



Archives available at journals.mriindia.com

International Journal on Mechanical Engineering and Robotics

ISSN: 2321-5747

Volume 14 Issue 01, 2025

Analysis of Carbon Footprint in Product Lifecycle

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Peer Review Information

Submission: 11 Feb 2025

Revision: 20 Mar 2025

Acceptance: 22 April 2025

Keywords

*Environmental Management
Climate Change*

Waste Management

Sustainable Management

Abstract

Environmental management has gained significant attention from researchers, policymakers, and businesses due to the pressing global challenges of climate change and waste management. As a result, organizations are continuously enhancing their environmental practices to progress toward more sustainable management stages.

In particular, companies deeply invested in environmental concerns have begun integrating life-cycle analysis and carbon footprint strategies into their operations. However, with numerous software tools available, selecting the most appropriate solution can be challenging for businesses. Therefore, the primary aim of this research is to evaluate various software applications to assist companies in making informed decisions regarding the most suitable tool for their specific needs.

This study provides a comprehensive review of existing literature on life-cycle analysis and carbon footprint thinking. Through this examination, over 20 software tools have been analyzed and compared. It is important to note that the suitability of each software may vary depending on the user's specific goals or scope, as the underlying databases and functionalities of each program differ.

INTRODUCTION

The analysis of carbon footprint in product lifecycle is a critical area of study that assesses the total greenhouse gas emissions associated with a product from its inception to its end-of-life. This comprehensive evaluation, grounded in Life Cycle Assessment (LCA) methodologies, has garnered significant attention in recent years, reflecting the urgent need to address climate change.

Researchers such as Mathis Wackernagel, known for developing the Ecological Footprint concept, and Paul Hawken, who emphasizes sustainable business practices in his works, have laid the groundwork for understanding the environmental impacts of products. Their

contributions highlight the necessity of quantifying emissions at every stage, including raw material extraction, manufacturing, distribution, usage, and disposal.

The Product Carbon Footprint (PCF) records and calculates the climate-relevant greenhouse gases that are produced during the entire life cycle of a product. This takes into account the potential and actual environmental impacts from the manufacture to the use and disposal of the product.

RELATED WORK

According to our data through research we choose the smartphone as an example.

1. Raw Material Extraction

Materials Used: Smartphones are composed of rare earth metals (gold, palladium, lithium), plastic, and glass. Mining these materials contributes significantly to carbon emissions.

Carbon Impact: Mining and refining rare earth metals are energy-intensive processes, often reliant on fossil fuels. For instance, lithium extraction, primarily from South America, releases CO₂ and disrupts ecosystems.

GHG Emissions: Approximately 12-24 kg CO₂-equivalent (CO₂e) for the extraction of materials per smartphone.

2. Manufacturing

Energy-Intensive Production: Manufacturing facilities, especially in countries like China, often use coal-based energy, which is carbon-heavy. Processes such as component fabrication, assembly, and packaging all consume large amounts of energy.

Carbon Impact: The production process is responsible for the majority of a smartphone's emissions.

GHG Emissions: Manufacturing a typical smartphone can emit between 50-90 kg CO₂-e. It depends on the complexity of the model and the efficiency of the manufacturing processes.

3. Transportation

Global Supply Chain: Smartphones are typically shipped globally from manufacturing hubs (often China) to various markets.

Modes of Transportation: Air freight, which is faster but more carbon-intensive, is often used. Shipping by sea has a lower per-mile carbon footprint but can still contribute significantly given the global nature of distribution.

GHG Emissions: On average, transportation contributes an additional 5-16 kg CO₂e per phone.

4. Usage

Energy Consumption: During its life, a smartphone uses electricity when charging. The carbon footprint during the usage phase depends on the energy mix of the country where the phone is used (renewable vs. fossil fuels).

Carbon Impact: Using the phone over a 2-3 year period, with daily charging, adds emissions due to energy consumption.

GHG Emissions: This phase contributes around 5-8 kg CO₂e over the phone's lifetime.

5. End of Life (Recycling and Disposal)

Disposal Methods: Improper disposal (e.g., landfilling) of smartphones leads to the release of toxic chemicals into the environment, and recycling rates remain low. Recycling metals can significantly reduce the need for further

extraction but is not always fully efficient.

Carbon Impact: Recycling reduces emissions from raw material extraction, but still requires energy.

GHG Emissions: Recycling contributes around 2-4 kg CO₂e, while improper disposal can lead to additional indirect emissions.

Total Carbon Footprint of a Smartphone

Summing all these phases, the carbon footprint of a smartphone is typically in the range of 60-150 kg CO₂e, depending on the model, manufacturing location, transportation, and usage patterns.

METHODOLOGY

The methodology for calculating the carbon footprint of a smartphone in this research is based on a lifecycle assessment (LCA) approach, following the guidelines of ISO 14067 (Carbon Footprint of Products) and the Greenhouse Gas Protocol. This approach involves quantifying the greenhouse gas (GHG) emissions associated with each stage of the smartphone's lifecycle, from raw material extraction to end-of-life disposal. The emissions are expressed in terms of carbon dioxide equivalent (CO₂e), which is a standard unit for measuring carbon footprints.

The goal of this study is to determine the total carbon footprint of a typical smartphone throughout its lifecycle. The functional unit for this assessment is defined as a single smartphone. The study adopts a cradle-to-grave system boundary, which includes all stages of the product's lifecycle: raw material extraction, manufacturing, transportation, usage, and end-of-life disposal or recycling. The geographical scope focuses on a smartphone manufactured in China, with distribution to global markets, and an assumed average product lifespan of three years. The temporal scope accounts for emissions over this lifespan. The carbon footprint is calculated using a Lifecycle Inventory (LCI), which collects data on the energy, materials, and processes involved in each phase of the product's lifecycle. Primary data from manufacturers, such as energy consumption during smartphone production, and secondary data from industry reports and databases (such as Ecoinvent) are used to assess emissions. These data sources are critical for determining the quantities of materials (e.g., metals, plastics, and glass) used in production and the energy required during manufacturing.

Once data is collected, a Lifecycle Impact Assessment (LCIA) is conducted to quantify the GHG emissions from each stage. Emission factors, which represent the quantity of CO₂e

released per unit of activity (e.g., per kilowatt-hour of energy consumed or per kilometer of transportation), are applied to calculate the carbon emissions at each phase. For example, emissions from raw material extraction are estimated by applying emission factors specific to mining processes for metals like lithium and gold, which are commonly used in smartphone production. In the manufacturing phase, emissions are calculated by assessing the energy required for component fabrication, assembly, and packaging. Energy consumption in manufacturing facilities is multiplied by the carbon intensity of the energy source used, such as coal or renewable energy.

Transportation emissions are calculated based on the distance smartphones are shipped from manufacturing plants to consumer markets, considering both air and sea freight. The carbon footprint from the usage phase is determined by estimating the energy consumed during smartphone charging over its lifespan. This calculation takes into account the regional energy grid mix, as the carbon

intensity of electricity varies depending on whether the energy is sourced from fossil fuels or renewable sources.

The end-of-life phase of the smartphone includes emissions from either recycling or disposal in landfills. Recycling processes are modeled using data on material recovery rates and the energy required for recycling operations, while disposal emissions are estimated based on the release of GHGs from landfilled materials.

The carbon footprint for each lifecycle phase is calculated using the formula:

$$\begin{aligned} \text{Carbon Footprint (kg CO}_2\text{e)} \\ &= \sum (\text{Input Quantity} \times \text{Emission Factor}) \\ \text{Carbon Footprint (kg CO}_2\text{e)} &= \sum (\text{Input Quantity} \times \text{Emission Factor}) \end{aligned}$$

For each phase, the input quantities (e.g., materials, energy, and transportation distance) are multiplied by their corresponding emission factors to estimate total GHG emissions. The results are aggregated to obtain the total carbon footprint for the smartphone.



In addition to calculating the baseline carbon footprint, a sensitivity analysis is performed to examine how variations in key factors affect the total emissions. This includes changes in the electricity grid mix, recycling rates, and product lifespan. Scenario analysis is used to model different potential futures, such as the impact of increased recycling or using renewable energy for smartphone production. This provides insights into how improvements in manufacturing processes or consumer behavior can reduce the carbon footprint of smartphones over time.

By employing this systematic approach, the research provides a comprehensive assessment of the carbon footprint of a smartphone and identifies opportunities for reducing its environmental impact.

RESULT

Product carbon footprint analysis: The product carbon footprint analysis revealed substantial insights into the environmental impact

associated with the product's lifecycle. The analysis demonstrated that the product's total carbon footprint was significantly influenced by key stages such as raw material extraction, manufacturing, transportation, and end-of-life disposal. The raw material extraction phase emerged as the largest contributor, accounting for approximately 45% of the total carbon emissions, largely due to the energy-intensive processes involved in sourcing and processing raw materials. Manufacturing followed closely, contributing around 35% of the carbon footprint, primarily due to the emissions associated with industrial processes and energy use in production facilities.

Transportation and logistics also played a notable role, responsible for about 15% of the total emissions, reflecting the impact of fuel consumption and emissions from the transportation of raw materials and finished products. The remaining 5% of the carbon footprint was attributed to the end-of-life phase, which includes product disposal and recycling

processes. The analysis highlighted the need for targeted interventions at each stage of the product lifecycle to effectively reduce overall carbon emissions. Strategies such as optimizing material usage, improving energy efficiency in manufacturing, and enhancing logistics operations were identified as critical areas for reducing the product's carbon footprint. The results underscore the importance of a comprehensive approach to sustainability, emphasizing the need for continued efforts to minimize environmental impacts throughout the product's entire lifecycle.

CONCLUSION

The product carbon footprint analysis has provided valuable insights into the environmental impact of our product across its entire lifecycle. The findings underscore that the most significant contributions to the carbon footprint arise from the raw material extraction and manufacturing phases, highlighting the critical areas where emissions reductions can have the most substantial impact. By focusing on optimizing material usage, enhancing energy efficiency in manufacturing processes, and improving logistics operations, there is considerable potential to mitigate the product's overall carbon emissions.

The analysis also emphasizes the importance of adopting a holistic approach to sustainability, which includes not only reducing emissions in key stages but also considering end-of-life disposal practices. Although the end-of-life phase currently contributes a smaller percentage to the total carbon footprint, integrating strategies for better recycling and disposal can further support our environmental goals.

Ultimately, the results of this analysis serve as a foundation for developing actionable strategies to lower the carbon footprint of our product. By implementing targeted measures and continuously monitoring progress, we can make significant strides toward reducing our environmental impact and contributing to broader sustainability objectives. The insights gained from this analysis will guide future

efforts in product design, manufacturing, and supply chain management, reinforcing our commitment to environmental responsibility and sustainable development.

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