Procedure for estimating the carbon footprint of a maintenance service

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Abstract: This article examines the role of carbon footprint (CF) in promoting sustainable practices within the industrial sector, particularly focusing on maintenance services. It defines CF, discusses calculation methods, and analyzes its significance in mitigating climate change. The paper highlights the integration of Environment Management Systems (EMS) and sustainable maintenance to achieve environmental and economic benefits. It also reviews innovative methodologies like the life cycle assessment (LCA) and the Compound Method Based on Financial Accounts (MC3) and emphasizes the importance of comprehensive climate action by considering all emission sources. The article concludes with a critical analysis of the current state and future directions for environmentally conscious industrial maintenance operations.

Key-Words: maintenance, carbon footprint, sustainability, Environment Management Systems, life cycle assessment, Compound Method Based on Financial Accounts

Contents

1. Introduction

Climate change, a global issue since the Industrial Revolution, has prompted nations, businesses, and individuals to prioritize sustainability. Ecosystem preservation is a critical objective for all sectors. Public awareness and adherence to environmental values are crucial in driving companies to adopt sustainable practices and achieve climate conservation [1].

The United Nations Sustainable Development Goal 13 (SDG 13) mobilizes nations and individuals to urgently address climate change. Its dual mission involves both combating climate change and mitigating its effects. By striving to limit global warming to well below 2°C (preferably 1.5°C), we protect ecosystems, prevent mass migrations, and ensure a sustainable future[2].

Incorporating the carbon footprint into company practices involves measuring it along the entire life cycle of products or services. Companies can choose specific stages within this life cycle for more effective reporting and better risk management [3].

Maintenance services are stage essential in companies for ensuring production equipment availability and reliability, reducing costs and time, and addressing sustainability concerns[4]. By assessing maintenance with environmental indicators like carbon footprint, insights are gained into its environmental impact [5].

This article explores carbon footprint (CF) and its role in driving sustainable practices in the industry sector, specifically in relation to maintenance services. It covers the definition, calculation methods, and significance of CF, including direct and indirect emissions, life cycle assessments, and innovative methodologies like the Compound Method Based on Financial Accounts (MC3). The article emphasizes the integration of Environment Management Systems (EMS) and sustainable maintenance practices as crucial factors in achieving environmental and economic synergies. Additionally, it provides a critical analysis of the current state and future directions of environmentally conscious industrial operations.

The paper will begin with a overview about the carbon footprint, followed by methods to calculate the carbon footprint, and then an analysis of the current state in the maintenance field conclude with a discussion about the challenges for maintenance to address the environment issues.

2. Carbon Footprint (CF) Overview

The carbon footprint serves as the primary indicator for assessing the impact of various activities and quantifying climate degradation. Developed by the ADEME (French Environment and Energy Management Agency), it acts as a diagnostic tool, quantifying and evaluating the greenhouse gas (GHG) emissions produced directly or indirectly by a company's activities[3, 6].

A significant body of research aligns on the definition of a carbon footprint, which was developed by ADEME. It quantifies a company's greenhouse gas (GHG) emissions in tons. The larger the carbon footprint, the more detrimental its impact on the climate. In more detail, as articulated by Muthu in 2020, the Carbon Footprint (CF) encompasses the total GHG emissions directly or indirectly associated with an activity or accumulated throughout a product's life cycle. It serves as a tool to assess key environmental hotspots and guide mitigation or improvement efforts[7, 8].

Integrating the carbon footprint (CF) into organizational practices aims to provide a clearer understanding of how companies address climate issues. It also allows for measuring progress in efforts to reduce environmental impact by adopting actions that minimize the carbon footprint[9].

The carbon footprint (CF) is an indispensable tool for companies committed to sustainable practices. It enables them to reduce greenhouse gas emissions and mitigate the negative effects of climate change. By designing and implementing carbon reduction plans at the company level, organizations contribute to the global carbon neutrality goal set by the Paris Agreement[9–11].

The Carbon Footprint (CF) concept quantifies the impact of human activities in terms of carbon emissions (or equivalent greenhouse gases). Beyond carbon dioxide (CO2), it encompasses other significant greenhouse gases like methane (CH4), nitrous oxide (N2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and chlorofluorocarbons (CFCs). By expressing data in carbon dioxide equivalent (CO2e).

Please see Figure 3 on page 14

This approach aids in identifying critical GHG sources and analyzing reduction potential, ultimately enhancing overall productivity[12].

For comprehensive climate action, we must consider all sources, as neglecting any one can contribute to climate change and an increase in carbon footprint. The concept of carbon footprint (CF) encompasses not only direct emissions—such as those resulting from fossil fuel combustion in manufacturing, heating, and transportation—but also the emissions required to produce the electricity associated with the goods and services we consume[13].

Direct emissions result from actions taken by a company within its own facilities. For instance, when a fossil fuel power plant burns coal to generate electricity or a factory releases CO2 as a by-product during goods production, these emissions are considered direct greenhouse gas (GHG) emissions. Furthermore, companies that utilize intermediate or final goods in their operations indirectly contribute to GHG emissions. This occurs because the production and transportation of these goods emit a certain amount of GHGs[14, 15].

Research consistently highlights that direct carbon emissions primarily stem from electricity production. However, this perspective doesn't encompass all emission sources. Consider scenarios where entities consume electricity—such as households or businesses. In these cases, electricity consumption becomes an indirect source of carbon emissions. Delving deeper into the intricacies of carbon emissions reveals another significant contributor: the manufacturing and transportation of consumer goods[16].

For instance, let's examine the carbon footprint of a seemingly innocuous item—the humble water bottle:

- During the manufacturing process, the production of the bottle itself emits a certain amount of CO2 or CO2 equivalent.
- Additionally, the transportation phase—from factory to consumer—contributes further emissions.

Recent research categorizes emissions into three scopes[3]:

Scope 1 (Direct Emissions): These arise directly from a company's activities within its facilities.

Scope 2 (Indirect Emissions from Energy): Associated with purchased energy generation (e.g., electricity).

Scope 3 (Other Indirect Emissions): These extend beyond the company's immediate control and relate to its value chain.

Please see Figure 4 on page 14

3. Carbon Footprint (CF) calculation

The CF serves as a valuable tool for organizations to assess their emissions, it's essential to consider all three scopes when calculating the CF. These scopes encompass various emission sources and provide a comprehensive view of an organization's environmental impact.

A variety of different tools exist for calculating the carbon footprints for individuals, businesses, and other organizations. Commonly used methodologies for calculating organizational carbon footprints include the Greenhouse Gas Protocol, developed by the World Resources Institute and the World Business Council for Sustainable Development, and ISO 14064, an International Organization for Standardization standard specifically addressing greenhouse gas emissions[17, 18].

Several organizations, such as the U.S. Environmental Protection Agency, the Nature Conservancy, and British Petroleum, have created online carbon calculators for individuals. These tools enable individuals to compare their estimated carbon footprints with national and global averages[16, 19, 20].In France, these tools are utilized for computing the Greenhouse Gas Emissions Inventory (BEGES), which is obligatory for companies under Article 26 of the Grenelle II law[21]. Carbon footprint calculators can employ different methodologies, all aiming to quantify the carbon emissions associated with a particular activity or set of activities. It's important for an organization to define which scopes will be implemented into the methodology to monitor the gas emission, as well as they should include the field of study to which it is confined (time domain and geographical borders).

The Carbon Footprint offers numerous benefits to businesses. It helps anticipate future regulations related to greenhouse gas emissions, reduce energy costs, guide environmental management decisions, and enhance the company's image [22]. In essence, the Carbon Footprint represents the essential first step in implementing a policy to monitor and reduce companies' impact on climate change [23].

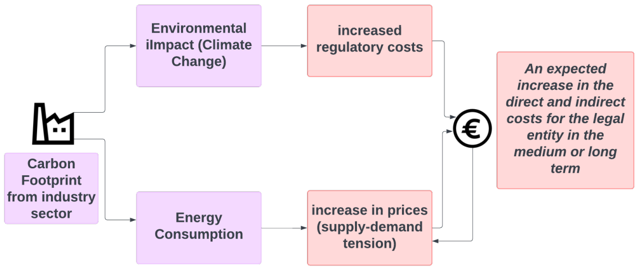

Figure 1: Environmental Impact in Industry Costs [24].

For a company, the principle of carbon neutrality primarily involves minimizing the origin of its greenhouse gas emissions (by reducing transport, energy consumption, and sourcing green energy). Subsequently, it must offset all remaining emissions (through renewable energy development projects, reforestation efforts, and distribution of energy-efficient equipment) [23].

Conducting a Carbon Footprint Assessment in a company can incur highly variable costs. These costs depend on several factors, including:

- Service Provider: Whether you choose Software as a Service (SaaS) solution or a consulting firm, pricing can vary.
- Scope: The extent of the assessment (e.g., a single facility or the entire company) impacts costs.
- Company Size: The number of employees and revenue play a role.
- Industry Sector: The cost of a carbon footprint assessment differs between agriculture and secondary or tertiary sectors.
- Provider's Time Investment: The more time the provider dedicates, the higher the costs may be.

For both large enterprises and small to medium-sized enterprises (SMEs), conducting a Carbon Footprint Assessment is crucial for sustainability efforts. Large enterprises typically invest between 20,000€ and 50,000€ when working with consulting firms for this assessment. Conversely, SMEs in Small and Medium companies have more cost-effective options available. Engaging a consulting firm for SMEs typically costs around 10,000€, while utilizing SaaS-based software, which relies on physical data, ranges from 8,000€ to 25,000€. Regardless of size, these assessments play a vital role in understanding and mitigating environmental impact [3].

The carbon footprint considers various greenhouse gases, not just carbon dioxide (CO2), by converting them into an equivalent amount of CO2 based on their global warming potential (GWP) over a specific time frame (usually 100 years) [25]. To determine the carbon footprint in units of kilograms of CO2 equivalent (kgCO2eq), just multiply the actual mass of the gas emitted by its corresponding GWP factor. This multiplication provides the CO2 equivalent mass, which is calculated after quantifying the gas emitted. Alternatively, if direct measurements aren't possible, data like energy consumption can estimate the footprint using the formula [26]:

The Carbon Footprint = Activity data $\times$ Emission Factor $\times$ Global Warming Potential.

Emission factors play a crucial role in converting activity data into quantities of emitted gases. They allow us to translate human actions (such as industrial production, transportation, or agriculture) into specific greenhouse gas emissions.

These factors are based on scientific measurements and consider the characteristics of each gas, its atmospheric lifetime, and its global warming potential.

When conducting an environmental assessment through a calculation method, it is crucial for the organization to utilize emission factors. The recommended default emission factors are those provided by the ADEME Carbon Database [27]. However, if alternative emission factors are used, it is essential to acknowledge and justify these data while safeguarding commercial confidentiality. The choice of emission factor should align with the specific type of activity considered.

Calculating your carbon footprint involves understanding the greenhouse gas (GHG) emissions associated with specific activities [28]. For instance:

- Electricity Usage: You'll need to know emissions per kilowatt-hour. Reputable sources like the EPA provide such data.
- Transportation and Waste: Again, the EPA and the UK's Defra offer reliable information.
- Materials: The Higg Index helps estimate emissions from materials.

For precise emission factors, consider consulting RMS or using cloud-based tools[3].

3.1. Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is one of methodology that employed to calculate the Carbon footprint. LCA has been defined as a systematic analysis to measure industrial processes and products by examining the flow of energy and material consumption, waste released into the environment and evaluate alternatives for environmental improvement [29].

First step in LCA methodology is defining goals and scopes will determine the purpose of the study system boundaries and selection of suitable functional units spatial and temporal boundary should also be included in the system boundary. Please see Figure ??

The second step is the data collection process of all relevant inputs and outputs of a product life cycle. This step known also under the title 'life cycle inventory (LCI)' defines the flows' interaction with the environment, raw materials consumed, and emissions. The main task is to collect data on energy consumption of various processes within the system boundary, and to calculate and establish an inventory of environmental inputs and outputs using scientifically approved and industry recognized methods.

Then in the third step will use data from LCI and subsequently evaluate potential environmental impacts 'calculate the value of Carbon footprint', The selection of indicators is always subjective but must be consistent with ISO recommendations, this phase is the point of LCA methodology, and is known Life Cycle Impact Assessment (LCIA)

Finally, identify significant issues, assess results to reach conclusions, explain the limitations and provide recommendations[29–32].

LCA considers a wide array of factors, including inputs, emissions, and resource consumption, providing a holistic understanding of the product's environmental footprint. This approach enables informed decision-making, identifies improvement opportunities aimed at minimizing environmental impacts throughout the product's life cycle [33].

ISO 14040:2006 is a standard that outlines the principles and framework for conducting Life Cycle Assessment (LCA) within the realm of environmental management. LCA is a systematic method for evaluating the environmental impacts of products or services throughout their entire life cycle. This standard provides guidance on key aspects of LCA methodology, ensuring consistency and reliability in environmental assessments [31].

A document written by A. Makhlouf recommends using Life Cycle Assessment (LCA) to evaluate the environmental impact of any potential process modifications or integration of new products, as it considers the entire life cycle of products [34].

In the same document, the discussion revolves around the factors contributing to climate challenges in Algeria. Notably, cement production witnessed a substantial increase, rising from 11 million tonnes in 2011 to a staggering 47.2 million tonnes in 2019 [35]. Each tonne of Portland cement requires 5.716 GJ of energy and emits 882.36 Kg CO2eq. While the carbon footprint is comparable to global averages, energy demand exceeds the global average by almost 20% [34].

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3.2. Compound Method Based on Financial Accounts (MC3)

MC3, an acronym for the Compound Method Based on Financial Accounts, represents an innovative approach for quantifying greenhouse gas (GHG) emissions arising from an organization's material consumption, goods utilization, services, and waste generation[36][37]. Developed with precision, this method takes into consideration critical factors such as space occupation and waste generation[38]. By integrating financial data and environmental impact, MC3 provides a comprehensive framework for assessing an organization's carbon footprint. The MC3 methodology, initially proposed by Doménech in 2004, serves as a robust framework designed to calculate the carbon footprint associated with goods and services. It specifically targets institutions and enterprises [38]. Additionally, the "Composed Method of Financial Accounts", developed by Carballo Penela and colleagues in 2009, provides an analytical framework for studying human demand for bioproductivity [39]

The method was designed to meet guidelines set by the Intergovernmental Panel on Climate Change (IPCC), as well as international standards such as ISO 14069, ISO 14064-1, ISO 14044, GHG Protocol, and PAS 2050[36]. The primary objective of the MC3 methodology is to quantify the carbon dioxide (CO2) emissions associated with the products and services offered by an organization.[38], It is a hybrid level-based method that combines factors from Input-Output Analysis (IOA) and Process Analysis to provide an inventory of GHG emissions in terms of Carbon Dioxide Equivalent (CO2e)[36]. The MC3 methodology, initially applied to the Gijón Port Authority, underwent further testing and refinement by the Working Group on Corporate Ecological Footprint Enhancement. Led by Doménech, this collaborative effort involved coordination among five Spanish universities. Over a span of a year and a half, the method was systematically applied to companies across diverse economic sectors to rigorously assess its effectiveness and reliability[37].

The initial step in applying the MC3 methodology involves meticulously determining the types and quantities of resources consumed by the cooperative over a typical year[39]. This comprehensive assessment includes details on:

- Fuel Consumption
- Energy Usage
- Materials Utilized
- Services Availed
- Natural Resources, such as agricultural produce, forest resources, water usage, land utilization, and waste generation.

The calculation tool employed within the MC3 framework encompasses a wide array of consumption-related categories. It takes into account factors like soil occupation and waste generation, ensuring a holistic evaluation of the organization's environmental impact, a notable strength of the MC3 methodology lies in its reliance on financial accounts as the primary data source for calculations. This standardized approach fosters consistency across diverse organizations, enabling more reliable and accurate comparisons and analyses[38]. An integral feature of the MC3 methodology lies in its dual capability: it simultaneously calculates both the carbon footprint and the ecological footprint using the same input data. This integrated approach significantly enriches the assessment by providing a holistic view of the organization's environmental impact. It takes into account not only carbon emissions but also broader ecological factors[40].

MC3, recognized in Spain as one of the most validated and accepted methods for quantifying Scope 3 emissions, plays a pivotal role in the Spanish Public Carbon Footprint Registry, bolstered by initiatives like CarbonFeel[36]. Here are the key advantages of the MC3 methodology:

1. Consistent Scope: MC3 ensures a uniform scope across all organizations employing the tool. This consistency streamlines the assessment process, enabling direct comparisons between different entities without the need for scope adjustments[40].
2. Flexibility and Transparency: MC3 stands out for its flexibility, transparency, and ease of application, making it accessible for organizations to accurately calculate their carbon footprint[36].
3. Financial Indicators: Unlike methodologies relying solely on physical indicators (such as kilograms or cubic meters), MC3 also incorporates financial indicators. Recognizing that some consumption data is more readily available in financial terms, this inclusion enhances accuracy[36].
4. Scope 3 Emissions: MC3 excels in calculating Scope 3 emissions for any organization. These indirect emissions from sources like purchased goods and services are often challenging to quantify but significantly impact an organization's overall carbon footprint[36].

The successful application of the MC3 method across diverse economic sectors underscores its versatility and adaptability. By providing valuable insights for improving environmental performance [37].

This method, validated by Alvarez et al. in 2015, has been recognized as effective for assessing Scope 3 emissions, particularly vital for service-oriented companies with limited direct and indirect energy emissions. Notably, MC3 presents a distinct advantage for implementation in service activities, as highlighted in a study by Sergio Alvarez and Agustín Rubio in 2015, marking the first application within a conservation and maintenance service context. Utilizing the Compound Method Based on Financial Accounts 'MC3' system, the carbon footprint of the conservation and maintenance service was assessed within defined physical, organizational, and operational boundaries. Results indicated a significant increase in greenhouse gas emissions from 2011 to 2012, with a corresponding rise in operational expenses and investments, exemplified by a notable 69% increase in the Repairs and Maintenance category during this period [10].

4. literature review

Industries typically exert a detrimental impact on the environment. To mitigate this hazard, it is essential to regulate the resources employed in production, such as energy consumption and raw materials, as well as monitor the production footprint encompassing emissions, water pollution, and waste. It is crucial to actively track and manage the environmental impact of industries [41–43].

In recent years, sustainability goals, particularly those related to climate change and environmental degradation, have gained significant importance in the context of company objectives[44]. These goals now stand alongside economic objectives. Additionally, companies recognize the need to conserve resources for the benefit of future generations. By minimizing energy consumption, optimizing material usage, and implementing recycling processes, companies can achieve both environmental and economic gains.

The integration of an Environment Management System (EMS) plays a crucial role in evaluating sustainable development. EMS can be applied across all hierarchical levels and within various departments of a company. It can also be selectively implemented in specific departments based on their significant environmental impact [45].

4.1. Environmental Impact and Strategies in Manufacturing Processes

Many research papers emphasize the importance of minimizing environmental impact by implementing solutions within the production processes.

Starting from the 1970s, there has been a growing emphasis on green production also known as Green Manufacturing, refers to a set of practices and strategies within the manufacturing field that focus on environmental sustainability [46]. This approach centers around several key aspects, including pollution prevention, clean production processes, product stewardship,recycling and reuse. The concept of green production has evolved and can be categorized into four main forms [47]:

- Green Products: These are environmentally friendly products designed with reduced environmental impact in mind.
- Green Processes: These refer to production methods that minimize resource consumption, waste, and pollution.
- Green Use: This aspect focuses on encouraging responsible and sustainable use of products by consumers.
- Green End-of-Life Management: It involves strategies for recycling, reusing, or properly disposing of products at the end of their lifecycle.

Recent research in production practices for environmental issues has seen significant advancements, particularly in methodologies for evaluating the environmental impact of products and processes. One notable study by Hertwich et al. (1997) compares six methods for assessing environmental impact [48].Furthermore, Norgate et al. (2007) employ Life Cycle Assessment (LCA) to identify high impact areas in metal production, shedding light on crucial areas for mitigation and improvement [49].

In 2015, a study was conducted to evaluate emissions throughout different phases of an agricultural company's operations, with a specific focus on crop-related activities. The results revealed that synthetic nitrogen fertilizers and mechanical operations significantly contribute to carbon footprints. The study employed the Full Life Cycle Assessment methodology for quantifying carbon footprints [50].

In 2010, a study set out to quantify emissions from dairy production. The findings revealed that the carbon footprints associated with milk production range from 0.37 to 0.69 kg CO2 per kilogram of milk, these emissions stem from various factors, including fuel, electricity, machinery, fertilizer, pesticides, and plastic [51].

A research investigation examines whether water production affects climate change. In 2007, a Parisian case study revealed that energy consumption during water production significantly contributes to emissions. Carbon footprint analyses since 2003 have consistently highlighted the importance of energy consumption in this context [52].

Another research study examines the processes involved in aluminum production, explores strategies for reducing emissions during industrial processes. It underscores the significance of utilizing low-carbon energy sources in production and addressing both direct and indirect emission sources within the production processes [53].

In a research paper from 2023, an in-depth examination of carbon emissions within manufacturing processes takes center stage. The study specifically on the carbon footprint resulting from material consumption across a spectrum of manufacturing procedures. Notably, the research delves into the evaluation of carbon emissions during wind turbine gearbox production. By meticulously quantifying the carbon emissions in the workshop layer for the wind turbine gearbox, the calculated value stands at 119,565.5379 kg CO2e. This figure vividly represents the environmental impact stemming from the manufacturing activities associated with producing these crucial components [54].

A study sheds light on how production activities impact ecosystems beyond direct human effects and provides new evidence on the link between economic production and ecosystem decline. It compiles longitudinal ecological sampling data across tens of thousands of locations in the United States from 1960 to 2015 [55].

A study highlights the importance of understanding and mitigating manufacturing-related environmental impacts and examines the environmental impact of manufacturing processes, products, and infrastructures. Specifically, it focuses on the carbon footprint[41].

A comprehensive review discusses hydrogen production, storage, and utilization, along with their environmental impacts. It covers various hydrogen production methods and compares the environmental impact of different hydrogen production routes using life cycle analysis [56].

4.2. Sustainable Maintenance: Enhancing Environmental Performance

Maintenance is one of the major activities in manufacturing as it highly influences production quality and quantity and directly affects production cost and customer satisfaction. As new manufacturing technologies emerge and global communication advances, new maintenance practices are developed to cope with these changes. The role of maintenance in maintaining asset value over time is getting more visible at the business level with the increase in its acquisition and maintenance costs [4].

As industries increasingly adopt a sustainability approach, maintenance plays a crucial role in achieving sustainability objectives. Sustainable Maintenance (SM) aims to minimize environmental and social impacts, reduce life cycle costs, and enhance equipment durability and socioeconomic well-being [57]. The aim of a sustainable management of maintenance processes is limiting the negative influence on environment, guaranteeing stakeholders' safety and achieving more efficient resource and energy management [58].

Effective and efficient maintenance processes hold significant potential in advancing sustainable manufacturing [59]. Over time, maintenance has transformed from a purely reactive function—lacking preventive actions—into a series of progressive stages. Initially, it adopted a preventive approach, followed by a lean process, and later evolved into a green process [60]. Today, maintenance is recognized as a critical process that must be managed from a sustainable perspective [61]. By integrating sustainable practices into maintenance strategies, organizations can harmonize operational efficiency, resource conservation, and societal well-being [62].

The Environmental Management System (EMS) necessitates a thorough definition of environmental aspects and their impacts for each process, including maintenance. In this context, companies are obligated to devise actions and procedures aimed at controlling these aspects and mitigating their impact on the environment. By implementing these measures, the maintenance department will adopt a fresh management approach that prioritizes environmental sustainability[63]. Despite the clear link between them, there is a scarcity of studies examining the relationship between environmental performance and industrial maintenance management performance.

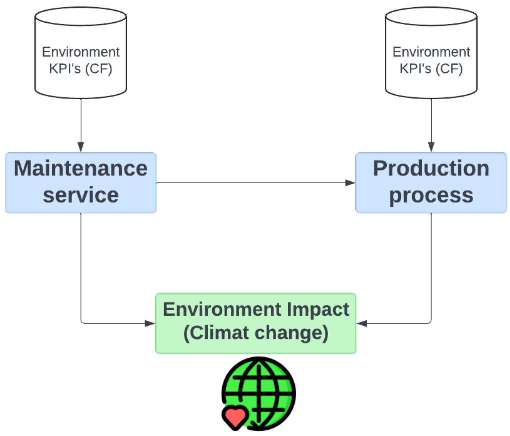

Figure 2: Maintenance Impact for Green Manufacturing and Environmental System.

However,The intersection of maintenance practices and environmental impact has garnered increasing attention in recent research endeavors, showcasing diverse examples across various sectors. For instance, Garcia-Teruel et al. (2022) delve into the evaluation of the environmental impact associated with the operation and maintenance of floating offshore wind farms, highlighting the significance of sustainable maintenance strategies in renewable energy infrastructure. In a different context [64], Lewis et al. (2011) explored the nexus between energy management and maintenance practices in buildings within California, emphasizing the potential for energy-efficient maintenance approaches to mitigate environmental footprints in the built environment [65]. Majerník et al. (2021) present a case study outlining methods for integrating informal green practices into automobile repair and maintenance processes, illustrating how small-scale initiatives can contribute to environmental sustainability within the automotive sector. Additionally [66], Nezami and Yildirim (2013) propose a sustainability-based approach for selecting appropriate maintenance strategies, offering a framework to minimize environmental impacts while ensuring optimal asset performance across diverse industrial settings [67]. An approach evaluates both environmental and economic impacts of different maintenance activities, Barbieri and Hernandez proposes a methodology rooted in sustainability indices and RAM (Reliability, Availability, and Maintainability) analysis to support decision-making regarding sustainable maintenance practices aims to minimize the impact of assets on the economy, society, and the environment while mitigating adverse consequences from maintenance activities.identifies areas for improvement, and provides insights for resource allocation to mitigate impacts [68].

Together, these examples underscore the crucial role of maintenance practices in shaping environmental outcomes across different domains

5. Discussion

Industry maintenance is a sector that plays a crucial role in ensuring the smooth functioning of production processes and all industry-related activities that are connected to maintenance, such as logistics, construction, and service providers. These interactions should aim to minimize environmental impact through effective maintenance management. This can be achieved by reducing resource consumption, utilizing eco-friendly materials, adopting renewable energy sources, implementing sustainable technologies, and following the 3Rs process (Recycle, Reuse, Reduce) to handle waste [62].

Integrating maintenance services into the environmental management system necessitates the alignment of methodologies and key performance indicators (KPIs) related to the environment. Notably, this includes metrics such as Life Cycle Assessment (LCA), Compound Method Based on Financial Accounts (MC3), and Carbon Footprint (CF).

Previous studies have extensively discussed and implemented the Life Cycle Assessment (LCA) method and the MC3 method within maintenance services to achieve environmental objectives. For example, a collaborative study involving researchers from institutions in China, the UK, and the USA focused on highway engineering. Specifically, they conducted a life cycle assessment of greenhouse gas emissions resulting from asphalt pavement maintenance in China. Notably, corrective maintenance was identified as a significant contributor to greenhouse gas (GHG) emissions due to the materials used and their impact on traffic [30].

The research findings revealed that by increasing the frequency of preventive maintenance and reducing the occurrence of corrective maintenance, a substantial reduction of 30% to 45% in GHG emissions could be achieved over the lifespan of the pavement. This underscores the importance of proactive maintenance practices in mitigating environmental impact [30].

Another example involves the application of the MC3 method to calculate the carbon footprint of a conservation and maintenance service in Madrid's urban area. This service encompasses various tasks, including monitoring water quality, controlling fish and birdlife, and cleaning the water surface, bed, and margins of the river. Interestingly, the research findings indicated that the total carbon footprint increased by 41% from 2011 to 2012. This highlights the need for continuous monitoring and optimization of maintenance practices to address environmental challenges effectively [10].

Despite the critical role of maintenance actions in both industry and environmental sustainability, research papers often overlook the specific environmental impact of maintenance services in the industry sector. While many authors emphasize the importance of maintenance for green manufacturing, there remains a scarcity of case studies that directly address this topic [5, 58–62, 69].

Remarkably, the construction industry has conducted substantial case studies aimed at implementing maintenance practices to reduce environmental impact [10, 30, 64, 70]. take on consideration recent statistics reveal that the cumulative impact of all industries on climate change surpasses that of the construction field.

Please see Figure 5 on page 14

To bridge this gap, further research is needed to explore and quantify the environmental consequences of maintenance services within the industry sector. Understanding these impacts can inform sustainable practices and contribute to a greener future.

The initial step in adopting these metrics involves data collection. It's important to recognize that LCA and MC3 serve as guidelines to facilitate the seamless integration of environmental KPIs, such as carbon footprint, within the chosen perimeter (maintenance in this case). The data collected from maintenance activities should directly relate to environmental impact, particularly when calculating the chosen Key Performance Indicator (KPI)—in our case, the carbon footprint. It's essential to recognize that maintenance actions can significantly influence all three scopes of the carbon footprint. Notably, the third scope is particularly affected because maintenance often involves substantial material usage (such as fats, lubricants, etc.) and generates waste, the type of data and the scope is essential to determinate the emission factor.

The selected methodology aims to ensure the effective implementation of the carbon footprint indicator within the maintenance sector. It facilitates continuous monitoring of the environmental impact resulting from maintenance activities until the predetermined targets are successfully met for both the maintenance department and the company.

On the other hand, maintenance services play a pivotal role in ensuring the efficient functioning of industrial equipment. Their interventions, specially preventive interventions, contribute significantly to reducing and controlling energy consumption. Additionally, these services help minimize waste generation and emissions at the source[69, 70].

The consideration of environmental issues is essential when optimizing maintenance practices. These issues act as constraints that influence decision-making in maintenance planning. By factoring in environmental impact, organizations can align their maintenance strategies with sustainability goals and minimize adverse effects on the ecosystem.

So, carefully controlling and monitoring environmental Key Performance Indicators (KPIs) in comparison to other KPIs, such as reliability, becomes paramount for maintenance in addressing the evolving objectives of the industry.

6. Conclusions

In this comprehensive article, we delve into the concept of Carbon Footprint (CF)—a powerful diagnostic tool for quantifying and evaluating greenhouse gas (GHG) emissions associated with a company's activities. Our exploration emphasizes the pivotal role of integrating CF into organizational practices. By doing so, companies gain insights to understand and address climate-related challenges, measure progress in reducing environmental impact, and actively contribute to global carbon neutrality goals.

In this article, we aim to emphasize the significance of controlling and monitoring the environmental impact of industries, particularly in relation to maintenance services. However, existing literature reveals a noticeable gap in research concerning the importance of addressing the environmental impact of maintenance specifically within the industrial sector, especially considering the essential role that maintenance plays in promoting sustainable manufacturing practices.

In conclusion, this article highlights the following key points:

- Robust methodologies, including Life Cycle Assessment (LCA) and the Compound Method Based on Financial Accounts (MC3), aid in precise CF calculations. These tools illuminate hidden emissions and guide mitigation efforts.

- Crucial Role of Environmental Management: Industries wield immense power to shape our planet. Hence, active tracking, regulation, and mitigation of resource consumption, emissions, and waste are non-negotiable.

- Sustainable Maintenance Practices: Proactive maintenance—preventing issues before they escalate—plays a pivotal role. Studies reveal that optimizing maintenance practices significantly reduces GHG emissions.

- Integration into Environmental Management: To achieve environmental objectives, maintenance services must be seamlessly integrated into the environmental management system. Aligning methodologies and key performance indicators ensures a holistic approach.

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A. Appendix A

Gas	Source	Lifetime (years)	GWP (20 years)	GWP (100 years)
CO_2	Fossil fuels, deforestation	Thousands	1	1
CH_4	Livestock, landfills	12	84	28
N_2O	Agricultural practices	114	298	265
CFCs, HFCs, SF_6	Industrial processes	Varies	High	High

Figure 3: Residence time in the atmosphere, global warming power [24].

B. Appendix B

Category	No	Emission Source	Example Emission Sources
Direct GHG Emissions (SCOPE 1)	1	Direct emissions from fixed combustion sources	Combustion of energy from fixed sources
	2	Direct emissions from mobile sources with internal combustion engines	Combustion of fuel from mobile sources
	3	Direct emissions from non-energy processes	Industrial processes not related to combustion, potentially including decarbonization, chemical reactions, etc.
	4	Direct fugitive emissions	Emissions from refrigerant leaks, nitrogen fertilizer, organic waste treatment, etc.
	5	Emissions from biomass (soil and forests)	Biomass related to soil activities, wetlands or forest operations
Indirect Energy GHG Emissions (SCOPE 2)	6	Indirect emissions from electricity consumption	Electricity production, transportation, and distribution
	7	Indirect emissions from steam, heat, or cold energy consumption	Steam, heat, or cold energy production, their transportation, and distribution
Other Indirect GHG Emissions (SCOPE 3)	8	Indirect energy emissions not included in "Direct GHG Emissions" and "Indirect Energy GHG Emissions"	Extraction, production, and transportation of fuels consumed by the organization
	9	Purchased goods or services	Extraction and production of raw materials and goods that are not classified elsewhere
	10	Capital goods	Extraction and production of tangible and intangible goods acquired by the organization
	11	Upstream transport of goods	Transportation of goods paid for by the organization
	12	Employee travel	Transportation of employees using non-organizational means
	13	Franchises	Franchisor activity
	14	Leased assets or equipment	Leased assets such as energy consumption and equipment manufacturing
	15	Investments	Sources related to projects or activities associated with financial investments
	16	Visitor and customer transportation	Energy consumption associated with transportation of visitors (customers, suppliers, or others)
	17	Product transportation	Transport and distribution of products not paid for by the organization
	18	Use of sold products	Energy consumption
	19	Waste from sold products	Waste treatment at the end of the product lifecycle
	20	Leased assets	Assets leased by the organization
	21	Employee home-to-work travel	Employee commutes and teleworking
	22	Other indirect emissions	Emissions not covered by categories 7 to 23

Figure 4: Elements taken into account within the framework of the regulatory carbon footprint [24].

C. Appendix C

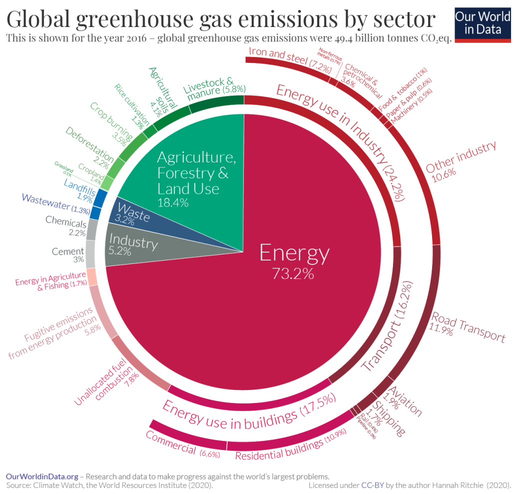

Figure 5: 2016 Global Greenhouse Gas Emissions by Sector [71].

D. Appendix D

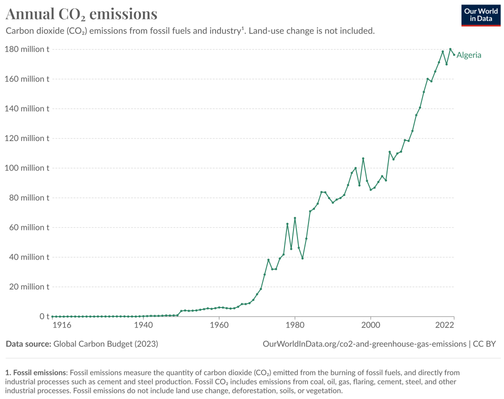

Figure 6: Carbon dioxide (CO2) emissions from fossil fuels and industry Algeria (2022) [71].