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Assessment of the Ecological Footprint of Industrial Processes: An Integrated Approach to Life Cycle Analysis

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Abstract: The ecological footprint is crucial in assessing industrial processes and is essential for understanding their impact. The integrated approach to life cycle assessment is essential for studying these footprints. The scientific paper describes a comprehensive approach to assessing the environmental footprint of industrial operations using life cycle analysis. The study's goal is to examine the environmental implications of various stages in the life cycle of industrial products or processes. A life cycle analysis framework is provided, which encompasses all processes from raw material extraction to product manufacture and consumption, as well as waste and recycling possibilities. Each phase is evaluated in terms of energy use, material consumption, and environmental impact. Concrete steps for implementing an integrated approach to life cycle analysis in industrial environments are presented, as are examples of the methodology's implementation in various areas of production. The article emphasises the need for incorporating environmental considerations into decision-making processes and assists organisations in identifying opportunities for optimising and reducing their environmental footprint.

Keywords: Ecological footprint; Life cycle analysis, Industrial processes, CO_2 emissions

Introduction

One of the most significant challenges facing humanity is environmental degradation and how to deal with it. Intensification of various forms of pollution, reduction of biodiversity, depletion of natural resources—all these processes pose a serious threat to ecosystems and human health. Industrial processes have a significant impact on the environment due to the large volume of production, the use of resources, and the emissions they generate. They constitute one of the main causes of environmental pollution and the ecological challenges we face. (Chambers et al., 2004)

Ecological Footprint

The ecological footprint is a summary indicator of the consumption of natural resources (energy and materials), just as economic indicators provide a framework for the financial economy. Prof. William Rees and Dr. Mathis Wackernagel developed the idea of an "ecological footprint" in the early 1990s (Wackernagel & Rees, 1996). Ecological footprint analysis is rapidly gaining popularity and is now widely used by governmental and non-governmental organisations. Its applications include policy analysis, performance benchmarking, education and public awareness, and scenario development. (Bastianoni et al., 2006) By its nature, the ecological footprint considers the use of the planet's renewable resources. The ecological footprint considers only the ecological component without engaging with the social and economic dimensions of sustainability. (Bergmark, 2022) Environmental footprint assessment plays an important role for industrial processes due to a number of significant aspects:

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

- Identification of environmental impacts: focus on the real environmental impacts of industrial processes. This includes greenhouse gas emissions, air and water pollution, the use of resources such as energy and water, and other parameters. By clearly defining and quantifying these impacts, businesses can understand where the main problem areas are concentrated and focus on them for improvement.
- Identification of opportunities for optimisation and environmental improvement: marking potential opportunities for optimisation and reduction of the negative impact on the environment By analysing the different phases of the life cycle, businesses can identify key points for improvement, such as energy efficiency, material efficiency, waste recycling, etc. This allows them to innovate, change production processes, and prioritise sustainable practices.
- Meeting environmental requirements and regulations: in many countries and regions, various environmental requirements and regulations are imposed on industrial activities. Environmental footprint assessment helps businesses meet these requirements and adhere to regulatory standards. This not only helps them avoid legal penalties but also proves their commitment to sustainability and environmental responsibility.
- Improvement of corporate image and competitiveness: marking a positive effect on the corporate image and competitiveness of enterprises Consumers and customers are increasingly paying attention to environmental aspects and looking for products and services that are good for the environment. Companies that actively work to reduce their environmental footprint have the opportunity to portray themselves as sustainable and responsible and attract consumers who share similar values.

Life Cycle Assessment

The first Life Cycle Assessment study was conducted in the 1960s in packaging studies, primarily focused on energy use rather than emissions (Samani, 2023). Life cycle analysis is a methodology for assessing the environmental impacts of products or processes from the beginning to the end of their life cycle. The process includes all phases related to raw materials, production, use, waste treatment, and final disposal or recycling. Life cycle analysis uses a systematic and quantitative approach to assess various impacts, such as energy consumption, greenhouse gas emissions, water and air pollution, and other parameters, in order to determine the overall ecological footprint of products or processes. (Ventura, 2022)

Ecological Footprint and Life Cycle Analysis are different but interrelated methods for measuring and evaluating the environmental impacts of products, services, organisations, and even human lifestyles. The relationship between them is that both methods are used to assess environmental impacts but focus on different aspects and scales. They are used to identify the key factors that contribute to the environmental burden and to identify opportunities for improvement and reduction of negative impacts. Table 1 presents a brief comparative analysis of the concepts.

Table 1. A comparative analysis of the concepts of ecological footprint assessment and life cycle analysis, (Author's research)

	Ecological Footprint Assessment	Life Cycle Analysis
Methodology	A method of measuring human consumption of natural resources and comparing it with the ability of planet Earth to restore them.	A method of assessing the environmental impacts of products and services throughout their life cycle, including production, use, and disposal.
Focus	It focuses on summing up all resources used by man and emissions produced by man's activities into a single number (global acres) expressed in area or land surface units.	It focuses on specific products or processes and analyses all stages of their life cycle, including raw materials, production, transport, and final processing.
Application	It is used to assess the sustainability of human lifestyles and to compare them with the Earth's biological capacity.	It is used to identify key areas where the sustainability of products or services can be improved.

The link between the methods occurs when life cycle analysis is used to analyse the life cycle of a specific product or service in order to determine its ecological footprint. Thus, life cycle analysis can provide detailed data on the impact of a product in different phases of its life cycle, which can then be aggregated and compared to the global ecological footprint of human lifestyles. This helps identify specific ways to reduce the environmental footprint of products and services.

Life cycle analysis, also called "life cycle environmental impact assessment," is a technique for identifying inputs of raw materials, energy, chemicals, etc. and outgoing waste, pollutants, recycling, etc. in the product life cycle and assessing potential environmental impacts. (Seol et al., 2021) Raw materials, water resources, and energy are inputs, and air emissions, water system emissions, solid waste, etc. in the production process, the use process, and the disposal process are the outputs. Figure 1 illustrates the technique with inputs and outputs, and the considered structure can be applied to various industrial processes.

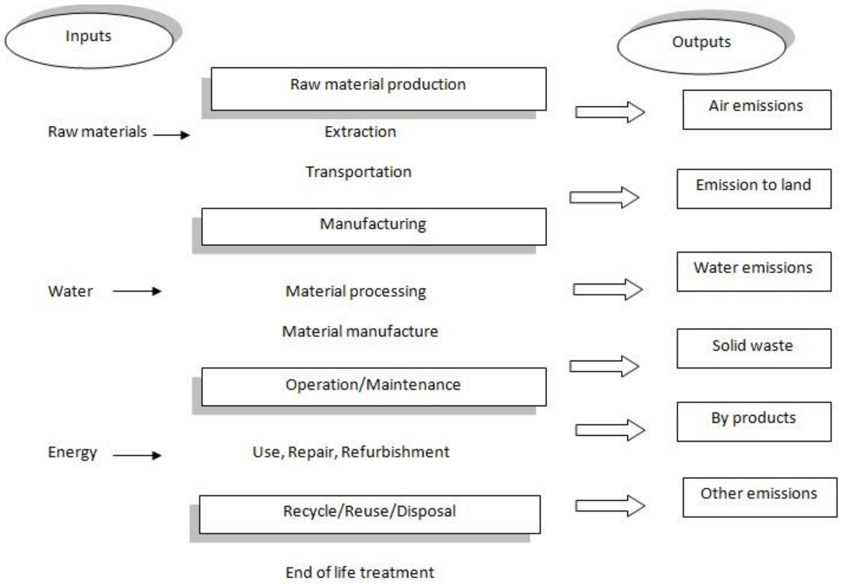

Figure 1. Life cycle assessment technique

Tools Used in Life Cycle Analysis

Life cycle analysis involves the use of various tools that are designed to measure and assess the environmental impacts of products or processes throughout their life cycle. Figure 2 highlights the main tools used in life cycle analysis.

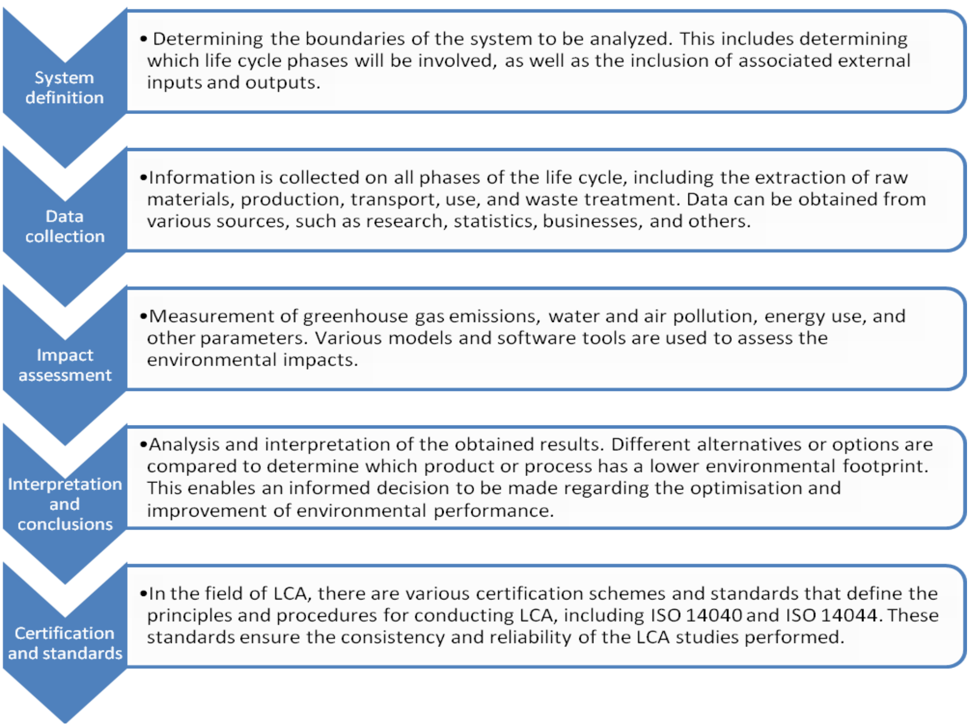

Figure 2. Tools for implementing life cycle analysis

The presented tools are used in combination to perform a complex and comprehensive life cycle analysis of products or processes. They help to understand and assess environmental impacts and identify opportunities for improvement and optimisation in accordance with the principles of sustainable development.

Indicators for Ecological Footprint Assessment

Environmental footprint assessment indicators are specific measures that are used to measure the impact of products or processes on the environment. (Vargas Gonzales et al., 2019) Different indicators can be used in an industrial context, and it is most important to choose those that are most appropriate for the specific sector or product. In general, these are:

- Energy efficiency: measures the energy efficiency of the product or process. It can be measured as the ratio of input energy to useful output or as the energy expenditure per unit of product.
- Water footprint: measures the water consumption or pollution associated with the product or process. The total amount of water used during the entire life cycle of the product or process is measured.
- Greenhouse gas emissions measure the amount of greenhouse gases emitted, such as CO_2, CH_4, and N_2O. It is used to estimate the carbon footprint of the product or process and its impact on climate change.
- Air and water pollution: measures the amount and types of pollution that is generated by the product or process and has an impact on air and water quality.
- Waste and recycling refers to the amount of waste that is generated by the product or process, as well as the possibilities of recycling materials and components. (Dimov et al., 2020)

When comparing different indicators and their applicability in the industrial context, it is important to take into account the specific needs and characteristics of the sector or product. Some indicators may be better suited to measuring climate impact, while others are better suited to assessing resource consumption or water and air pollution. It is important to choose indicators that are relevant to the specific industry and can provide information that can be used to improve and optimise the environmental footprint. (Vanham et al., 2019)

Application of the Integrated Approach to Life Cycle Analysis in Industrial Environments

The integrated life cycle analysis approach has wide applications in industrial processes, playing an important role in the management of environmental sustainability and the optimisation of products and processes. (Schaubroeck et al., 2021) Some of the main applications of the integrated life cycle analysis approach in industrial settings are:

- Design of products: allows assessment of their potential impact on the environment from the early stages of development. This includes choosing appropriate materials, processes, and technologies to reduce the adverse environmental impact throughout the product's life cycle.
- Supplier and supply chain management helps industrial enterprises assess and manage the environmental impact of their suppliers. This includes assessing energy consumption, greenhouse gas emissions, and other environmental parameters of supply, as well as supporting supply chain sustainability and responsibility.
- Process management provides an opportunity to assess and optimise the environmental footprint of industrial processes, including identifying environmental risks, measuring emissions and waste, optimising resource consumption (energy, water, and raw materials), and introducing more sustainable technologies and methods.
- Decision-making process: provides information and analysis that supports the decision-making process in industrial environments. This allows companies to balance and consider environmental, economic, and social aspects when choosing alternatives and strategies.

Communication and marketing enable businesses to communicate their efforts to optimise the environmental footprint of their products and processes to consumers and other stakeholders. This can have a positive effect on the image and positioning of the brand, as well as provide a competitive advantage in the market. The use of the integrated approach to life cycle analysis in industrial environments contributes to achieving sustainable and responsible entrepreneurship, reducing the adverse impact on the environment, and improving the environmental performance of products and processes.

Industrial Examples in the Field

The integrated life cycle analysis approach is used in various industries and processes in order to manage the ecological footprint and achieve sustainability. (Bockin et al., 2022)

- Assessment of the ecological footprint of food production, including assessment of soil and water pollution from agriculture, greenhouse gas emissions from food production and transport, and the impact of packaging and food chain waste. (Dilawar et al., 2019)
- Assessment of the environmental footprint in the automotive industry, in the production of cars and their components This includes measuring greenhouse gas emissions from production, in-use fuel, and electricity consumption, as well as recycling and waste disposal options for cars.
- Assessment of the ecological footprint in construction and in the production of building materials and processes This includes measuring the energy efficiency of buildings, the impact on air and water quality, waste management, and the possibilities of recycling materials.
- Evaluation of the ecological footprint in the field of information technologies and in the production of electronic devices and computer systems. This includes measuring the energy efficiency of devices, sources of materials and components, waste management, and electronics recycling options.
- Assessment of the ecological footprint in the textile industry in the production of textile products and materials, including the processing of textiles and the use and disposal of clothing. This includes measuring energy efficiency, water and chemical use, and opportunities to recycle textile waste.

Identification of the Key Factors Influencing the Ecological Footprint and Opportunities for Optimisation

Identifying the key factors that influence the ecological footprint is an important step in the process of environmental analysis and management. There may be different factors that apply to specific industries or processes, but here are some of the general key factors:

- Energy consumption: The energy used during production, transport, use, and disposal of products is one of the main factors affecting the ecological footprint. Identifying energy-efficient methods and technologies can significantly reduce the footprint. Optimisation opportunities include using energy-saving electrical appliances, improving thermal insulation, using energy-efficient lighting and heating systems, and implementing processes to optimise energy operations.
- Water consumption: Water is another important factor to consider when evaluating the ecological footprint. Identifying methods to optimise water resources reduce losses, and reuse water can contribute to reducing the footprint. Optimisation occurs by using technologies to reduce water consumption, recycle and reuse water, and optimise wastewater treatment and disposal processes.
- Sources of greenhouse gas emissions: greenhouse gas emissions such as carbon dioxide (CO_2), methane (CH_4), and nitrogen oxide (NOx) have a significant impact on climate change. Identifying and reducing emissions from various sources, such as manufacturing, transportation, heating, and cooling, is an important goal in reducing the footprint.
- Waste management: Effective waste management, including recycling, re-engineering, and the use of secondary raw materials, is a key factor in reducing the environmental footprint. Identifying methods to reduce waste and move towards sustainable waste management systems is essential.
- Use of raw materials: The use of raw materials, including extraction, processing, and transportation, also has an important impact on the ecological footprint. Identifying sustainable sources of raw materials, optimising material flows, and reducing excess consumption can reduce the footprint. Optimisation opportunities include choosing materials with lower energy and water consumption during production, fewer emissions of harmful substances, and better degradability or recyclability.
- Innovation in processes: The research and implementation of innovative processes and technologies can lead to a significant reduction of the ecological footprint. For example, the development of green and sustainable production methods, the use of renewable energy sources, the development of processes for circularity and wear resistance of materials, as well as the application of eco-design principles, can contribute to reducing the footprint.

Researches

An author's study was carried out, which tracks CO_2 as a leading factor in environmental pollution. Statistical methods were used for data processing. Figure 3 tracks the progression of carbon emissions released from industrial processes.

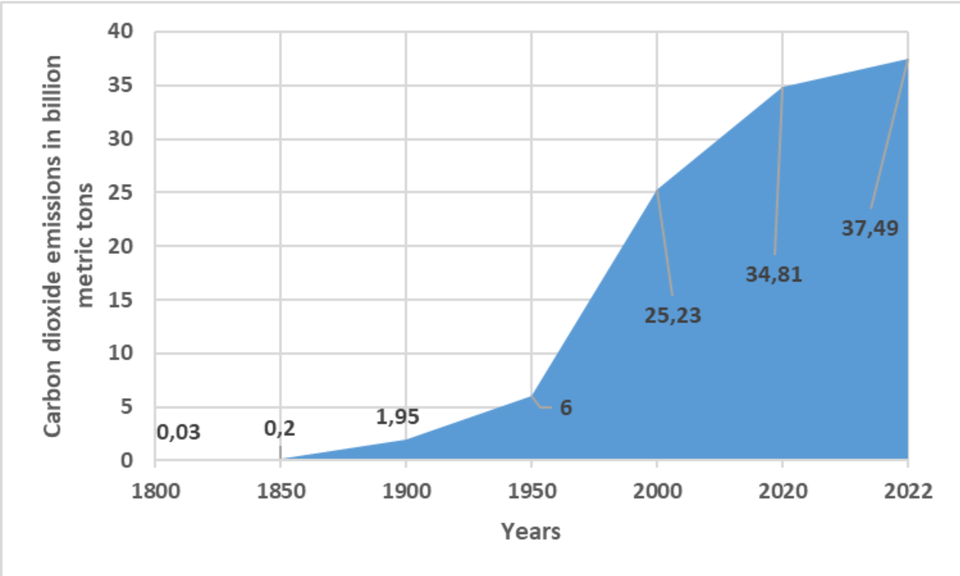

Figure 3. Levels of carbon dioxide emissions, released from industrial processes, in billion metric tons, (Author's research)

The dramatic increase in emissions with the onset and development of the industrial revolution is impressive. These processes are well supported in the scientific literature. CO_2 emissions are often linked to global warming and climate change, which are fundamental challenges for the world today. Therefore, today the world is undertaking efforts, including international agreements such as the Paris Agreement, to reduce emissions and limit climate change.

Nevertheless, the size of the population also has a significant role in determining the quantity of carbon emissions. There exists a robust and very significant association between pollution and population. The graphical representation of the dependence is depicted in Figure 4.

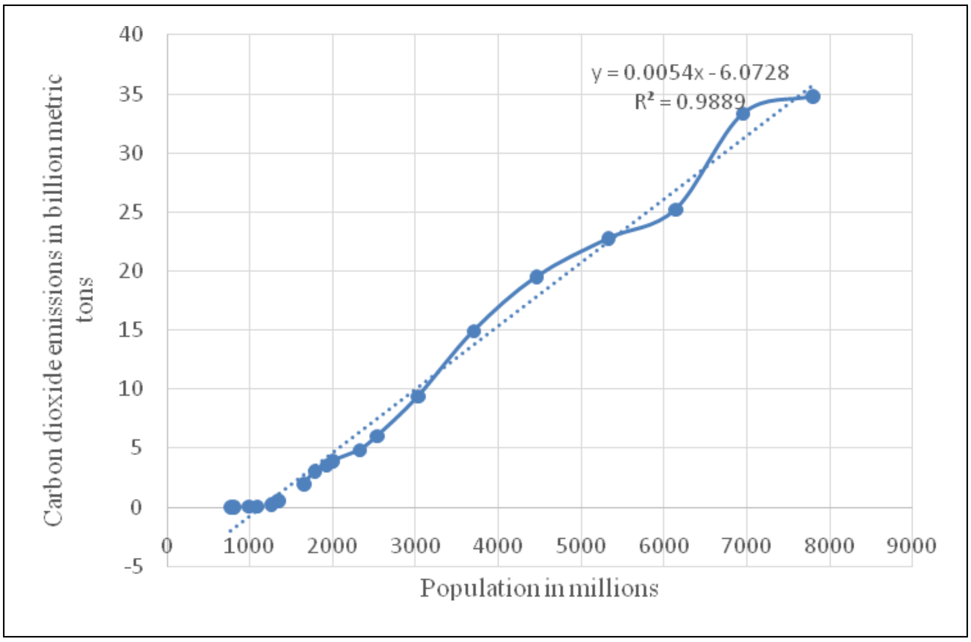

Figure 4. Correlation between carbon dioxide emissions and world population, (Author's research)

The equation illustrating the relationship and the coefficient of determination R^2=0.9889 are also shown. Based on this model, it is possible to make predictions regarding the projected pollution levels in the year 2050, coinciding with an estimated global population of 9735 million individuals. According to the estimate, it is anticipated that carbon emissions would reach a value of 519.6388.

A larger population leads to increased energy consumption, requires larger production capacities and implies greater mobility, which in turn leads to higher levels of greenhouse gas emissions. In practice, population growth leads to an increase in energy consumption for heating, cooling, lighting, transportation, etc. In addition, increased consumption of food, goods and services also contributes to carbon emissions associated with agriculture, industry and transport. To reduce the carbon emissions associated with population growth, strategies for sustainable development and efficient use of resources are needed. (Global Footprint Network, 2017) This may include promoting energy efficiency in buildings, promoting renewable energy sources, improving public transport, moving towards more sustainable and ecological production and consumption models. In addition, education and public awareness play an important role in consciously reducing carbon emissions. Raising environmental awareness and promoting responsible consumption are essential to achieving a sustainable future.

Conclusion

The evaluation of the ecological footprint is essential for industrial processes, as it allows the identification of opportunities for optimisation and reduction of the footprint. By using methods and tools such as energy efficiency, waste and water management, sustainable material selection, and process innovation, industrial companies can reduce their negative impact on the environment and achieve sustainable practices. In turn, the integrated approach to life cycle analysis provides a complex and systematic methodology for assessing the ecological footprint of industrial processes. It includes consideration of all phases of the life cycle of a product or process, from raw material extraction to waste treatment, and applies quantitative assessment to various aspects such as greenhouse gas emissions, energy and water consumption, and air and water pollution. Identifying the key factors that influence the ecological footprint is of great importance in carrying out the assessment. This includes an analysis of energy efficiency, waste management, greenhouse gas emissions, and water resource use. Identifying these factors allows companies to focus on specific areas for improvement and implement targeted optimisation measures. The use of the integrated life cycle analysis approach in industrial environments has been applied in various industries and processes. For example, in the production of food products, an assessment of the ecological footprint of raw materials, production and packaging processes, as well as waste management, is carried out. In the field of electronics, life cycle analysis is used to assess the energy efficiency of devices, e-waste management, and the use of rare materials. The research done proves the correlation between the levels of CO_2 emissions with the world population and, in this context, the effectiveness of ecological footprint and life cycle assessment, which analyse in detail various aspects such as energy and material efficiency, greenhouse gas emissions, recycling, and others.

Scientific Ethics Declaration

The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Acknowledgements or Notes

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