually reached and calculated overall total score in the use case is 86. The actual grade is now calculated by dividing 86 with 100 and multiplying it with 100 to get a percentage.

$$\text{Grade} = \frac{86}{100} = 0.86 \times 100 = 86\,\%$$

The calculated overall score of circularity is 86%. Now the grading can be determined. Table 17 shows the grading scheme of the CE oriented maintenance score. This grading scale helps to clearly communicate the effectiveness of a maintenance approach in terms of its contribution to the circular economy, providing actionable insights for improvement. With a scoring of 86%, the maintenance approach is rated regarding the circularity with the grade A, which is the highest rate.

Table 17: Grading scale for the scoring of level of circularity

Grading Scale	
Grade	**Score Range [%]**
A	85-100
B	70-84
C	55-69
D	40-54
E	25-39
F	0-24

The A grade “excellent” indicates that the maintenance approach is highly effective in promoting the CE principles. It represents industry best practices in CE and setting a benchmark for other companies and approaches. The B grade “very good” reflects a strong adherence to the CE principles by representing an advanced practice in CE but can be optimized further. Achieving a C “good” signifies a moderate contribution to the CE. It indicates average efficiency in resource use and sustainability efforts and typically represents common industry practices which have a potential for optimization.

The D grade “fair” suggests limited submission to CE principles and represents basic practices in this area that need significant enhancement. Signs are a suboptimal efficiency in resource efficiency and the applied sustainable elements are not sufficient and the maintenance approach is considered as inefficient and does not help the improvement of circularity now.

Receiving the E grade “poor” reflects minimal contribution to the CE which can be seen regarding poor resource efficiency, ineffective waste management, the practices are unsustainable and likely to have a negative impact on the environment. Companies with outdated practices would fall into this category.

The F grade stands for “failing” and signifies a failure in adhering to any CE principles. It has no impact on it and shows a high inadequate resource use as the practices are highly unsustainable and have a negative impact on the environment. Their practices are even counterproductive and must be completely overhauled to achieve any level of circularity.

Nevertheless, it must be noted at this point that, depending on the application, a poor CE rating is not decisive when it comes to choosing a new maintenance approach Several factors such as external circumstances, the economic situation, know-how and the size of the company can play a role. The whole tool can be found in Appendix F. The following chapters show possible maintenance strategies based on the grading.

5.1.5 Background of the R based Maintenance Strategies

According to the literature research, the application of the 9R's and DIN 17666, different maintenance tasks are defined and presented based on their CE orientation. Figure 37 depicts the individual maintenance actions. They are categorized into the three main groups: System switch, classical maintenance and circular oriented maintenance, and into five smaller subgroups. The position in the graph depends on the complexity of its functional capabilities and the level of circularity. By moving further to the right, the greater the challenge of implementation and the complexity becomes, but the level of circularity increases. It also shows the chronological relationship between current, old and long standing and future maintenance actions.

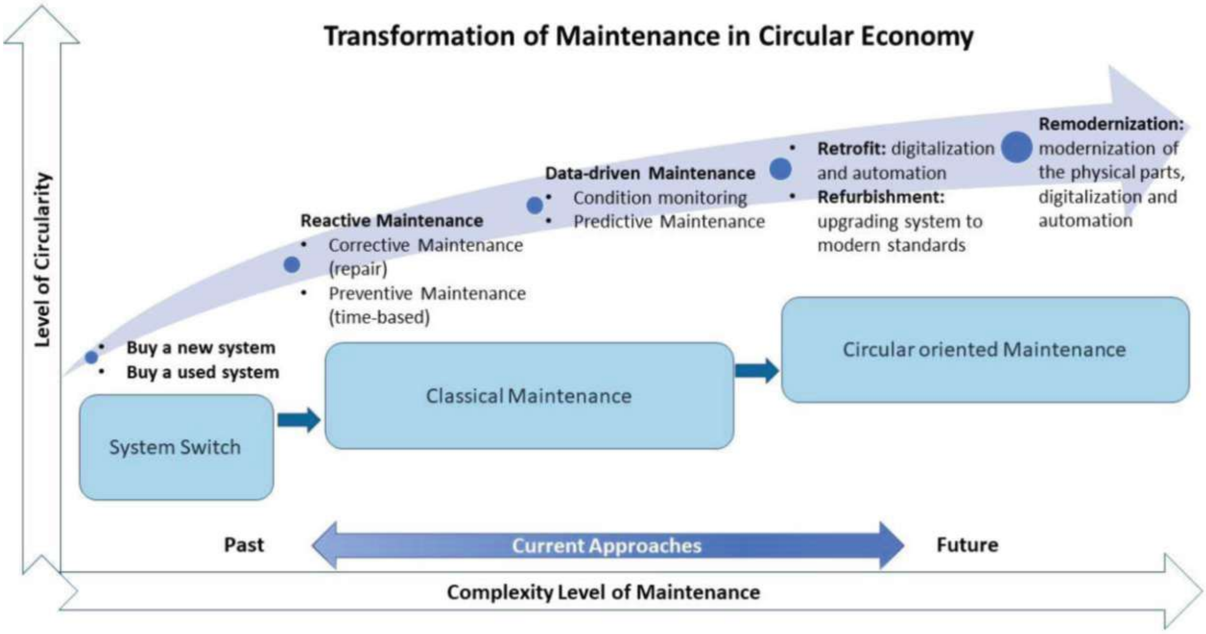


Figure 37: Maintenance actions in the CE

The system switch option suggests replacing the system, with the new system either being used before or coming as a new product from a manufacturer. It is the change of an object where another version replaces the original object without changing the required function or improving the functional reliability of the object and is referred in the norm as a replacement and does not constitute a change (DIN, 2019). It has a low level of maintenance complexity, as it is solely failure oriented. The level of circularity is not given unless the system is second hand and thus fulfills the reuse case.

Classical maintenance strategies can be divided into the two subgroups: Reactive maintenance and data-driven maintenance. Reactive maintenance actions are corrective maintenance (repair after a breakdown) as well as preventive maintenance applications such as condition based and time based maintenance. For these approaches, no life data insight about the system and its environment is needed. On the other hand, data-driven maintenance approaches work with the data to make better predictions and enable a better timing of maintenance measures. Current methods include continuous condition monitoring and predictive maintenance.

CE oriented maintenance describes approaches that have emerged in recent years but will play an increasingly important role in the future. These three actions, retrofitting, refurbishment, and remodernization are therefore discussed in more detail in the following paragraphs.

Retrofit

One of the primary roles of Industry 4.0 applications involves utilizing advanced sensor technology to gather process data efficiently. Comprehensive data collection and analysis serve as the foundation for enhancing performance and efficiency. Among the most economical approaches are retrofitting solutions, which enhance the functionality of current systems and seamlessly integrate them into an Industry 4.0 network. Figure 38 shows the level of retrofitting and the requirements.

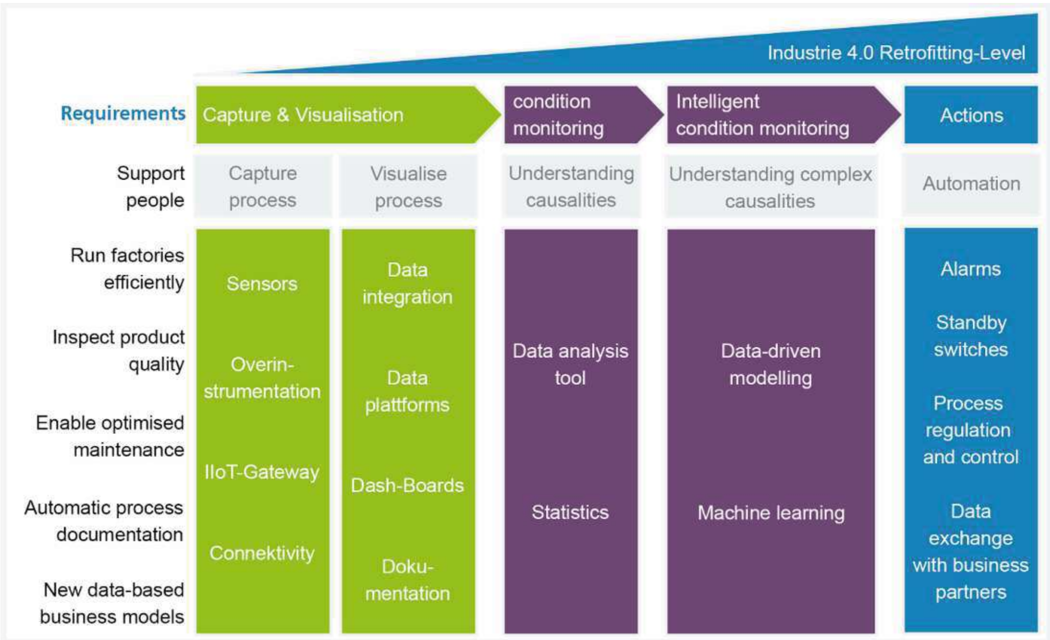


Figure 38: Industry 4.0 retrofit stage model based on Fraunhofer (2022)

In conclusion, retrofitting aligns with the concept of CE with several of the "Rs" principles, primarily reuse, as it involves upgrading or modifying existing products, as well as equipment and their infrastructure. Furthermore, it meets the principles of repairing rather than replacing, as it can be found in the “Rs” of repair and remanufacture. Therefore, it has a higher level of circularity and is associated with higher maintenance complexity and expenditure than the previous maintenance actions.

Refurbishment

Refurbishment involves the renovation or improvement where the general structure of a large multi-component system remains intact. It typically includes repairing any existing damage, replacing worn-out parts, and upgrading components to enhance their functionality, performance, or appearance in order to meet modern standards or specifications. Refurbishment extends the lifespan of assets, reducing the need for new production and minimizing waste. This process aligns with the CE principle of reusing existing resources efficiently and effectively (Reike, Vermeulen, & Witjes, 2018). In conclusion, refurbishment aims to improve the function of the machine and can be seen on the same level of circularity and complexity as retrofit.

Remodernization

Remodernization describes an all-included update and overhaul of a system, combining the modernization of the physical technical parts as well as the digitalization and automation of the whole machine and system. It can be seen as a combination of retrofitting and refurbishment. Thus, it aims to modify and modernize the existing plant to extend the area of application (Brumby, 2023). Therefore, it has a high level of circularity but also a high level of maintenance action complexity due to an all-encompassing overhaul.

The following chapter shows how the right maintenance approach for each use-case can be chosen among others based on the need and level of circularity and with the assist of the CMI set.

5.1.6 Usage of CMI grading for the Circular Maintenance Strategies

Given that the grading (A-F) reflects the overall CE performance of a specific maintenance approach, the following guidelines assist the selection process of the most suitable maintenance strategy based on the obtained grade and is also depicted in Figure 39.

Grade A defines the achievement of an already very sophisticated level of maintenance and circularity. Therefore, the most suitable strategy is remodernization to further extend the systems' lifecycle and improve functionality. In the energy sector, a wind farm operator might remodernize turbines by integrating sensors that monitor wind conditions and blade performance in real-time, further optimizing energy generation and prolonging the lifetime of the turbine blades (Hardie et al., 2024). For assembly processes in a manufacturing system the implementation of AI support industrial robots in the automation of assembly processes. It increases the efficiency, improve precision and reduce waste (Simeth, Kumar, & Plapper, 2022; Weber, 2024).

Grade B systems are recommended to use the strategies of refurbishment or retrofitting. Refurbishment is needed to meet modern standards, just a moderate upgrade is necessary. Retrofitting is as an ideal solution for systems that are already efficient but require integration with modern technologies. A wind farm operator can install wind turbine blades that significantly enhance the efficiency, durability, and environmental compatibility of wind turbines due to their modern material properties (Firoozi, Firoozi, & Hejazi, 2024).

The utilization of condition monitoring and predictive maintenance is the next step for maintenance approaches with a grade C. They already have a moderate circularity and now pursue the aim to improve performance and extend lifespan through data insights. For instance, a manufacturing company producing automotive parts. By implementing condition monitoring systems on critical equipment such as CNC machines, the company can track variables like vibration, temperature, and load. The manufacturer can use the gained data knowledge to perform replacements or recalibrations, which leads to a reduction of resource waste, increase the energy efficiency but also minimize downtime and enhancing the efficiency of maintenance processes (Ahmed Murtaza et al., 2024).

Maintenance activities with grade D involve the classical corrective maintenance and preventive maintenance. It is suitable for systems with low to moderate circularity, where immediate repairs and basic preventive measures are needed to maintain functionality. As most of the maintenance approaches nowadays are in these categories, the aim for firms with that grade should be to get a higher classification and to improve their CE level. Grade E companies are on the same level but focus mainly on the corrective maintenance approaches by acting after a breakdown failure. Therefore, the systems have low circularity, requiring at least fundamental preventive actions to avoid failures. Grade F works with a system switch or component switch after a breakdown. This strategy should ideally be employed least as it is not circularity and inefficient in the long run. It should be noted that, depending on the circumstances, only a specific option may be feasible to implement, and as such, it should not be viewed exclusively as negative.

By linking these grading results to specific maintenance strategies, informed decisions to enhance the circularity and performance of a systems can be made. Each grade provides a direction for selecting the most appropriate strategy, ensuring that maintenance actions align with the overall goals of the CE. Nevertheless, the circularity is not solely dependent on maintenance strategies and the level of circularity can differ by a greater margin with the maturity of maintenance as other important CMIs are involved in the calculation process. Therefore, there is a need for further research between the maturity of maintenance and level of CE of systems.

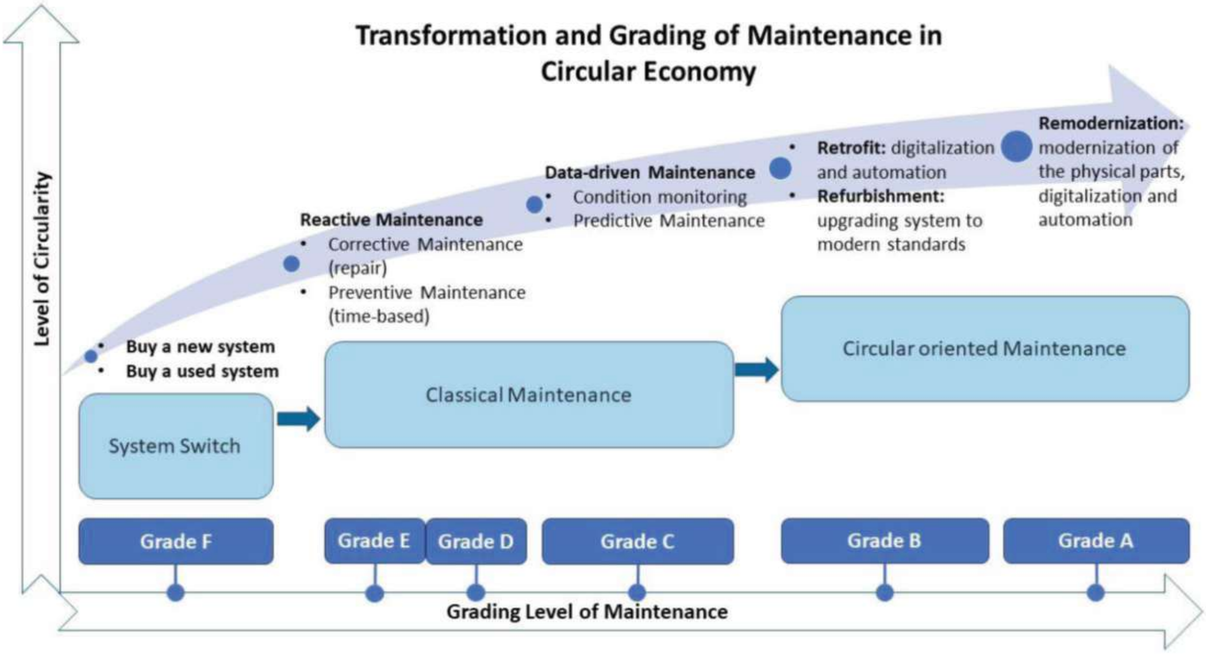


Figure 39: Grading level of the maintenance strategies

5.2 Evaluation of the Indicator Set on Industrial Use Case

In this chapter, the indicator set is applied to an industrial use case, showing the implementation, calculation and grading of circularity with the CMI set.

5.2.1 The company in the Industrial Use Case

This case study examines an international mid-sized company within the textile industry, a leading manufacturer of specialty fibers sourced from sustainable wood resources. The company is focused on producing cellulose-based fibers for various industries, including apparel, home products, medical textiles, and hygiene products. With headquarters in Europe and additional production facilities across Asia, South America, and North America, this organization operates globally and employs over 8,000 individuals, of which approximately 40% work in the headquarters region.

Sustainability and innovation are central to the company's operations, particularly in its commitment to renewable raw materials and environmentally friendly production. This focus includes reducing the environmental impact of textile production through CE technologies, lowering water usage, and cutting CO_2 emissions. Additionally, the company has been recognized with an "A" rating in a global climate change rating index, reflecting its dedication to climate-conscious initiatives.

5.2.2 Application of the Indicator Set on Industrial Use Case

Out of the 37 CMIs in the indicator set, 15 have been chosen as applicable and usable for the company and are adequate to make a conclusion about the circularity. With that, the rule that at least two indicators were chosen from each of the main categories was fulfilled. A barrier was the different complexity level of the indicators. Some indicators, such as "Environmental Impact", are only available for the whole company in the sustainability report of the firm. In contrast, "Refurbished Parts Cost Benefit" are not quantified for all occasions but only for specific use cases. Also, MTBF is analyzed for specific objects in the company, as the MTBF depends on the type of equipment and can't be numbered for all types of equipment in the same way.

The preselection of the 15 indicators and data from annual report and surveys can be seen in Table 18. The orange marked cells describe which indicators are not used for the grading process, as they are either implemented in other indicators or there are after the clarification of the indicator not the precise data from the company available.

Table 18: Indicators for the company with data

Indicator	Data
Environmental Impact	Seen in the annual sustainability report 2023 of the firm. Reduction of CO_2 by 19% from the baseline of 2021.

Energy Consumption Rate	Seen in the annual sustainability report 2023 of the firm. The consumption increases by 10%, however the renewable energy of 100% was achieved.
Employee Satisfaction Index	Based on the safety cross report and anonymous satisfaction survey in the company, 73% of the employees define the company as a "very healthy" or "healthy" work environment.
Workplace Safety and Health Assessment	Total Recordable Injury Frequency Rate (TRIFR) is 0.7 injuries per million hours worked.
Employee Stress Assessment	Now, no data is measured for this indicator. As it is an important indicator, the CMI tool shows where companies still have improvements despite their overall efforts.
Refurbished Parts Cost Benefit	As the manufacturer has its own workshop, all destroyed components and equipment get repaired and remanufactured on-site.
Component Importance Index	The ABC criticality for components is at the moment only implemented in a few departments but should be implemented in companywide.
Parts Delivery Frequency	It is different for every component and equipment, therefore there is no clear data available and an average is not precisely enough for this company.
Preventive Maintenance Activity Index	This indicator is very important but at the moment is only performed in 8% of all maintenance related areas.
Emergency Maintenance Ratio	The emergency maintenance ratio is right now at 15%, with the aim to reduce it to 10%.
Mean Time Between Failure	Depends strongly on the measured object, e.g. pumps in a small facility of the company have an MTBF of 18 months, which are with 3 shifts and every day 13,000 hours.
Overall Equipment Effectiveness	Overall Technical Performance, which includes breakdown und planned maintenance, is right now at 94.77%
Maintenance Cost	A small facility in middle Europe has a spending on maintenance of € 5.7 million. Regarding the total maintenance costs in the company in 2023 was € 177 million in comparison to a total company revenue of € 2.5 billion.
Strategic Maintenance Investment	A small facility in middle Europe has an average spending of € 500,000, which means a share of 8.8 %.
Maintenance Cost per Unit Production	The maintenance cost per ton of material A is € 200. The production cost per ton of material A is € 1,750.

Four indicators are demonstrated below with a detailed calculation approach, including the formulas used and the resulting values. Appendix E shows the formulas for the other indicators and Table 19 includes the remaining indicators and their fulfillment rates. Through these calculations, the grading process and its outcome are explained in greater detail.

Environmental Impact

This indicator measures the reduction in environmental emissions, related to CO_2 emissions, over a fiscal year of the company. The company wants to reduce their emissions regarding their baseline emissions in 2021, which were 200,000 metric tons of CO_2, to become CO_2 neutral by 2035. In the current year 2023, emissions have been reduced to 150,000 metric tons of CO_2. This means, that the "Environmental

Impact" reduction in comparison to the base year is 25%. This is depicted in the grading tool with a fulfillment rate to achieve the goal of rounded 0.3.

$$\text{Environmental Impact} = \frac{Total\ CO_2\ Emissions\ (kg\ CO_2eq.)}{Business\ year}$$

$$\text{Environmental Impact}_{2023} = 150{,}000\ tons\ \ CO_2eq$$
$$\text{Environmental Impact}_{2021\ (base\ year)} = 200{,}000\ tons\ \ CO_2eq$$

$$\text{Fulfillment Rate}_{\text{Environmental Impact}} = \frac{200{,}000 - 150{,}000}{200{,}000} \times 100\% = 25\%$$

Formula 7: Environmental Impact and its fulfillment rate

Workplace Safety and Health Assessment

This indicator is calculated based on the total incidents or hazards reported in a certain time. The company tracks the TRIFR which is calculated based on the total recordable injuries within a set number of hours worked, expressed per one million hours. The TRIFR from 2023 is 0.7 injuries per one million hours worked. With the industrial standards and the internal company regulations saying that a TRIFR below 1 is very good, the fulfillment rate of the manufacturer has the rating 1.

$$\text{Workplace Safety} = \frac{Incidents\ or\ hazards\ reported\ in\ time}{Total\ time\ (hours)} \times 100$$

$$\text{Workplace Safety}_{2023}(TRIFR) = \frac{Total\ Recordable\ Injuries}{Total\ hours\ worked} \times 1{,}000{,}000$$
$$= \frac{7\ injuries}{10{,}000{,}000} \times 1{,}000{,}000 = 0.7$$

$$\text{Fulfillment Rate: Workplace Safety} < 1 = 100\%$$

Formula 8: Workplace Safety and Health Assessment and its fulfillment rate

Refurbished Parts Cost Benefit

As the company has its own workshop, most of the parts can be refurbished on-site. The formula considers both the typical cost of buying new parts and the cost savings associated with in-house refurbishment. New parts cost in average € 100 per part from external suppliers. The refurbishment costs, including labor, materials and overhead costs for producing each part on-site amount to € 40 per part. The quantity of parts refurbished annually is 800. The target of the manufacturer for the cost benefit in 2023 was € 50.000. As the company achieved 96% of its target for this indicator, the CMI is weighted as 1 in the fulfillment rate of the grading tool.

$$\text{Refurbished Parts Cost Benefit} \\ = (Cost\ of\ new\ parts - cost\ of\ refurbished\ parts) \\ \times Number\ of\ refurbished\ parts\ used$$

$$\text{Refurbished Parts Cost Benefit}_{2023} = (100 - 40) \times 800 = 48{,}000\ €$$
$$\text{Plannend Refurbished Parts Cost Benefit}_{2023} = (100 - 40) \times 800 = 50{,}000\ €$$

$$\text{Fulfillment Rate} = \frac{Actual\ Refurbishment\ Costs}{Targeted\ Refurbishment\ Costs} = \frac{48{,}000}{50{,}000} = 0.96$$

Formula 9: Refurbished Parts Cost Benefit and its fulfillment rate

Emergency Maintenance Ratio

This indicator represents the ratio of emergency maintenance hours to total maintenance hours in the company's financial year. The company recorded 1,520 emergency maintenance hours out of a total of 10,000 maintenance hours over the year. With the aim to reduce the ratio of 10% and the actual ratio is at 15.2%, the fulfillment rate, calculated as 66%, can be quantified as 0.7.

$$\text{Emergency Maintenance Ratio} = \frac{Unplannend\ maintenance\ hours}{Total\ maintenance\ hours} \times 100$$

$$\text{Emergency Maintenance Ratio}_{2023} = \frac{1{,}520}{10{,}000} \times 100 = 15.2\%$$

$$\text{Fulfillment Rate} = \frac{10\ \%}{15.2\%} \times 100 = 0.66$$

Formula 10: Emergency Maintenance Ratio and its fulfillment rate

Grading of the company with the CMI grading tool

As with the four exemplary indicators, the other CMIs are calculated based on the company data and compared with the target value of the company or the legal regulations. This then results in the fulfillment rate for each individual indicator, which can be seen in Table 19. After the fulfillment rates are defined, the circularity grading is calculated, cf. chapter 5.2.1.

Every individual indicator has its own weighting score, which is multiplied by the fulfillment rate. For example, the fulfillment rate of the "Environmental Impact" of the company is 0.3 and the weighted score is 25.44, which is multiplied an achieved score of 7.63.

$$\text{Score}_{Environmental\ Impact} = 25.44 \times 0.3 = 7.63$$

The "Workplace Safety and Health Assessment" has a fulfillment rate of 1 and a weighted score of 6.65. Therefore, the achieved score of the CMI is 6.65.

$$\text{Score}_{Workplace\ Safety\ and\ Health\ Assessment} = 6.65 \times 1 = 6.65$$

All the achieved scores of the CMIs are added up together and are compared to the maximum possible score.

$$\text{Total Score} = 7.63 + 10.47 + 1.42 + \cdots + 76.32 + 2.35 + 2.37 = 126$$

$$\text{Maximum Possible Score} = 25.44 + 14.96 + 2.02 + \cdots + 76.32 + 2.35 + 2.63 = 153$$

The company achieved a total score of 126, with the maximum possible score to reach 153.This results in a circularity of 82%, which corresponds to the circularity rating B in this industrial use case.

$$\text{Grade} = \frac{126}{153} = 0.82 \ \times 100 = 82\ \% \ \rightarrow \mathit{Grade\ B}$$

Table 19: Grading of the industrial use case

Main	CMI	Weighted Score - normalized	Fulfillment Rate (0-1)	Achieved Score of the CMI	Maximum Possible Score per CMI	Maximum Possible Score	Total Score	Grade
Environment	Environmental Impact	25.44	0.3	7.63	25.44	153	126	B
	Energy Consumption Rate	14.96	0.7	10.47	14.96			
Social	Employee Satisfaction Index	2.02	0.7	1.42	2.02			
	Workplace Safety and Health Assessment	6.65	1	6.65	6.65			
	Employee Stress Assessment	1.69	0	-	0.00			
Economic	Refurbished Parts Cost Benefit	1.96	1	1.96	1.96			
	Component Importance Index	2.49	0.7	1.75	2.49			
	Parts Delivery Frequency	2.65	0	-	0.00			
Economic-Maintenance related	Preventive Maintenance Activity Index	1.72	0.1	0.17	1.72			
	Emergency Maintenance Ratio	3.44	0.7	2.41	3.44			
	Mean Time Between Failure	4.74	1	4.74	4.74			
	Overall Equipment Effectiveness	8.71	0.9	7.84	8.71			
	Maintenance Cost	76.32	1	76.32	76.32			
	Strategic Maintenance Investment	2.35	1	2.35	2.35			
	Maintenance Cost per Unit Production	2.63	0.9	2.37	2.63			

Analysis and further steps for the company

The B grade "very good" reflects a good adherence to the CE principles by representing an advanced knowledge and implementation of CE that can be optimized further. It acknowledges the endeavor of becoming a sustainable company and shows that they are already investing in CE oriented production. Especially the big CMIs "Environmental Impact" and "Energy Consumption" will remain important targets in the next few years to fulfill the sustainability ambitions. Nevertheless, the maintenance related indicators need to be improved, especially regarding the ability to measure them. "Preventive Maintenance Activity" is declared as a very important indicator, however, there is no data available in most of the facilities. The "Component Importance Index" in the form of an ABC-Analysis is already in use for a few departments but the aim is to have the analysis company wide. The "Emergency Maintenance Ratio" right now is around 15%, however the aim is to reduce it to 10%. In the case of maintenance strategies, remanufacturing and repair in the in-house workshop is already an effective means of always maintaining the availability of machines and equipment. However, there is the need for retrofit as an ideal way for the facilities that are already efficient but require more integration with modern technologies. The digitalization of the processes enables the collection of new data or a better use of available data. In general, the majority of CMIs are in a good shape and can only be challenged by changing the company's sustainability targets.

In summary, the company is already on the right way to becoming a sustainable and CE oriented firm, but improvements still need to be made in various areas to ensure consistent circularity. Restrictions must also be made in the indicator set because the indicators are measured at different hierarchical company levels. Nevertheless, the indicator set assists to get a good overview of progress and further action.

5.3 Summarization of the Key Findings

This chapter explores the use of the CMI set to evaluate circularity in industrial maintenance, covering environmental, social, and economic aspects. Based on industry survey feedback and literature analysis, an initial set of CMIs was refined by applying a 55% importance cut-off, with 37 CMIs left. A major contribution of this thesis lies in the formulation of the grading methodology and the practical validation of this CMI set. The grading tool represents a novel framework that combines weighted scoring, company-specific performance measurement and an adaptable indicator pool to evaluate circularity in maintenance practices systematically. The grading methodology was conceptualized and implemented as follows:

- Each CMI receives a weighted score based on its industry relevance and research frequency.
- An achieved score for each indicator is calculated by multiplying the fulfillment rate, a measure of the company's performance compared to the target, with the weighted score.
- These scores are summed to produce a Total Score, which is compared to the Maximum Possible Score to calculate an overall circularity grade. For example, the circularity rate is 83%, the grade will be B.

The grading tool allows the company to assess its grading of circularity at the moment and can be taken as a guideline for further maintenance measure. By applying the grading tool to a company in the textile industry, the set was tested for its applicability. In the process, 13 CMIs have been chosen out of the indicator pool. The example company achieved a grade of B (82%), indicating a strong commitment to CE but highlighting areas for improvement. It revealed opportunities for digitalization in the company in the case of maintenance approaches and data measurement. Based on this, retrofitting and increased digitalization are recommended as potential subsequent measures to enhance maintenance efficiency and data collection.

The external input in the form of the case study provided insights into real-world constraints and opportunities, ensuring that the tool remains adaptable and applicable. However, the structured approach to linking circularity assessment with actionable maintenance strategies and its grading methodology, weighted scoring system, and conceptual framework were independently designed and implemented. This work bridges the gap between theoretical concepts and practical execution, making the grading tool a valuable instrument for assessing the circularity level and identifying areas for improvement.

6 Conclusion and Outlook

This chapter concludes the findings and limitations of these thesis and gives an outlook on further research and implementation possibilities of the indicator set.

6.1 Conclusion

In accordance with the work at hand's title and the research questions posed, a performance indicator set was created to evaluate CE oriented maintenance. The model is intended as a support for manufacturing companies that have already implemented CE maintenance workflows, but also as a guideline for companies not experienced in CE approaches. The research questions (RQ1-RQ3) from chapter 1.2 are answered based on the findings of this master thesis as follows.

- RQ1: What are the drivers and modes of circularity in maintenance (management) systems?

The drivers for circularity in maintenance include reliability, cost efficiency, safety, regulatory compliance and performance optimization. These drivers shape the strategies within maintenance systems, aiming to reduce costs, extend asset life and improve resource utilization. Modes of circularity are categorized by corrective maintenance, preventive maintenance, and more advanced, data-driven approaches, which leads to further expansion through circularity. For instance, a system switch strategy involves full replacement, enhancing circularity through reusability or second-hand deployment, while remodernization combines retrofitting and refurbishment, targeting high complexity and circularity for extended functional lifespan.

- RQ2: What are significant KPIs of circular oriented maintenance in literature and today's practical industrial applications?

The indicators for CE oriented maintenance were identified through an extensive literature review and corroborated by industry practitioners through a survey. Indicators were selected based on their ability to measure environmental impact, social influence, and economic effectiveness within maintenance operations. This means it includes environmental indicators that measure the emission, pollution and waste, resource consumption, resource recovery and waste management. To identify the social component, employees' health, safety, development and training is defined in form of indicators. The economic component takes a closer look at the production process, readiness for digitalization and supply chain management. The maintenance related indicators focus on maintenance in the form of work identification, planning, scheduling and execution. But also, on lagging indicators with the measurement of equipment and cost effectiveness. These indicators support a standardized assessment of circular practices in industrial maintenance contexts.

- RQ3: How can these KPIs represent a transparent CE oriented maintenance measurement?

Through a structured grading system, which includes weighting indicators based on relevance and importance from the scientific and industrial side and the fulfillment in the use case. In general, the CMI set is used as an indicator pool. CMIs can be easily chosen from the set, which allows the set to be tailored to the specific assessment needs of different companies and their unique use cases. Furthermore, it involves a grading scale from A to F, aligning maintenance strategies with circularity levels, from basic corrective maintenance (Grade F) to advanced remodernization (Grade A). This grading approach allows stakeholders to track improvements and align maintenance actions with CE principles, providing a clear framework for decision-making in maintenance management.

6.2 Limitation of the Research

6.2.1 Limitation of the Indicator Set

While the indicator set developed in this thesis offers a comprehensive framework for assessing various aspects of the daily maintenance operations, several limitations were identified. The primary concern is a relatively high number of indicators, which complicates their practical application in daily decision-making by the maintenance responsibilities. The extensive set of indicators, though valuable in providing detailed insights, may be overwhelming for users, making it difficult to efficiently monitor and manage maintenance activities. To address this, there is a clear need to consolidate these indicators by aggregating similar or related metrics into more comprehensive, higher-level indicators and see the indicator set as a pool of indicators to choose from.

Secondly, while the grading of indicators was rigorously determined based on the calculated importance from both the survey conducted and the literature review, it is important to acknowledge that this grading alone is insufficient to dictate the overall maintenance strategy. The grading provides valuable guidance, but it should be integrated with other contextual factors and expert judgment to decide on an effective maintenance approach. Furthermore, the importance of grading does not reflect the value of each indicator in a company, as there is a need to identify the real value of each indicator with its own specific formula.

Thirdly, the indicator set has different levels of abstractions and therefore information from different company levels is required. The industrial use case with the company showed that an exact description of the use case and what needs to be analyzed is necessary.

6.2.2 Limitations of the Survey

Regarding the survey design, a clearer definition or explanation for some of the indicators is needed in future surveys. It is necessary to revise the survey instructions or to add descriptions to ensure respondents understand what each indicator means.

In addition to the biases presented below, the sample representation in general might be a limitation of the survey. First of all, the representatives are all located in the German speaking part of Europe. In addition, due to the anonymous online questionnaire, it was not completely clear who filled out the questionnaire. In a potential future survey the geographical scope should be more international to find out if there are other opinions to be found in different parts of the expert world.

Another obstacle has been the participation rate, consisting of 39 people. Even though over 400 emails have been sent out, there was only a small number of responses. In future surveys, the direct contact via LinkedIn needs to be enforced even more to get more substantial answers for drawing statistical conclusions.

The following shows and elaborates the already mentioned bias types in detail.

Sample Bias

In this instance, the study encompassed 39 participants, which provides a focused snapshot of opinions and behaviors. This small sample size presents an opportunity to delve deeply into the perspectives of a selected group with the profession in or in relation to maintenance, although it may not capture the full diversity of the broader population. Hernan, Hernandez-Diaz, and Robins (2004) note that a smaller, less representative sample can sometimes lead to conclusions that may not fully reflect the larger population, potentially affecting the external validity of the study. However, these findings still offer valuable insights and a foundation for further research on CE related maintenance attitudes.

Social Desirability Bias

Social desirability bias is especially important when conducting surveys on controversial social topics such as sustainability and environmental responsibility. Participants might choose to give answers they perceive as being more socially acceptable or favorable, rather than their true thoughts and behaviors. Due to growing societal focus on environmental awareness, individuals might exaggerate their dedication to sustainable practices or support green behaviors to seem more responsible. Fisher (1993) examines how social desirability bias can result in exaggeratedly positive answers, distorting the true attitudes and behaviors of the individuals surveyed. However, especially the maintenance CMIs are not solely focused on the environmental but on the economic aspect as well.

Extreme Response Bias

Extreme response bias happens when participants mostly select the extreme options on the Likert scale, like "not important" or "very important," without considering the question's content. This may skew the survey findings by either boosting or reducing the apparent strength of viewpoints. Greenleaf (1992) points out that respondents' inclination to choose extreme options when using a Likert scale could bias the measurement of attitudes, leading to an overemphasized representation of participants' attitudes. Bias in interpreting response scales.

Response Scale Interpretation Bias

Interpretation bias of response scales occurs when respondents interpret the points on a Likert scale in varying ways. Differences in interpretation between participants can result in varying responses, with one person marking "slightly important" while another marks "moderately important." This problem becomes more challenging in surveys that focus on intricate subjects such as CE, as there can be a wide range of personal interpretations and understandings of sustainability-related concepts. Krosnick (1999) states that differences like these can make it difficult to analyze and interpret data, since a single response choice may not have the same significance for every participant.

6.3 Future Work and Adaptions of the Indicator Set

In future works, efforts should be directed toward enhancing and refining the CMI set through targeted research avenues, as outlined in the following paragraphs (F1-F4).

F1: Refinement of Calculation Methods and the Indicator Selection

In future works, efforts should be directed towards refining the calculation methods for each indicator by focusing on the specific formulas used. This will enhance the precision and reliability of the indicator set, allowing for the creation of a more sophisticated grading system. Furthermore, developing an additional layer within the grading system could allow for a more nuanced evaluation, such as incorporating multiple indicators under a broader category like environmental impact. This would provide a more comprehensive assessment and facilitate better-informed decision-making, not only regarding the importance identified through the survey but also based on the concrete number and impact of each indicator in the company. Furthermore, indicators, which are not recognized as important at the moment by the industry, can become an important factor in the future as industry standards develop. Therefore, a revision of the indicator importance should be done every three to five years.

F2: Sector-Specific Adaptation of the Indicator Set

Moreover, it is crucial to tailor the indicator set to the specific needs of different sectors, recognizing that the relevance and importance of certain indicators can vary significantly across industries. To achieve this, future research should consider conducting more extensive surveys and face-to-face interviews with stakeholders from various sectors. This approach will help with capturing sector-specific nuances and ensuring that the indicator set is adaptable and relevant across diverse applications.

F3: Integration with other Measurement Frameworks

Additionally, integrating the indicator set with other measurement frameworks, such as life cycle costing and life cycle assessment could be essential for developing a more holistic decision-making tool. By combining these methodologies, it would be possible to offer a more comprehensive evaluation of maintenance strategies, ultimately leading to more effective and sustainable maintenance decisions.

F4: Development of a Comprehensive Decision-Support Tool

Building on the integrated frameworks in F3, this integrated approach could also serve as the foundation for creating a meaningful suggestion tool, aiding practitioners in selecting the most appropriate maintenance strategy based on a well-rounded analysis that align with CE objectives.

In conclusion, this thesis gives an overview of the current status of maintenance in the CE in the form of an indicator set. It aims to provide an initial assessment and evaluation of the circularity of a maintenance measure and offers a good starting point for further research in the area of CE oriented maintenance.

7 Bibliography

Abdi, A., & Taghipour, S. (2019). Sustainable asset management: A repair-replacement decision model considering environmental impacts, maintenance quality, and risk. *Computers & Industrial Engineering, 136*, 117-134. doi:10.1016/j.cie.2019.07.021

Agustiady, T. K., & Cudney, E. A. (2018). Total productive maintenance. *Total Quality Management & Business Excellence*, 1-8. doi:10.1080/14783363.2018.1438843

Ahmad, S., Wong, K. Y., & Rajoo, S. (2019). Sustainability indicators for manufacturing sectors. *Journal of Manufacturing Technology Management, 30*(2), 312-334. doi:10.1108/jmtm-03-2018-0091

Ahmed Murtaza, A., Saher, A., Hamza Zafar, M., Kumayl Raza Moosavi, S., Faisal Aftab, M., & Sanfilippo, F. (2024). Paradigm shift for predictive maintenance and condition monitoring from Industry 4.0 to Industry 5.0: A systematic review, challenges and case study. *Results in Engineering, 24*. doi:10.1016/j.rineng.2024.102935

Alhaddi, H. (2015). Triple Bottom Line and Sustainability: A Literature Review. *Business and Management Studies, 1*, 6-10.

Ansari, F., Glawar, R., & Nemeth, T. (2019). PriMa: a prescriptive maintenance model for cyber-physical production systems. *International Journal of Computer Integrated Manufacturing, 32*(4-5), 482-503. doi:10.1080/0951192x.2019.1571236

Australia, G. (2024). *Indicator Set*. Retrieved from https://meteor.aihw.gov.au/content/462812

Ayu, K., & Yunusa-Kaltungo, A. (2020). A Holistic Framework for Supporting Maintenance and Asset Management Life Cycle Decisions for Power Systems. *Energies, 13*(8). doi:10.3390/en13081937

Ben-Daya, M., Raouf, S. O. D. A., Knezevic, J., & Ait-Kadi, D. (2009). *Handbook of Maintenance Management and Engineering*.

Bidhan, A. (2010). Questionnaire Design.

Biedermann, H., & Kinz, A. (2019). Lean Smart Maintenance—Value Adding, Flexible, and Intelligent Asset Management. *BHM Berg- und Hüttenmännische Monatshefte, 164*(1), 13-18. doi:10.1007/s00501-018-0805-x

Birtel, F. (2018). *Return on Maintenance – Paradigmenwechsel in der Instandhaltung durch Industrie 4.0*. Retrieved from

Bishop, D. A. (2018a). How to Create “Killer” KPIs. *IEEE Engineering Management Review, 46*(2), 21-23. doi:10.1109/emr.2018.2825431

Bishop, D. A. (2018b). Key Performance Indicators: Ideation to Creation. *IEEE Engineering Management Review, 46*(1), 13-15. doi:10.1109/emr.2018.2810104

Bititci, U. S., Bourne, M., Cross, J. A., Nudurupati, S. S., & Sang, K. (2018). Editorial: Towards a Theoretical Foundation for Performance Measurement and Management. *International Journal of Management Reviews, 20*(3), 653-660. doi:10.1111/ijmr.12185

Bourne, M., Melnyk, S., & Bititci, U. S. (2018). Performance measurement and management: theory and practice. *International Journal of Operations & Production Management, 38*(11), 2010-2021. doi:10.1108/ijopm-11-2018-784

Brumby, L. (2017). Instandhaltung und Asset Management. In *Betriebliche Instandhaltung* (Vol. 2, pp. 67-88).

Brumby, L. (2023). *Keep production in use: Instandhaltung in der Circular Economy*. Paper presented at the 43. VDI-Forum Instandhaltung.

Chan, E. (2014). Building Maintenance Strategy: A Sustainable Refurbishment Perspective. *Universal Journal of Management, 2*(1), 19-25. doi:10.13189/ujm.2014.020103

ClickMaint. (2024). 5 Ways CMMS Software Cuts Maintenance Costs. Retrieved from https://www.clickmaint.com/blog/5-ways-cmms-software-reduces-maintenance-costs

Commission, E. (2019). European Green Deal. Retrieved from https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

Commission, E. (2020). Circular Economy Action Plan. Retrieved from https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

Connolly, L. E., Sheilsa; Martin, Lambb; Alan, O'Connora; Eugene, OBriena; Helen, Vinerb; Helen, Baileyb; Vijay, Ramdasb; Katerina, Varveri. (2023). Circular economy in road construction and maintenance. *Transportation Research Procedia*.

Crespo Marquez, A., Gomez Fernandez, J. F., Martínez-Galán Fernández, P., & Guillen Lopez, A. (2020). Maintenance Management through Intelligent Asset Management Platforms (IAMP). Emerging Factors, Key Impact Areas and Data Models. *Energies, 13*(15). doi:10.3390/en13153762

de Toni, A., & Tonchia, S. (2001). Performance measurement systems - Models, characteristics and measures.

de Wilde, P. (2018). Building Performance Analysis.

DerMietpark. (2024). Vermietung von Baumaschinen. Retrieved from https://dermietpark.at/

Dhillon, B. S. (2002). *Engineering Maintenance - A Modern Approach*.

DIN. (2019). DIN 31051. In.

DIN. (2022). DIN EN 17666. In.

Duffuaa, S. O., & Raouf, A. (2015). *Planning and Control of Maintenance Systems* (2 ed.): Springer Cham.

Eckerson, W. (2012). *Performance Dashboards*.

EEA. (2023). *Trends and projections in Europe 2023*. Retrieved from https://www.eea.europa.eu/publications/trends-and-projections-in-europe-2023

Elkington, J. (1994). Towards the Sustainable Corporation: Win-Win-Win Business Strategies for Sustainable Development. *California Management Review, 36(2)*, 90-100.

Elkington, J. (1997). *Cannibals with forks - The Triple Bottom Line of 21st Century*. Oxford Centre for Innovation: Capstone Publishing Limited.

Firoozi, A. A., Firoozi, A. A., & Hejazi, F. (2024). Innovations in Wind Turbine Blade Engineering: Exploring Materials, Sustainability, and Market Dynamics. *Sustainability, 16*(19). doi:10.3390/su16198564

Fisher, R. J. (1993). Social Desirability Bias and the Validity of Indirect Questioning. *Journal of Consumer Research, 20*(2). doi:10.1086/209351

Fitzgerald, L., Brignall, T. J., Johnston, R., & Silvestro, R. (1991). Performance Measurement in Service Businesses. *Management Accounting, 69*.

Fontana, A., Barni, A., Leone, D., Spirito, M., Tringale, A., Ferraris, M., . . . Goncalves, G. (2021). Circular Economy Strategies for Equipment Lifetime Extension: A Systematic Review. *Sustainability, 13*(3). doi:10.3390/su13031117

Foundation, C. E., & Deloitte. (2024). *The Circularity Gap Report 2024*. Retrieved from https://www.circularity-gap.world/2024#download

Foundation, E. M. (2021). Europe's first circular economy factory for vehicles: Renault. Retrieved from https://www.ellenmacarthurfoundation.org/circular-examples/groupe-renault

Foundation, E. M. (2023). The Circular Economy in Detail. Retrieved from https://www.ellenmacarthurfoundation.org/the-circular-economy-in-detail-deep-dive

Franciosi, C., Voisin, A., Miranda, S., Riemma, S., & Iung, B. (2020). Measuring maintenance impacts on sustainability of manufacturing industries: from a systematic literature review to a framework proposal. *Journal of Cleaner Production, 260*. doi:10.1016/j.jclepro.2020.121065

Fraunhofer, I.-I. (2022). Scalable Industrie 4.0 retrofit solutions. Retrieved from https://www.iosb-ina.fraunhofer.de/en/divisions/Intelligent-sensor-systems/Research-topics-and-projects/scalable-industry-4-0-retrofit-solutions.html

Freund, C. (2010). Die Instandhaltung im Wandel.

Ghaleb, M., & Taghipour, S. (2022). Evidence-based study of the impacts of maintenance practices on asset sustainability. *International Journal of Production Research, 61*(24), 8719-8750. doi:10.1080/00207543.2022.2152893

Gray, D., Micheli, P., & Pavlov, A. (2012). *Measurement Madness*.

Greenleaf, E. (1992). Measuring Extreme Response Style. *Oxford Journals*.

Grüning, P., Banionienè, J., Dagilienè, L., Donadelli, M., Jüppner, M. K., Renatas, & Lessmann, K. (2021). The Quadrilemma of a Small Open Circular Economy Through a Prism of the 9R Strategies.

Gunasekara, H. G., Janaka; Punchihewa, Himan (2020). Remanufacture for sustainability: Barriers and solutions to promote automotive remanufacturing.

Güntner, G., Eckhoff, R., Isopp, J., Loidl, G., & Markus, M. (2014). Bedürfnisse, Anforderungen und Trends in der Instandhaltung 4.0 [Press release]

Hardie, A., Foose, R., Wang, L., Osibogun, R., Bakshi, W., Small, D., & Yuen, R. (2024). How AI can help make Wind Energy a Breeze. *Smith Business Insight*. Retrieved from https://smith.queensu.ca/insight/content/How-AI-Can-Help-Make-Wind-Energy-a-Breeze.php

Heller, T., & Schroll, M. (2021). Vorbeugen statt reparieren - Ein Leitfaden für Smart Maintenance. In *Fallstudien zur Digitalisierung im Mittelstand*.

Hernan, M. A., Hernandez-Diaz, S., & Robins, J. M. (2004). A structural approach to selection bias. *Epidemiology, 15*(5), 615-625. doi:10.1097/01.ede.0000135174.63482.43

Hevner, A. R. (2007). A Three Cycle View of Design Science Research. *Scandinavian Journal of Information Systems, 19*.

Hevner, A. R., Salvatore, T. M., Jinsoo, P., & Sudha, R. (2004). Design Science in Information Systems Research.

IBM. (2024). What is reliability centered maintenance (RCM)? Retrieved from https://www.ibm.com/topics/reliability-centered-maintenance

Ibrahim, Y. M., Hami, N., & Othman, S. N. (2019). Integrating Sustainable Maintenance into Sustainable Manufacturing Practices and Its Relationship with Sustainability Performance: A Conceptual Framework. *International Journal of Energy Economics and Policy, 9*(4), 30-39. doi:10.32479/ijeep.7709

IEA. (2023). Industry Energy Consumption. Retrieved from https://www.iea.org/energy-system/industry

Iivari, J. (2007). A paradigmatic analysis of information systems as a design science.

Ikart, E. M. (2019). Survey Questionnaire Survey Pretesting Method: An Evaluation of Survey Questionnaire via Expert Reviews Technique. *Asian Journal of Social Science Studies, 4*(2). doi:10.20849/ajsss.v4i2.565

Instandhaltung.de. (2024). Instandhaltung nimmt Vorreiterrolle für grüne Industrie seit Jahren ein. Retrieved from https://www.instandhaltung.de/experten/instandhaltung-nimmt-vorreiterrolle-fuer-gruene-industrie-seit-jahren-ein-498.html

Kaplan, R. S., & Norton, D. P. (1992). The Balanced Scorecard—Measures that Drive Performance. *Harvard Business Review*.

Kara, S., Hauschild, M., Sutherland, J., & McAloone, T. (2022). Closed-loop systems to circular economy: A pathway to environmental sustainability? *CIRP Annals, 71*(2), 505-528. doi:10.1016/j.cirp.2022.05.008

Karki, B. R., Basnet, S., Xiang, J., Montoya, J., & Porras, J. (2022). Digital maintenance and the functional blocks for sustainable asset maintenance service – A case study. *Digital Business, 2*(2). doi:10.1016/j.digbus.2022.100025

Keegan, D. P., Eiler, R. G., & Jones, C. R. (1989). Are your performance measures obsolete *Management Accounting, 70*, 45–50.

Khaw-ngern, K., Peuchthonglang, P., & Klomkul, L. K.-n., Chainarong. (2021). The 9Rs Strategies for the Circular Economy 3.0. *PSYCHOLOGY AND EDUCATION (2021), 58(1)*.

Khurram, K. (2011). Understanding performance measurement through the literature. *African Journal of Business Management, 5*(35). doi:10.5897/ajbmx11.020

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling, 127*, 221-232. doi:10.1016/j.resconrec.2017.09.005

Kolar, G., Holly, F., Fließer, N., & Berger, M. (2023). *Zukunft Kreislaufwirtschaft*. Retrieved from

Komatsu. (2024). Remanufactured components. Retrieved from https://www.komatsu.eu/en/genuine-parts/remanufactured-components

Krosnick, J. A. (1999). Survey Research. *Annual Review of Psychology, 50*, 537-567.

Kumar, U., Kumar, U., Galar, D., Parida, A., Stenström, C., & Berges, L. (2013). Maintenance performance metrics: a state-of-the-art review. *Journal of Quality in Maintenance Engineering, 19*(3), 233-277. doi:10.1108/jqme-05-2013-0029

Lenzing. (2022). Linear to circular. Retrieved from https://reports.lenzing.com/nachhaltigkeitsbericht/2021/

Lübke, I. (2024). Maximieren Sie Effizienz und Lebensdauer: Kompressor-Wartung. Retrieved from https://www.industrietechnik-luebke.de/maximieren-sie-effizienz-und-lebensdauer-kompressor-wartung/

Lynch, R. L., & Cross, K. F. (1991). *Measure Up!: Yardsticks for Continuous Improvement*: Blackwell Business.

Mahpour, A. (2023). Building Maintenance Cost Estimation and Circular Economy: The Role of Machine-Learning. *Sustainable Materials and Technologies, 37*. doi:10.1016/j.susmat.2023.e00679

MaintWiz. (2024). The Science of Scheduling: Optimizing Preventive Maintenance for Efficiency. Retrieved from https://www.maintwiz.com/blog/optimizing-preventive-maintenance-scheduling/

Matyas, K. (2018). *Instandhaltungsstrategien* (Vol. 7): Hanser.

McKinsey. (2022). Capturing the true value of Industry 4.0. Retrieved from https://www.mckinsey.com/capabilities/operations/our-insights/capturing-the-true-value-of-industry-four-point-zero

Melnyk, S. A., Bititci, U., Platts, K., Tobias, J., & Andersen, B. (2014). Is performance measurement and management fit for the future? *Management Accounting Research, 25*(2), 173-186. doi:10.1016/j.mar.2013.07.007

Morseletto, P. (2020). Targets for a circular economy. *Resources, Conservation and Recycling, 153*. doi:10.1016/j.resconrec.2019.104553

Muchiri, P., Pintelon, L., Gelders, L., & Martin, H. (2011). Development of maintenance function performance measurement framework and indicators. *International Journal of Production Economics, 131*(1), 295-302. doi:10.1016/j.ijpe.2010.04.039

Naughton, P., & Repko, A. (2023). Theoretical Framework for Circularity in Asset Management.

Neely, A., Kennerley, M., & Adams, C. (2002). *The Performance Prism: The Scorecard for Measuring and Managing Business Success*: Pearson Education.

Neely, A., Kennerley, M., & Adams, C. (2007). Performance measurement frameworks: a review. In *Business Performance Measurement* (pp. 143-162).

Negri, M., Neri, A., Cagno, E., & Monfardini, G. (2021). Circular Economy Performance Measurement in Manufacturing Firms: A Systematic Literature Review with Insights for Small and Medium Enterprises and New Adopters. *Sustainability, 13*(16). doi:10.3390/su13169049

NonStopGroup. (2024). Maintenance Audit | Maximizing Efficiency Beyond Compliance. Retrieved from https://reliability.thenonstopgroup.com/maintenance-audit/

Parida, A., & Chattopadhyay, G. (2007). Development of a multi-criteria hierarchical framework for maintenance performance measurement (MPM). *Journal of Quality in Maintenance Engineering, 13*(3), 241-258. doi:10.1108/13552510710780276

Parmenter, D. (2019). *Key Performance Indicators*.

Pearce, D. W., & Turner, K. R. (1990). *Economics of Natural Resources and the Environment*. Baltimore: The John Hopkins University Press.

Peres, R. S., Jia, X., Lee, J., Sun, K., Colombo, A. W., & Barata, J. (2020). Industrial Artificial Intelligence in Industry 4.0 - Systematic Review, Challenges and Outlook. *IEEE Access, 8*, 220121-220139. doi:10.1109/access.2020.3042874

Pires, S. P., Sénéchal, O., Loures, E. F. R., & Jimenez, J. F. (2016). An approach to the prioritization of sustainable maintenance drivers in the TBL framework. *IFAC-PapersOnline, 49-28*, 150-155.

PNNL. (2022). An Advanced Maintenance Approach: Reliability Centered Maintenance. Retrieved from https://www.pnnl.gov/projects/om-best-practices/advanced-maintenance-approach-reliability-centered-maintenance

PWC. (2024). Sicherheit & Compliance von Prozessen. Retrieved from https://www.pwc.de/de/strategie-organisation-prozesse-systeme/sicherheit-und-compliance-von-prozessen.html

Raworth, K. (2017). *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist*: Chelsea Green Publishing.

Raworth, K. (2024). What on Earth is the Doughnut? Retrieved from https://www.kateraworth.com/doughnut/

Reike, D., Vermeulen, W. J. V., & Witjes, S. (2018). The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. *Resources, Conservation and Recycling, 135*, 246-264. doi:10.1016/j.resconrec.2017.08.027

Rockwell, A. (2024). Reliability centered maintenance (RCM). Retrieved from https://fiixsoftware.com/maintenance-strategies/reliability-centered-maintenance/

Samadhiya, A., Agrawal, R., Kumar, A., & Garza-Reyes, J. A. (2023). Blockchain technology and circular economy in the environment of total productive maintenance: a natural resource-based view perspective. *Journal of Manufacturing Technology Management, 34*(2), 293-314. doi:10.1108/jmtm-08-2022-0299

Schang, L., Blotenberg, I., & Boywitt, D. (2021). What makes a good quality indicator set? A systematic review of criteria. *Int J Qual Health Care, 33*(3). doi:10.1093/intqhc/mzab107

Schenk, M. (2009). *Instandhaltung technischer Systeme*.

Sensemore. (2024). Asset Management in Maintenance: Maximizing Efficiency. Retrieved from https://sensemore.io/asset-management-in-maintenance-maximizing-efficiency/

Shaheen, B. W., & Németh, I. (2022). Integration of Maintenance Management System Functions with Industry 4.0 Technologies and Features—A Review. *Processes, 10*(11). doi:10.3390/pr10112173

Sidahmed Alamin, K. S., Chen, Y., Gaiardelli, S., Spellini, S., Calimera, A., Beghi, A., . . . Vinco, S. (2022). *SMART-IC: Smart Monitoring and Production Optimization for Zero-waste Semiconductor Manufacturing*. Paper presented at the 2022 IEEE 23rd Latin American Test Symposium (LATS).

Simeth, A., Kumar, A. A., & Plapper, P. (2022). Using Artificial Intelligence to Facilitate Assembly Automation in High-Mix Low-Volume Production Scenario. *Procedia CIRP, 107*, 1029-1034. doi:10.1016/j.procir.2022.05.103

SKF. (2020). Industrial bearing remanufacturing and the circular economy. Retrieved from https://evolution.skf.com/industrial-bearing-remanufacturing-and-the-circular-economy/#

Sobral, J., & Ferreira, L. (2018). The Importance of Reliability and Maintenance for the Circular Economy from Consumers to Users.

Striteska, M., & Spickova, M. (2012). Review and Comparison of Performance Measurement Systems. *The Journal of Organizational Management Studies*, 1-13. doi:10.5171/2012.114900

Su, R.-H., Weng, M.-W., Yang, C.-T., & Hsu, C.-H. (2023). Optimal Circular Economy and Process Maintenance Strategies for an Imperfect Production–Inventory Model with Scrap Returns. *Mathematics, 11*(14). doi:10.3390/math11143041

Surajit, B. T., A. (2018). Business Logistics Optimization Using Industry 4.0: Current Status and Opportunities.

Takata, S. (2013). Maintenance-centered Circular Manufacturing. *Procedia CIRP, 11*, 23-31. doi:10.1016/j.procir.2013.07.066

Turner, C., Okorie, O., Emmanoulidis, C., & Oyekan, J. (2020). A Digital Maintenance Practice Framework for Circular Production of Automotive Parts.

UN. (2015). Sustainable Development Goals. Retrieved from https://sdgs.un.org/goals

Velenturf, A. P. M., & Purnell, P. (2021). Principles for a sustainable circular economy. *Sustainable Production and Consumption, 27*, 1437-1457. doi:10.1016/j.spc.2021.02.018

Venable, J., Pries-Heje, J., & Baskerville, R. (2017). FEDS: a Framework for Evaluation in Design Science Research. *European Journal of Information Systems, 25*(1), 77-89. doi:10.1057/ejis.2014.36

Weber, A. (2024). The Growing Role of AI in Automotive Assembly. *Assembly Magazine*. Retrieved from https://www.assemblymag.com/articles/98295-the-growing-role-of-ai-in-automotive-assembly

WestFA, F. (2024). Keine Kompromisse bei Qualität und Sicherheit – von Anfang an. Retrieved from https://www.westfa-fluessiggas.de/sicherheit/wartung-pruefung.html

Wienerberger. (2024). Kreislaufwirtschaft bei Wienerberger. Retrieved from https://www.wienerberger.at/nachhaltigkeit/kreislaufwirtschaft.html

Wittmann, F. M. (2017). Sort Google Scholar. Retrieved from https://github.com/WittmannF/sort-google-scholar

Zonta, T., da Costa, C. A., da Rosa Righi, R., de Lima, M. J., da Trindade, E. S., & Li, G. P. (2020). Predictive maintenance in the Industry 4.0: A systematic literature review. *Computers & Industrial Engineering, 150*. doi:10.1016/j.cie.2020.106889

8 Appendix

Appendix A: 104 pre-selected indicators

104 Indicators Part 1/2

			Categories			directly related	can be related	
Rank	KPI Name	Sum	Social	Environment	Economic	Main Dimension	Sub Dimension	Maintenance Dimension
1	Maintenance Cost	27				Economic	Maintenance	maintenance cost
2	Remaining Useful Life	25				Economic	Maintenance	equipment effectiveness
3	Co2 Emissions	24				Environment	emission	
4	Energy Consumption	18				Environment	resource consumption	
5	Level Of System Intelligence	17				Economic	production process	
6	Downtime	15				Economic	maintenance	equipment effectiveness
7	Maintenance Time	14				Economic	maintenance	work planning and scheduling
8	Failure Rate Of Components	14				Economic	production process	
9	Repairment Cost	9				Economic	maintenance	maintenance cost
10	Cost Of Spare Parts	9				Economic	maintenance	maintenance cost
11	Skill Of Workforce	9				Social	employee development and training	
12	Repairment Rate	8				Economic	maintenance	work execution
13	Availability Of Spare Parts	7				Economic	production process	
14	Mean Time Between Failure	7				Economic	production process	
15	Reliability	7				Economic	production process	
16	Disassembly Time	6				Economic	maintenance	work execution
17	Availability Rate	6				Economic	production process	
18	Remanufacturing Cost	6				Economic	maintenance	maintenance cost
19	Disposal Cost	6				Environment	waste management	
20	Safety And Health For Employees	6				Social	Occupational Health and Safety	
21	Environmental Impact	6				Environment	emission, pollution and waste	
22	Maintenance Scheduling	6				Economic	maintenance	work planning and scheduling
23	Level Of Knowledge	5				Economic	production process	
24	Overall Equipment Effectiveness	5				Economic	maintenance	equipment effectiveness
25	Mean Time To Failure	5				Economic	maintenance	equipment effectiveness
26	Mean Time To Repair	5				Economic	maintenance	equipment effectiveness
27	Volume Of Waste	5				Environment	waste management	
28	Quality Of End Products	4				Economic	production process	
29	Disassembly Cost	4				Economic	maintenance	work execution
30	Lifespan Extension	4				Economic	maintenance	equipment effectiveness
31	Material Consumption	4				Environment	resource consumption	
32	Number Of Maintenance Action	4				Economic	maintenance	work execution
33	Cost Of Supplying	4				Economic	production process	
34	Availability Of Resources	3				Economic	maintenance	equipment effectiveness
35	Average Lifetime Of A Product	3				Economic	maintenance	equipment effectiveness
36	Assembly Time	3				Economic	maintenance	work execution
37	Human Harmness Potential	3				Social	Occupational Health and Safety	
38	Production Cost	3				Economic	production process	
39	Cost Of Tools	3				Economic	production process	
40	Process Efficiency	3				Economic	production process	
41	Number Of Employees	3				Social	human resources	
42	Remanufacturing Time	3				Economic	maintenance	work execution
43	Labor Productivity	3				Social	employee development and training	
44	Net Present Value	3				Economic	production process	
45	Labor Cost	3				Economic	human resources	
46	Reusability	3				Environment	resource consumption	
47	Maintenance Investment Cost	3				Economic	maintenance	maintenance cost effectiveness
48	Backorder Cost Rate	2				Economic	production process	
49	Resource Efficiency	2				Environment	resource consumption, efficiency	
50	Inspection Time	2				Economic	maintenance	work execution

104 Indicators Part 2/2

51	Inspection Cost	2				Economic	maintenance	work execution
52	Number Of Inspections	2				Economic	maintenance	work execution
53	Repairment Time	2				Economic	maintenance	work execution
54	Replacement Rate	2				Economic	maintenance	work execution
55	Replacement Cost	2				Economic	maintenance	work execution
56	Warranty Period	2				Social	customer	
57	Recyclability	2				Environment	ressource consumption, recycling	
58	Upgradeability	2				Economic	production process	
59	Level Of (Preventive) Maintenance Effort	2				Economic	maintenance	work identification
60	Spare Part Usage Rate	2				Environment	resource consumption	
61	Recovery Delay Time	2				Economic	maintenance	work planning and scheduling
62	Availability Of Tools	1				Economic	production process	
63	Cost Saving Of Refurbished Parts	1				Economic	production process	
64	Downtime Cost	1				Economic	maintenance	equipment effectiveness
65	Repair Efficiency	1				Economic	maintenance	work execution
66	Maintenance Efficiency	1				Economic	maintenance	equipment effectiveness
67	Stress Level For Employees	1				Social	occupational health and safety	
68	Material Energy	1				Environment	resource consumption	
69	Process Energy	1				Environment	resource consumption	
70	Impact On Production	1				Social	human resources	
71	Remaining Sustainable Life	1				Economic	maintenance	equipment effectiveness
72	Repairment Time	1				Economic	maintenance	work execution
73	Replacement Time	1				Economic	maintenance	work execution
74	Refurbishment Rate	1				Economic	resource recovery	
75	Refurbishment Cost	1				Economic	resource recovery	
76	Net Recoverable Value	1				Environment	waste management	
77	Mean Measurement Time	1				Economic	maintenance	work execution
78	Warranty Cost	1				Social	customer	
79	Quality Of Component	1				Economic	production process	
80	Remanufacturing Readiness Level	1				Economic	production process	
81	Shop Floor Space	1				Economic	production process	
82	Life Cycle Impact Assessment	1				Environment	resource consumption	
83	Workforce Satisfaction	1				Social	human resources	
84	Maintenance Budget	1				Economic	maintenance	maintenance cost effectiveness
85	Maintenance Related Risk	1				Economic	maintenance	work identification
86	Virtual Remaining Life	1				Economic	maintenance	equipment effectiveness
87	Production Lossesby Maintenance Actions	1				Economic	maintenance	maintenance cost effectiveness
88	Maintenance Cost Per Unit Production	1				Economic	maintenance	maintenance cost effectiveness
89	Maintenance Schedule Compliance	1				Economic	maintenance	work execution
90	Maintenance Backlog	1				Economic	maintenance	work execution
91	Percentage Emergency Work	1				Economic	maintenance	equipment effectiveness
92	Relative Functional Importance	1				Economic	production process	
93	Resource Consumption	1				Environment	resource consumption	
94	Feasibility of Repair Using New Spare Parts	1				Economic	maintenance	cost effectiveness
95	Remaining Energy-Efficient Lifetime	1				Economic	maintenance	equipment effectiveness
96	So2 Emissions	1				Environment	emission	
97	Expected Service Life Cycles For Component	1				Economic	maintenance	work planning and scheduling
98	Size Of Maintenance Team	1				Social	human resources	
99	Internal Stock Of Refurbished Parts	1				Economic	Supply and Distribution	
100	Resource Recovery Rate	1				Environment	resource consumption	
101	Mean Arrival Rate Of Spare Parts	1				Economic	Supply and Distribution	
102	Mean Dispose Process	1				Environment	waste management	
103	Work Order Compliance	1				Economic	maintenance	work identification
104	Overtime Hours	1				Social	human resources	

Appendix B: Questionnaire

Survey to Circular oriented Maintenance Indicators

Dear participant,

This survey is part of the master thesis at TU Wien focusing on research on Circular Economy oriented Maintenance Indicators (CMIs).

In the following survey I ask you to evaluate the importance of the pre-selected indicators. Please give your professional and honest opinion. There are no right or wrong answers. Your ratings will help to understand the relative importance of each indicator from the perspective of maintenance in the industry.

This survey takes about **8 minutes** to complete. The questionnaire works best when completed on a laptop. If you are using a phone and have difficulty seeing all possible answers, please turn the phone sideways.

The deadline for the survey is **June 21, 2024**.

If you have any questions or need further information, please do not hesitate to contact via email: **philipp.stricker@tuwien.ac.at**.

The structure of the survey is as follows

1. general question about your company and your maintenance approaches
2. questions on the evaluation of the pre-selected performance indicators
3. personal information and e-mail

1. Your **responses** are completely **confidential** and will only be used for the **research purposes** of this thesis. *

   Markieren Sie nur ein Oval.

   ◯ I agree with the general data protection regulation and would like to take part in the survey

1. General Information regarding your company (Section 1/3)

2. Please specify the (main) sector of your company. *
Multiple answers possible:

Wählen Sie alle zutreffenden Antworten aus.

- ☐ a) Agriculture, Forestry and Fishing
- ☐ b) Mining and Quarrying
- ☐ c) Manufacturing
- ☐ d) Electricity, Gas, Steam and Air Conditioning Supply
- ☐ e) Water Supply; Sewerage, Waste Management and Remediation Activities
- ☐ f) Construction
- ☐ g) Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles
- ☐ h) Transportation and Storage
- ☐ i) Information and Communication
- ☐ j) Financial and Insurance Activities
- ☐ k) Professional, Scientific and Technical Activities
- ☐ l) Other Service Activities
- ☐ Sonstiges: ______________________

3. What type of business relationship does your company pursue? *
Multiple answers possible:

Wählen Sie alle zutreffenden Antworten aus.

- ☐ a) Business to Business (B2B)
- ☐ b) Business to Consumer (B2C)
- ☐ c) Business to Public Administration (B2PA)
- ☐ Sonstiges: ______________________

4. Please provide the total number of employees in full-time equivalents (Vollzeitäquivalent) in your company. *

Markieren Sie nur ein Oval.

- a) Micro-enterprises (up to 9 employees)
- b) Small enterprises (up to 49 employees)
- c) Medium-sized enterprises (up to 249 employees)
- d) Large enterprises (250 employees or more)

5. What percentage of your employees work in maintenance or carry out maintenance-related activities? *
Percentage [%]:

6. What type of maintenance concept does your company primarily follow? (e.g., preventive maintenance, predictive maintenance, corrective maintenance) *
Multiple answers possible:

Wählen Sie alle zutreffenden Antworten aus.

- a) Corrective Maintenance (Reactively addressing equipment failures after they occur-repairing or replacing equipment only when it breaks down)
- b) Preventive Maintenance (Scheduled maintenance activities performed at regular intervals to prevent equipment failures before they occur
- c) Condition-Based Maintenance (Monitoring equipment in real-time to detect signs of deterioration or malfunction)
- d) Predictive Maintenance (Monitoring equipment condition and performance to predict when maintenance is needed)

7. How are maintenance services **mainly** carried out in your company? *
Multiple answers possible:

Markieren Sie nur ein Oval.

- a) On premise (your company has a maintenance team within your facility)
- b) Outsourced (your maintenance tasks are outsourced to third-party service providers who specialize in maintenance services)

8. To what extent is your company familiar with the concept of the circular economy? *

Markieren Sie nur ein Oval.

- a) The company and its employees are not familiar with the concept of the circular economy.
- b) Top management and/or experts are familiar with the concept of the circular economy.
- c) The management and/or experts and some managers in the company know and understand the concept of the circular economy.
- d) There is company-wide knowledge of the concept of the circular economy.
- e) The concept of the circular economy is part of the corporate culture and is constantly updated and improved.

9. To what extent is the circular economy anchored in your corporate strategy? *

Markieren Sie nur ein Oval.

- a) The circular economy is not part of the corporate strategy.
- b) Circular economy has influenced a single project within the organization.
- c) Circular economy has influenced several projects within the organization.
- d) Circular economy is part of project and process management.
- e) The circular economy is part of the corporate vision.

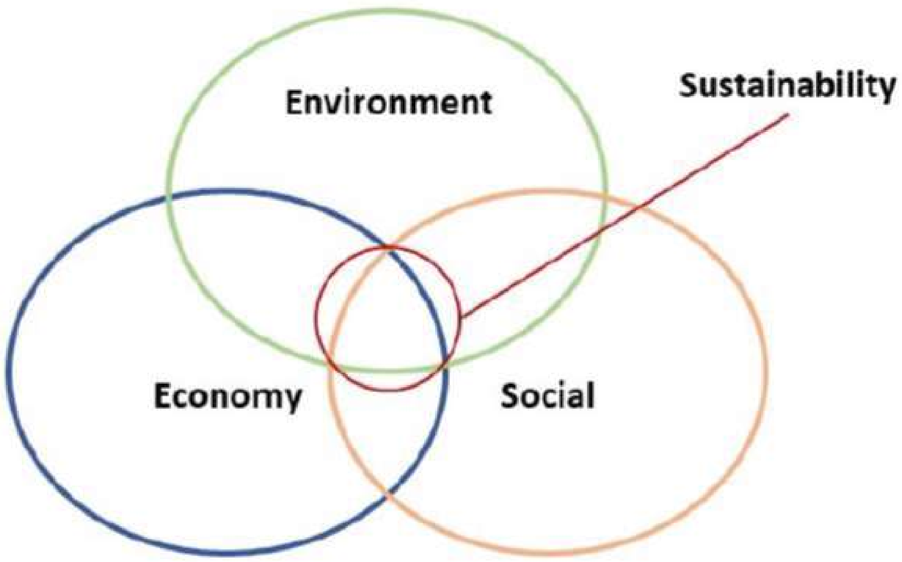
10. How would you rate the influence of maintenance on the circular economy on a scale from 1 (no influence) to 7 (very strong influence)? *

Markieren Sie nur ein Oval.

	1	2	3	4	5	6	7	
no ir	◯	◯	◯	◯	◯	◯	◯	very strong influence

2. Rating of the preselected Circular Economy oriented Maintenance Indicators (CMIs) (Section 2/3)

General information on the various indicator categories:
One of the most renowned sustainability frameworks is the so-called "triple bottom line". It divides sustainability into three dimensions that are interrelated: Environmental, Social and Economic (see graphic).
Examples:
- Environmental: resource consumption, emissions and pollution, waste management
- Social: aspects of human resources and occupational safety
- Economic: key financial figures of the company and the production process



2.0 Circular oriented maintenance dimensions

How important is the following CMI dimension from your professional standpoint of maintenance?

11. CMI-Dimension *

Markieren Sie nur ein Oval pro Zeile.

	Not important	Slightly important	Moderately important	Important	Very Important
Environment	◯	◯	◯	◯	◯
Social	◯	◯	◯	◯	◯
Economic	◯	◯	◯	◯	◯

11. CMI-Dimension *

Markieren Sie nur ein Oval pro Zeile.

	Not important	Slightly important	Moderately important	Important	Very Important
Environment	⬭	⬭	⬭	⬭	⬭
Social	⬭	⬭	⬭	⬭	⬭
Economic	⬭	⬭	⬭	⬭	⬭

12. Environmental CMIs *

Markieren Sie nur ein Oval pro Zeile.

	Not important	Slightly important	Moderately important	Important	Very important	Unknown
Environmental impact (CO_2 eq.)	⬭	⬭	⬭	⬭	⬭	⬭
Energy Consumption Rate (kWh)	⬭	⬭	⬭	⬭	⬭	⬭
Material Consumption Rate (kg)	⬭	⬭	⬭	⬭	⬭	⬭
Resource Utilization Efficiency (%)	⬭	⬭	⬭	⬭	⬭	⬭
Product Reuse Potential (%)	⬭	⬭	⬭	⬭	⬭	⬭
Resource Recovery Rate (%)	⬭	⬭	⬭	⬭	⬭	⬭
Net Waste Management Cost (€)	⬭	⬭	⬭	⬭	⬭	⬭
Waste Management Efficiency (%)	⬭	⬭	⬭	⬭	⬭	⬭

2.2 Social CMIs

How important is the following circular oriented maintenance indicator (CMI) from your professional standpoint in the industry?

13. Social CMIs *

Markieren Sie nur ein Oval pro Zeile.

	Not important	Slightly important	Moderately important	Important	Very important	Unknown
Employee Skill Proficiency (Scale)	◯	◯	◯	◯	◯	◯
Workforce Efficiency Ratio (%)	◯	◯	◯	◯	◯	◯
Employee Satisfaction Index (Scale)	◯	◯	◯	◯	◯	◯
Workforce Allocation for Maintenance (integer)	◯	◯	◯	◯	◯	◯
Overtime Workload (h)	◯	◯	◯	◯	◯	◯
Workplace Safety and Health Assessment (Scale)	◯	◯	◯	◯	◯	◯
Employee Stress Assessment (Scale)	◯	◯	◯	◯	◯	◯

2.3 Economic CMIs

How important is the following circular oriented maintenance indicator (CMI) from your professional standpoint in the industry?

14. Economic CMIs *

Markieren Sie nur ein Oval pro Zeile.

	Not important	Slightly important	Moderately important	Important	Very important	Unknown
System Knowledge and Intelligence Level (Scale)	⬭	⬭	⬭	⬭	⬭	⬭
Manufacturing Efficiency Index (%)	⬭	⬭	⬭	⬭	⬭	⬭
Net Present Value (€)	⬭	⬭	⬭	⬭	⬭	⬭
Readiness for System Evolution and Upgradeability (%)	⬭	⬭	⬭	⬭	⬭	⬭
Refurbished Parts Cost Benefit (€)	⬭	⬭	⬭	⬭	⬭	⬭
Component Importance Index (%)	⬭	⬭	⬭	⬭	⬭	⬭
Supply Chain Expenses (€)	⬭	⬭	⬭	⬭	⬭	⬭
Parts Delivery Frequency (h)	⬭	⬭	⬭	⬭	⬭	⬭

2.3 Economic CMIs - Focus Maintenance

How important is the following circular oriented maintenance indicator (CMI) from your professional standpoint in the indusry?

15. Economic CMIs - Focus Maintenance *

Markieren Sie nur ein Oval pro Zeile.

	Not important	Slightly important	Moderately important	Important	Very important	Unknown
Preventive Maintenance Intensity Index (%)	○	○	○	○	○	○
Work Order Compliance Rate (%)	○	○	○	○	○	○
Maintenance Time (incl. assembly, disassembly, inspection, measurement repairment, refurbishment, remanufacturing, replacement) (h)	○	○	○	○	○	○
Scheduled Maintenance Compliance (%)	○	○	○	○	○	○
Recovery Delay Time (h)	○	○	○	○	○	○
Emergency Maintenance Ratio (%)	○	○	○	○	○	○
Expected Service Life Cycles (integer)	○	○	○	○	○	○
Mean Time to Repair (h)	○	○	○	○	○	○

Inspection Frequency (%)						
Component Replacement and Refurbishment Rate (%)						
Maintenance Backlog (integer)						
Remaining Useful Life (h)						
Downtime (plannend and unplanned (h)						
Mean Time Between Failure (h)						
Reliability Rate (%)						
Overall Equipment Effectiveness (%)						
Downtime Cost (€)						
Maintenance Efficiency (%)						
Maintenance Cost (incl. disassembly, inspection, repairment,						

replacement, remanufacturing, refurbishment costs) (€)						
Spare Parts Procurement Expenses (€)	◯	◯	◯	◯	◯	◯
Strategic Maintenance Investment (€)	◯	◯	◯	◯	◯	◯
Maintenance Budget (€)	◯	◯	◯	◯	◯	◯
Maintenance cost per unit production (€)	◯	◯	◯	◯	◯	◯
Spare Parts Repair Viability Assessment (€)	◯	◯	◯	◯	◯	◯
Maintenance Risk Assessment (integer)	◯	◯	◯	◯	◯	◯

3. Personal Informationen and further contact (Section 3/3)

16. Are you currently working in a maintenance related job? *

Markieren Sie nur ein Oval.

- ◯ Yes, I am currently working in a maintenance related job *Fahren Sie mit Frage 17 fort*
- ◯ Yes, I have worked in the maintenance related job *Fahren Sie mit Frage 18 fort*
- ◯ No, but I still have expert knowledge in the maintenance field *Fahren Sie mit Frage 19 fort*
- ◯ No *Fahren Sie mit Frage 20 fort*

17. Please describe your current role/field at your company *

Fahren Sie mit Frage 20 fort

18. Please describe your last role/position in your company in which you came into contact with the topic of maintenance *

Fahren Sie mit Frage 20 fort

19. Please describe your role/position in your company where you gained your expertise in the field of maintenance *

Fahren Sie mit Frage 20 fort

Further information and contact

If you fill out this questionnaire and enter your e-mail address at the end, I will be happy to share the results of my research with you or possibly contact you for a follow-up interview

20. **OPTIONAL:** Please enter the name of the company you work for:

21. **OPTIONAL:** If you are interested in receiving either the results of this survey or the final Master's thesis and possibly being available for a follow-up interview, please enter your e-mail address here.

22. What would you like to receive?

Wählen Sie alle zutreffenden Antworten aus.

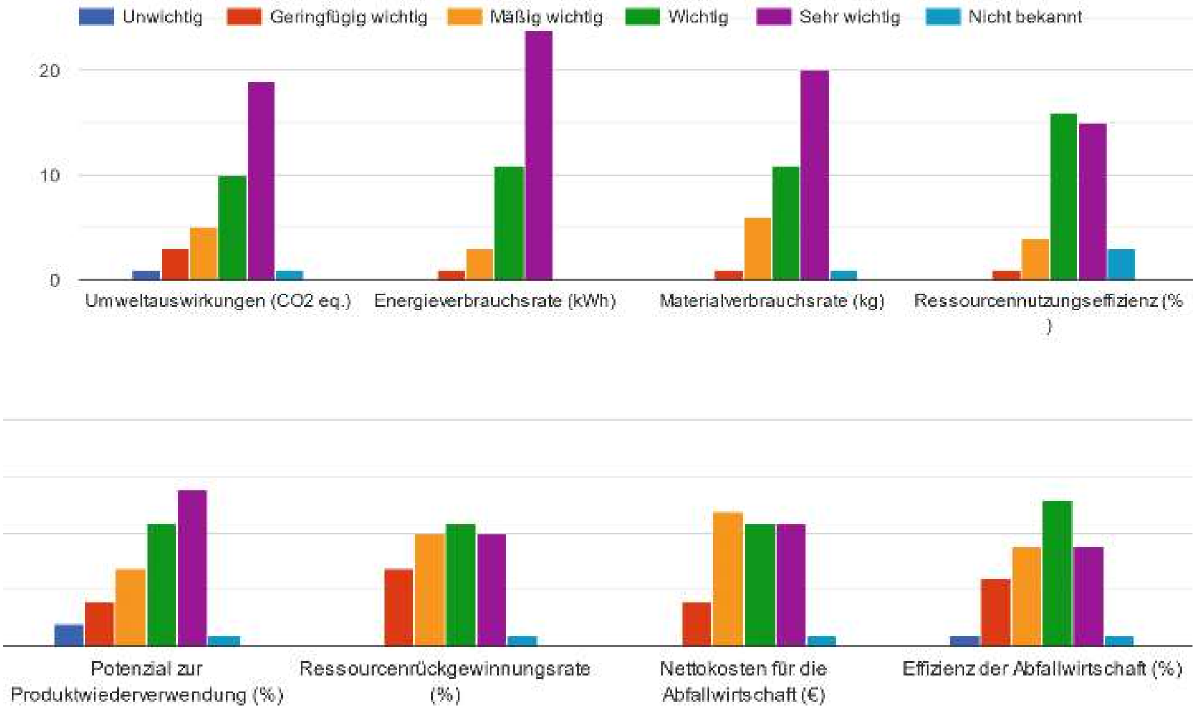
- [ ] Follow-up interview
- [ ] Results of this study
- [ ] The final work
- [ ] Nothing

Thank you very much for your participation! Your expertise is crucial for the success of my research and is a valuable contribution to my Master's thesis!

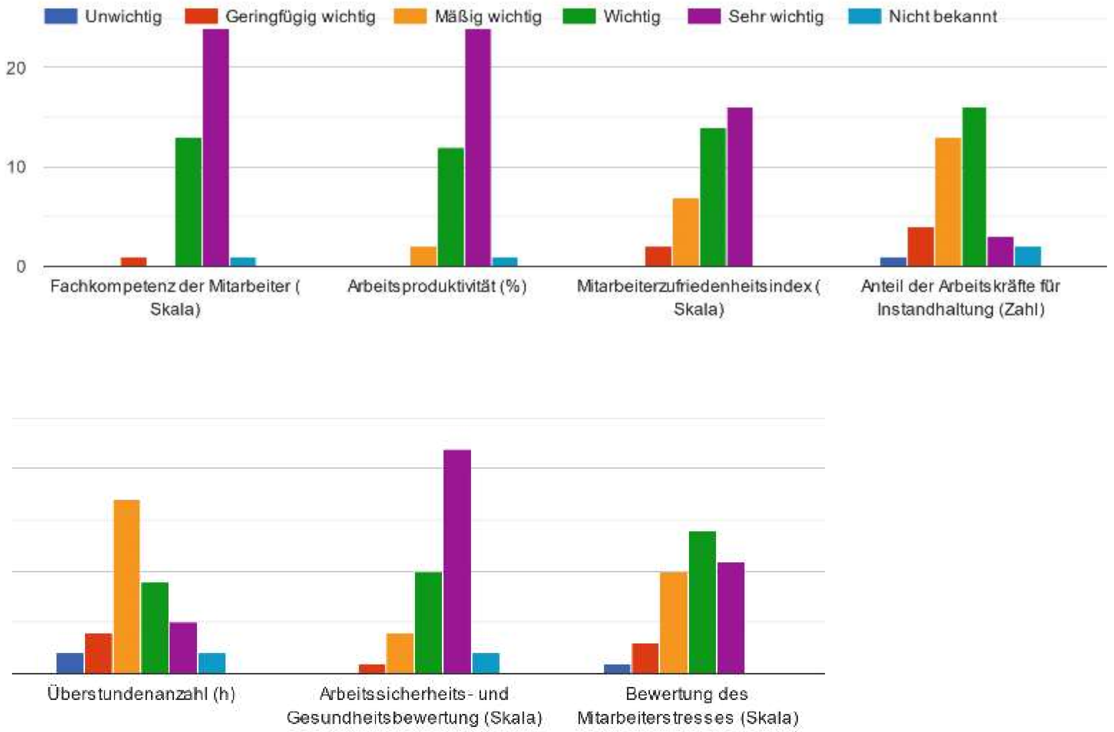
Please click on the senden button to complete the survey.

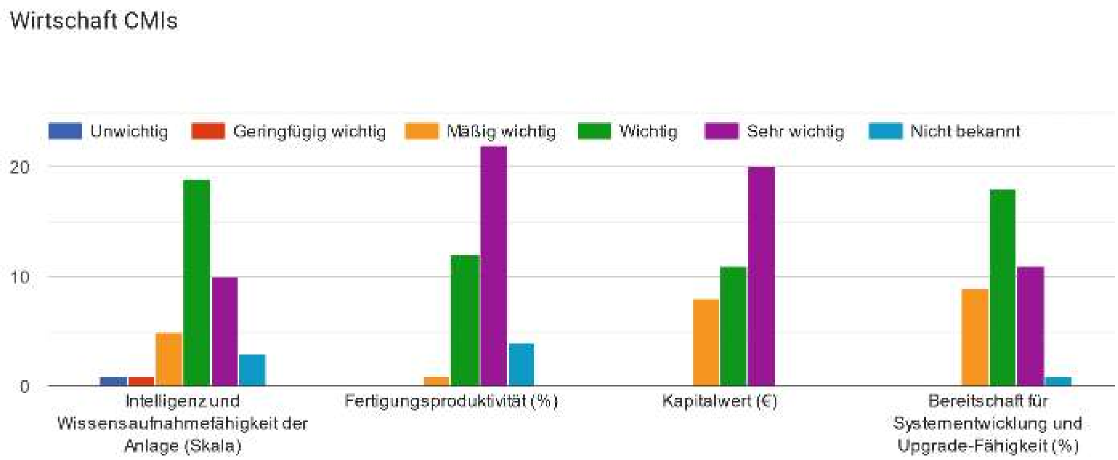
Appendix C: Results of the Questionnaire

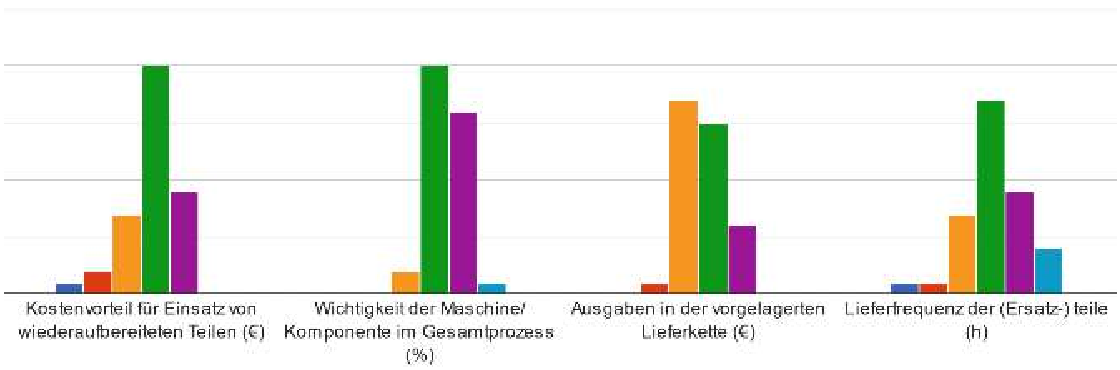
Umwelt CMIs



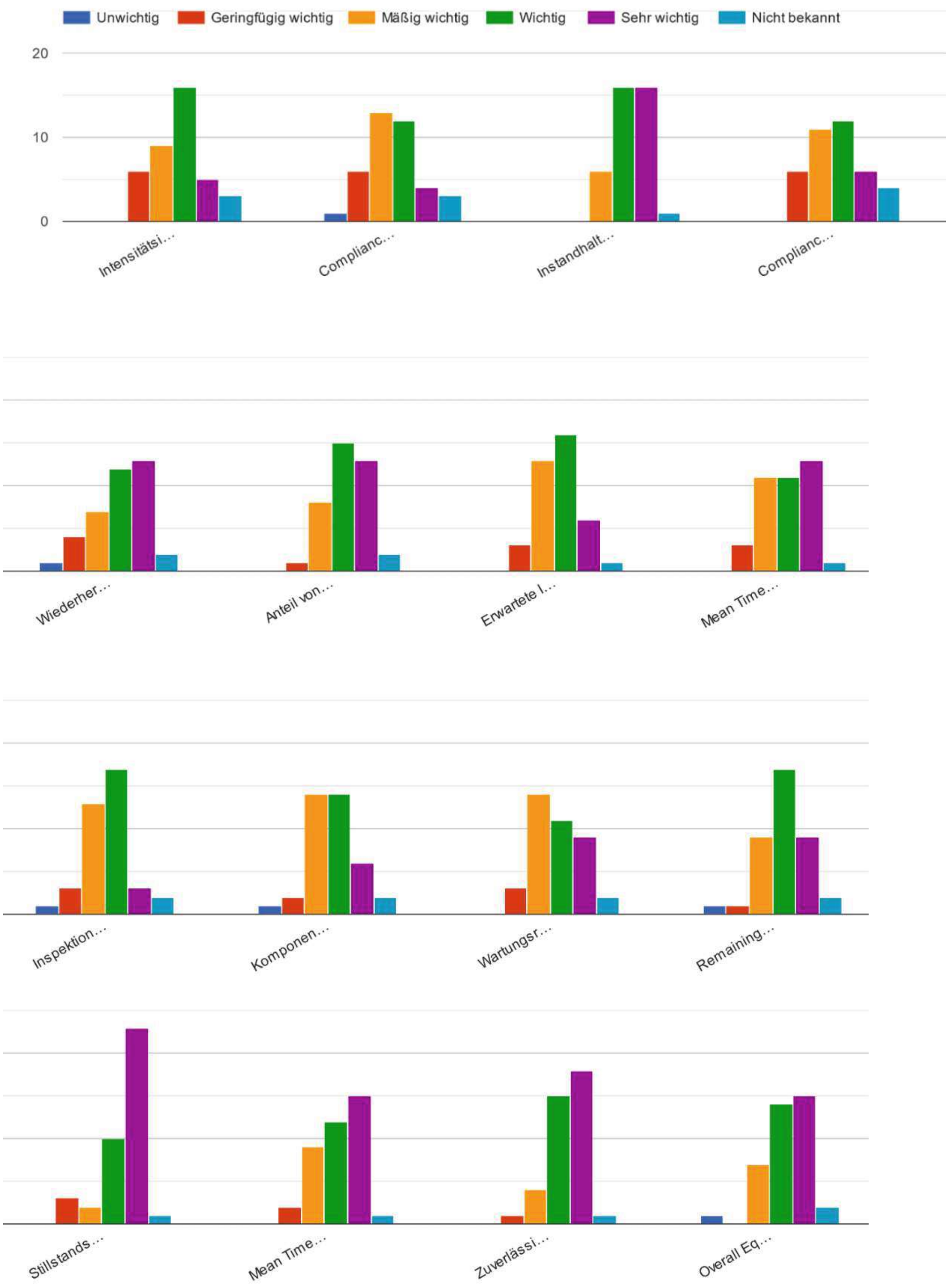
Soziale CMIs

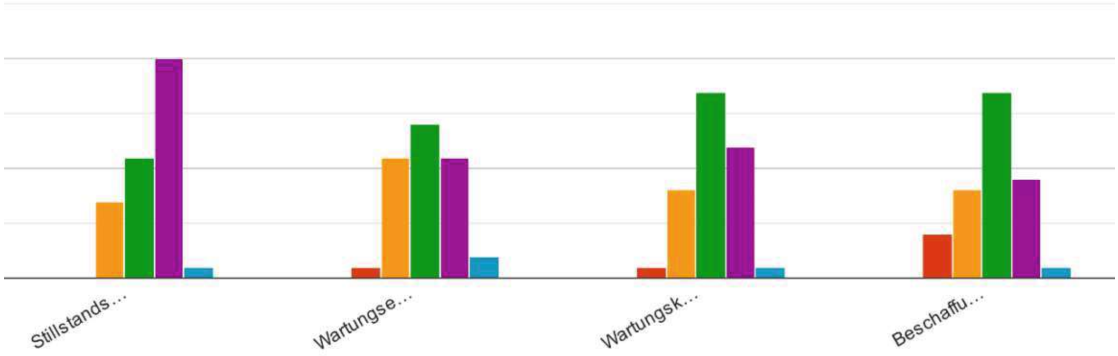


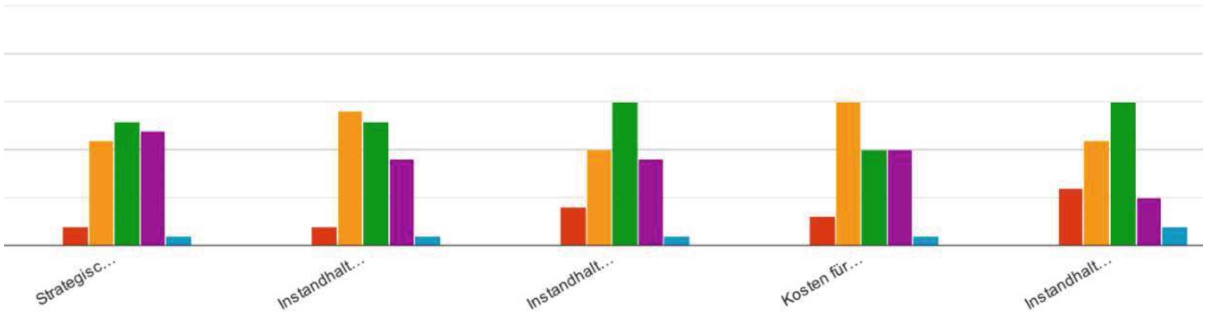

Wirtschaft CMIs
Unwichtig
Geringfügig wichtig
Mäßig wichtig
Wichtig
Sehr wichtig
Nicht bekannt
20
10
0
Intelligenz und Wissensaufnahmefähigkeit der Anlage (Skala)
Fertigungsproduktivität (%)
Kapitalwert (€)
Bereitschaft für Systementwicklung und Upgrade-Fähigkeit (%)


Kostenvorteil für Einsatz von wiederaufbereiteten Teilen (€)
Wichtigkeit der Maschine/ Komponente im Gesamtprozess (%)
Ausgaben in der vorgelagerten Lieferkette (€)
Lieferfrequenz der (Ersatz-) teile (h)

Wirtschaft CMIs - Fokus Instandhaltung

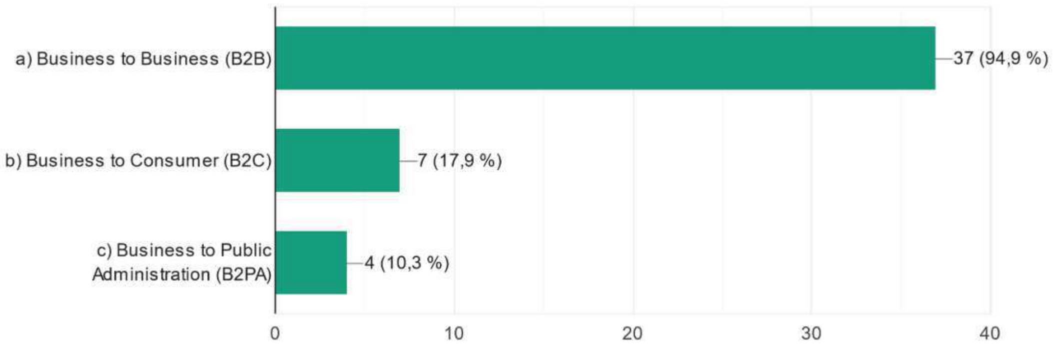






Welche Art von Geschäftsbeziehung verfolgt Ihr Unternehmen? Mehrere Antworten möglich:

39 Antworten

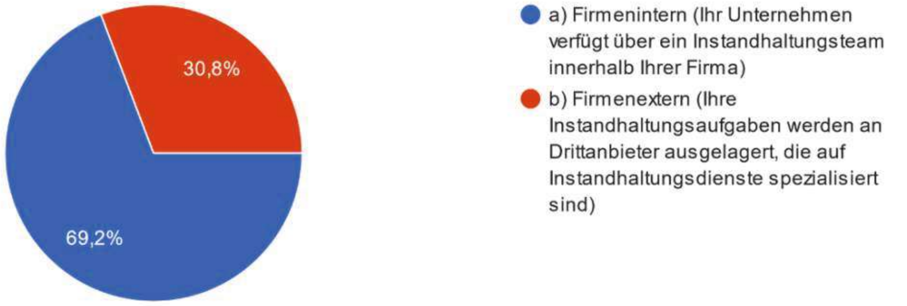


Bitte geben Sie die Gesamtzahl der Mitarbeiter*innen in Vollzeitäquivalenten in Ihrem Unternehmen an.

39 Antworten

Wie werden die Instandhaltungsdienste überwiegend in Ihrem Unternehmen durchgeführt? Mehrere Antworten möglich:

39 Antworten



Arbeiten Sie derzeit in einem Beruf mit Bezug oder Berührungspunkten zur Instandhaltung?

39 Antworten

Appendix D: Importance Level of indicators (addition)

Main	Sub Category	CMI	Importance Level: Not important	Slightly Important	Moderately Important	Important	Very Important	Unknown
Economic-Maintenance related	maintenance: work identification	Preventive Maintenance Intensity Index	0	6	9	16	5	3
		Work Order Compliance Rate	1	6	13	12	4	3
	maintenance: work planning and scheduling	Maintenance Time (inklusive assembly, disassembly, inspection, measurement repairment, refurbishment, remanufacturing, replacement)	0	0	6	16	16	1
		Scheduled Maintenance Compliance	0	6	11	12	6	4
		Recovery Delay Time	1	4	7	12	13	2
		Emergency Maintenance Ratio	0	1	8	15	13	2
		Expected Service Life Cycles	0	3	13	16	6	1
	maintenance: work execution	Mean Time to Repair	0	3	11	11	13	1
		Inspection Frequency	1	3	13	17	3	2
		Component Replacement and Refurbishment Rate	1	2	14	14	6	2
		Maintenance Backlog	0	3	14	11	9	2
	maintenance: equipment effectiveness	Remaining Useful Life	1	1	9	17	9	2
		Downtime (planned and unplanned)	0	3	2	10	23	1
		Mean Time Between Failure	0	2	9	12	15	1
		Reliability Rate	0	1	4	15	18	1
		Overall Equipment Effectiveness	1	0	7	14	15	2
		Downtime Cost	0	0	7	11	20	1
		Maintenance Efficiency	0	1	11	14	11	2
	maintenance: cost effectiveness	Maintenance Cost (including disassembly, inspection, repairment, replacement, remanufacturing, refurbishment costs)	0	1	8	17	12	1
		Spare Parts Procurement Expenses	0	4	8	17	9	1
		Strategic Maintenance Investment	0	2	11	13	12	1
		Maintenance Budget	0	2	14	13	9	1
		Maintenance cost per unit production	0	4	10	15	9	1
		Spare Parts Repair Viability Assessment	0	3	15	10	10	1
	maintenance: safety and environment	Maintenance Risk Assessment	0	6	11	15	5	2

Appendix E: Formula of the Indicators

CMI	Formula	Unit
Environmental Impact	$\frac{Total\ CO_2\ Emissions\ (kg\ CO_2 eq.)}{Business\ year}$	kg CO2 eq.
Energy Consumption Rate	$\frac{Total\ energy\ consumed\ (kWh)}{Business\ year}$	kWh
Material Consumption Rate	$\frac{Total\ material\ consumed\ (kg)}{Business\ year}$	kg
Resource Utilization Efficiency	$\frac{Useful\ output\ (kg, units)}{Total\ input\ of\ resources\ (kg, units)} \times 100$	%
Product Reuse Potential	$\frac{Reused\ products\ or\ components\ (units)}{Total\ available\ components\ (units)} \times 100$	%
Resource Recovery Rate	$\frac{Recovered\ resources\ (kg)}{Total\ waste\ generated\ (kg)} \times 100$	%
Net Waste Management Cost	$\frac{Total\ cost\ of\ waste\ disposal\ (€)}{Total\ waste\ generated\ (kg)}$	€/kg
Waste Management Efficiency	$\frac{Total\ waste\ recycled\ or\ reused\ (kg)}{Total\ waste\ generated\ (kg)} \times 100$	%
Employee Skill Proficiency	$\frac{Number\ of\ employees\ proficient}{Total\ number\ of\ employees\ asssessed} \times 100$	%
Workforce Efficiency Ratio	$\frac{Output\ produced\ (units, tasks)}{Expected\ Output\ (units, tasks)} \times 100$	%
Employee Satisfaction Index	$\frac{Employees\ satisfaction\ score}{Total\ possible\ satisfaction\ score} \times 100$	%
Workplace Safety and Health Assessment	$\frac{Incidents\ or\ hazards\ reported\ in\ time}{Total\ employees\ or\ total\ time\ (hours)} \times 100$	%
Employee Stress Assessment	$\frac{Sum\ of\ stress\ levels\ reported\ by\ employees}{Total\ possible\ stress\ score} \times 100$	%
System Knowledge and Intelligence Level	$\sum Points\ for\ knowledge\ and\ intelligence\ metrics$	integer
Manufacturing Efficiency Index	$\frac{Actual\ Output}{Potential\ Output} \times 100$	%
Net Present Value	$\sum \frac{Cash\ Inflow - Cash\ Outflow}{(1+r)^t}$ Where *r* is discount rate and *t* is time period	€
Readiness for System Evolution and Upgradeability	$\sum Points\ for\ key\ readiness\ criteria$	%
Refurbished Parts Cost Benefit	$(Cost\ of\ new\ parts - cost\ of\ refurbished\ parts) \times Number\ of\ refurbished\ parts\ used$	€
Component Importance Index	$\sum Weight_{Criterion} \times Score\ of\ Component_{Criterion}$ Where *criterion* can be reliability, cost, criticality,…	integer
Parts Delivery Frequency	$\frac{Total\ time\ period\ (days, weeks, months)}{Number\ of\ parts\ deliveries}$	h

Preventive Maintenance Activity Index	$\frac{Preventive\ Maintenance\ hours}{Total\ Maintenance\ hours} \times 100$	%
Maintenance Time	$\sum Time\ for\ maintenance\ related\ activities$	h
Recovery Delay Time	$Start\ time\ recovery\ action - time\ failure\ occurence$	h
Emergency Maintenance Ratio	$\frac{Emergency/unplanned\ maintenance\ hours}{Total\ maintenance\ hours} \times 100$	%
Expected Service Life Cycles	$\frac{Total\ Operating\ Time\ (hours)}{Cycle\ Time\ (hours\ per\ cycle)}$	integer
Mean Time to Repair	$\frac{Total\ repair\ time\ (hours)}{Number\ of\ Repairs\ (integer)}$	h
Remaining Useful Life	$Expected\ total\ life - current\ usage\ or\ degradation$	h
Downtime (planned and unplanned)	$Planned\ downtime + Unplanned\ downtime$ Where *unplanned* is time lost due to failures, breakdowns or unscheduled repairs/maintenance	h
Mean Time Between Failure	$\frac{Total\ operating\ time\ (hours)}{Number\ of\ Failures\ (integer)}$	h
Reliability Rate	$\frac{Number\ of\ successful\ operations\ (uptime)}{Total\ number\ of\ operations} \times 100$	%
Overall Equipment Effectiveness	$Availability \times Performance \times Quality$	%
Downtime Cost	$\frac{Lost\ Production\ (units)\ \times Unit\ Cost}{Total\ Downtime\ (hours)}$	€
Maintenance Efficiency	$\frac{Plannend\ maintenance\ hours}{Total\ maintenance\ hours} \times 100$	%
Maintenance Cost	$\sum Costs\ for\ maintenance\ related\ activities$	€
Spare Parts Procurement Expenses	$Number\ of\ parts\ purchased \times Unit\ cost\ per\ part + additional\ procurement\ costs$	€
Strategic Maintenance Investment	$\sum Costs\ for\ maintenance, upgrades\ and\ enhancements$	€
Maintenance Cost per Unit Production	$\frac{Total\ maintenance\ costs\ (€)}{Total\ units\ produced\ (integer)}$	€

Appendix F: Grading Tool

Main	Sub Category	CMI	Unit	Importance Rate: "important" or "very important"	Ranking by Frequency in the Literature	Weighted Score: IR*(1/Rank)	Weighted Score - normalized	Fulfillment Rate (0-1)	Achieved Score of the CMI	Maximum Possible Score per CMI	Maximum Possible Score	Total Score	Grade
Environment	emission, pollution and waste	Environmental Impact	kg CO2 eq.	76.32%	3	0.2544	25.44	0.7	17.81	25.44	100	86	A
	resource consumption and efficiency	Energy Consumption Rate	kWh	89.74%	6	0.1496	14.96	0	-	0.00			
		Material Consumption Rate	kg	81.58%	24	0.0340	3.40	0	-	0.00			
		Resource Utilization Efficiency	%	86.11%	28	0.0308	3.08	0	-	0.00			
	resource recovery	Product Reuse Potential	%	65.79%	15	0.0439	4.39	0	-	0.00			
		Resource Recovery Rate	%	55.26%	34	0.0163	1.63	0.4	0.65	1.63			
	waste management	Net Waste Management Cost	€/kg	57.89%	19	0.0305	3.05	0	-	0.00			
		Waste Management Efficiency	%	57.89%	19	0.0305	3.05	0	-	0.00			
Social	employee development and training	Employee Skill Proficiency	%	97.37%	13	0.0749	7.49	0	-	0.00			
		Workforce Efficiency Ratio	%	94.74%	28	0.0338	3.38	0.6	2.03	3.38			
	human resources	Employee Satisfaction Index	%	76.92%	38	0.0202	2.02	0	-	0.00			
	Occupational Health and Safety	Workplace Safety and Health Assessment	%	86.49%	13	0.0665	6.65	1	6.65	6.65			
		Employee Stress Assessment	%	64.10%	38	0.0169	1.69	0	-	0.00			
Economic	production process	System Knowledge and Intelligence Level	integer	80.56%	5	0.1611	16.11	0	-	0.00			
		Manufacturing Efficiency Index	%	97.14%	19	0.0511	5.11	0	-	0.00			
		Net Present Value	€	79.49%	28	0.0284	2.84	1	2.84	2.84			
		Readiness for System Evolution and Upgradeability	%	76.32%	38	0.0201	2.01	0	-	0.00			
		Refurbished Parts Cost Benefit	€	74.36%	38	0.0196	1.96	1	1.96	1.96			
		Component Importance Index	integer	94.74%	38	0.0249	2.49	0	-	0.00			
	supply and distribution	Parts Delivery Frequency	h	74.29%	28	0.0265	2.65	0	-	0.00			
Economic-Maintenance related	maintenance: work identification	Preventive Maintenance Activity Index	%	58.33%	34	0.0172	1.72	0	-	0.00			
	maintenance: work planning and scheduling	Maintenance Time (including assembly, disassembly, inspection, measurement repairment, refurbishment, remanufacturing, replacement)	h	84.21%	2	0.4211	42.11	1	42.11	42.11			
		Recovery Delay Time	h	67.57%	34	0.0199	1.99	0	-	0.00			
		Emergency Maintenance Ratio	%	75.68%	22	0.0344	3.44	0	-	0.00			
		Expected Service Life Cycles	integer	57.89%	7	0.0827	8.27	0	-	0.00			
	maintenance: work execution	Mean Time to Repair	h	63.16%	22	0.0287	2.87	0	-	0.00			
	maintenance: equipment effectiveness	Remaining Useful Life	h	70.27%	4	0.1757	17.57	0	-	0.00			
		Downtime (planned and unplanned)	h	86.84%	7	0.1241	12.41	0	-	0.00			
		Mean Time Between Failure	h	71.05%	15	0.0474	4.74	1	4.74	4.74			
		Reliability Rate	%	86.84%	10	0.0868	8.68	0	-	0.00			
		Overall Equipment Effectiveness	%	78.38%	9	0.0871	8.71	0.7	6.10	8.71			
		Downtime Cost	€	81.58%	15	0.0544	5.44	0	-	0.00			
		Maintenance Efficiency	%	67.57%	34	0.0199	1.99	0	-	0.00			
	maintenance: cost effectiveness	Maintenance Cost (including disassembly, inspection, repairment, replac	€	76.32%	1	0.7632	76.32	0	-	0.00			
		Spare Parts Procurement Expenses	€	68.42%	10	0.0684	6.84	0	-	0.00			
		Strategic Maintenance Investment	€	65.79%	28	0.0235	2.35	0	-	0.00			
		Maintenance Cost per Unit Production	€	63.16%	24	0.0263	2.63	0.6	1.58	2.63			

9 List of Figures

10 List of Formula

11 List of Tables

12 List of Abbrevations

CE	Circular Economy
CMI	Circular Economy oriented Maintenance Indicator
CO_2	Carbon Dioxide
DSR	Design Science Research
EU	European Union
HSE	Health, Safety and Environment
IR	Importance Ratio
KPI	Key Performance Indicator
LCES	Life Cycle Extension Strategies
MES	Manufacturing Execution System
MPM	Maintenance Performance Measurement
MTTR	Mean Time to Repair
MTBF	Mean Time between Failure
OEE	Overall Equipment Effectiveness
PMM	Performance Measurement and Management
RUL	Remaining Useful Life
SDGs	Sustainable Development Goals
SOTA	State of the Art
SO_2	Sulphur Dioxide
TBL	Triple Bottom Line
TPM	Total Productive Maintenance
UN	United Nations