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Understanding the potential for renewable energy in supply chain decarbonization

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Abstract
Life Cycle Assessment (LCA) is a comprehensive methodology for evaluating environmental impacts across a product's entire life cycle, from raw material extraction to disposal. This systematic approach enables informed decision-making by identifying critical environmental impacts and trade-offs at each stage. LCA is widely used in industries such as agriculture, textiles, and radiological protection to optimize eco-efficiency and material selection. The Ecoinvent database plays a crucial role in LCA by providing high-quality inventory data that enhances the accuracy of environmental impact assessments. Additionally, reducing industrial emissions requires a multifaceted approach, including energy efficiency improvements, renewable energy integration, and carbon capture technologies. Supply chain decarbonization, particularly Scope 3 emissions, is vital for achieving net-zero targets, as these indirect emissions often constitute the majority of a company's carbon footprint. LCA serves as a powerful tool for identifying high-emission stages in supply chains and implementing targeted reduction strategies. By integrating LCA with supply chain management, industries can enhance sustainability efforts and contribute to global climate goals.

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Introduction

Life Cycle Assessment (LCA) is a comprehensive methodology used to evaluate the environmental impacts associated with all stages of a product's life cycle, from raw material extraction to disposal. This approach provides a holistic view of the environmental effects of products, processes, and services, enabling informed decision-making for sustainability. LCA examines the entire life cycle of a product, including raw material acquisition, production, distribution, use, and end-of-life disposal. This comprehensive analysis helps identify environmental impacts at each stage and understand how changes in one part of the life cycle affect others (Wewer, 2023) [1]. LCA assesses various environmental impacts, such as climate change, ozone depletion, and resource depletion. It provides a multi-criteria approach to evaluate these impacts, allowing for a balanced understanding of trade-offs (Wattier *et al*., 2023) [2]. The LCA framework typically includes four phases: goal and scope definition, inventory analysis (LCI), impact assessment (LCIA), and interpretation. This standardized approach ensures consistency and comparability across different studies (Jhanji, 2023) [3]. LCA is used to benchmark and assess environmental impact reductions, informing decisions on product design and process adaptation. It is particularly beneficial in optimizing eco-efficiency and material selection in various industries, including textiles and agriculture (Jhanji, 2023) [3] (Fan *et al*., 20220) [4]. LCA is applied in diverse sectors, such as radiological protection, carbon dioxide supply chains, and agriculture, to quantify environmental impacts and guide sustainable practices (Wattier *et al*., 2023) [2] (Leonzio, 2023) [5] (Fan *et al*., 2022) [19].

Ecoinvent is a pivotal resource for LCAs due to its comprehensive and high-quality LCI data, which is essential for accurate and reliable environmental impact assessments. It serves as a global reference for inventory data, facilitating the evaluation of environmental impacts across various sectors and geographies. The database's importance is underscored by its extensive use in both academic research and practical applications, providing a standardized foundation for LCA studies. Ecoinvent offers a wide range of datasets covering numerous sectors, including electricity generation, transportation, and water use, which are critical for conducting thorough LCAs. For instance, the database includes detailed inventories for electricity production across 71 geographic regions, enhancing the representativeness and accuracy of LCA studies worldwide (Treyer & Bauer, 2016).The database's modular approach allows users to adapt datasets to specific needs, such as the electric passenger car transport datasets, which can be customized based on vehicle characteristics (Duce *et al*., 2016) [7]. Ecoinvent's integration with other databases, such as EXIOBASE, allows for the creation of hybrid LCA databases that reduce truncation errors and provide more realistic lifecycle emissions and impacts (Agez, 2020) [8]. The hybridization process involves adding missing inputs, such as services, to ecoinvent processes, thereby enhancing the comprehensiveness of the LCA results (Agez, 2020) [9]. Ecoinvent provides multiple system models, such as the recycled content and consequential models, which are crucial for aligning LCA studies with specific goals and ensuring meaningful assessments. The database's transparency is further supported by detailed documentation and tutorials, which guide users in making informed methodological choices (Saade *et al*., 2019) [10].This paper proposes using structural path analysis in order to identify and disaggregate the electricity-related carbon contribution of LCIs from the Ecoinvent database. This disaggregation can provide an insight into how replacing fossil based electricity with renewable electricity can reduce the embodied emissions of any product.

Options for reducing emissions in industry

Reducing emissions within the industrial sector is a multifaceted challenge. The industrial sector is a significant contributor to global greenhouse gas emissions, and addressing this requires innovative approaches that span from energy efficiency measures to far fetched technological advancements. Enhancing energy efficiency in industrial processes can significantly reduce emissions. This includes optimizing energy use in manufacturing and design, as well as improving material efficiency (Racz, 2019) [11]. Integrating renewable energy sources, such as solar and wind, into industrial operations can reduce reliance on fossil fuels. For instance, rooftop solar PV systems and solar light tubes have been shown to significantly cut electricity consumption and emissions in industrial complexes (Yadav *et al*., 2021) [12]. On the technological side, CCS is a promising technology for reducing emissions by capturing CO2 from industrial processes and storing it underground. This method is particularly effective for industries with high CO2 purity in their exhaust, such as steel and cement manufacturing, which can lower the cost of capture (Psarras *et al*., 2017) [13]. This process produces low-carbon hydrogen and solid carbon, which can be sequestered or used as a manufacturing feedstock. It offers a cost-competitive alternative to other decarbonization methods, especially when combined with policy incentives like the California Low Carbon Fuel Standard (Wald *et al*., 2020) [14]. These technologies enable real-time monitoring and optimization of industrial processes, leading to more energy-efficient operations and reduced emissions. By simulating and predicting future behaviors, industries can make informed decisions to minimize their carbon footprint (Digital Twin and Industrial Internet of Things Architecture to Reduce Carbon Emissions, 2022) [15]. However, these strategies primarily address direct emissions from industry and do not account for indirect emissions from the supply chain.

Importance of Supply Chain decarbonization

Scope 3 decarbonization is crucial for achieving net-zero emissions targets as it encompasses the indirect emissions that occur in a company's value chain, which often constitute a significant portion of an organization's total greenhouse gas (GHG) emissions. These emissions are not directly controlled by the company but are a result of activities from sources such as purchased goods and services, transportation, and waste disposal. Addressing Scope 3 emissions is essential for a comprehensive approach to decarbonization, as it ensures that all aspects of the value chain are considered in the transition to a low-carbon economy. Scope 3 emissions can account for up to 75% of a company's total GHG emissions, making them a critical area for reduction efforts (Downie & Stubbs, 2010) [16]. This highlights the necessity of including these emissions in any comprehensive decarbonization strategy. Scope 3 emissions encompass the entire lifecycle of products and services, from raw material extraction to end-of-life disposal. This broad scope means that reducing these emissions can have a significant impact on the overall carbon footprint of industries. Utilizing LCA to assess and mitigate Scope 3 emissions can help identify the most carbon-intensive stages of a product's lifecycle and target them for reduction (Sadhukhan, 2022) [17].

Using LCA for supply chain decarbonization

LCA is a powerful tool that companies can leverage to decarbonize their supply chains by systematically evaluating the environmental impacts associated with all stages of a product's life. This approach not only aligns with global climate goals but also improves competitiveness and brand image. LCA allows companies to assess the entire supply chain, from raw material extraction to end-of-life disposal, identifying stages with the highest carbon emissions. By pinpointing specific areas of high emissions, companies can implement targeted strategies to reduce their carbon footprint. In the automotive industry, for example, focusing on materials like steel and aluminum can lead to significant emission reductions (Poschmann *et al*., 2023) [18]. Companies can use LCA to explore the use of alternative materials and recycling processes. For instance, the use of circular materials and recycling in the automotive sector can decrease emission intensities by up to 91% by 2050 (Poschmann *et al*., 2023) [18]. Effective supply chain decarbonization requires collaboration with suppliers. Walmart's use of LCA to evaluate and reduce Scope 3 emissions through supplier management practices exemplifies this approach (Asif *et al*., 2022) [19]. Integrating LCA with supply chain management and design for environment principles can lead to improved environmental performance by addressing significant impacts at different life cycle stages (Weil, 2023) [20].

Methodology

Structural path analysis (SPA) is a technique used to identify and quantify the significant pathways through which environmental impacts, such as emissions, are transferred within an economic system. When applied to ecoinvent data, SPA can help in understanding the intricate pathways of environmental impacts across different sectors and regions. SPA can be performed using the open-source pyspa package. pyspa is an object-oriented Python package designed for conducting parametric structural path analysis on square A matrices, which can represent processes or input-output relationships. This tool accommodates any number of environmental, social, or economic variables and allows for the examination of multiple stages within a supply chain. The package generates a SupplyChain object that encompasses various components, including Pathway and Node objects. Additionally, the results obtained from the analysis can be exported to CSV format with a single command. The development of pyspa arose from the need for accessible open-source software capable of performing structural path analysis in a systematic and object-oriented way (Stephan *et al*., n.d.). Details on how to perform the analysis can be found on the pyspa github repository.

The approach suggested in this paper is as follows:

1. Perform an LCA for the goods that the company manufactures.
2. Identify the hot spots to reduce the carbon impact of the goods.
3. Employ strategies such as energy efficiency, renewable energy in manufacturing, material substitution, recycled material integration, etc. in order to reduce the embodied carbon of the product.
4. Within the LCA, perform a structural path analysis using pyspa on the Ecoinvent data used in order to understand the contribution of electricity related carbon emissions to the total embodied emissions of the raw materials.
5. Work with suppliers of the raw materials enable them to procure renewable energy for their operations.
6. Again, using structural path analysis on the Ecoinvent data, replace the fossil electricity emissions with the appropriate life cycle renewable electricity emissions.
7. Perform the LCA again using the updated raw material emission factor in order to claim the benefit of suppliers using renewable energy.

Example Implementation

Assuming the company is a bicycle manufacturing company. An LCA of bicycles produced will provide a comprehensive evaluation of their environmental impacts from production to disposal. LCA of bicycles involves analyzing various stages such as material extraction, manufacturing, usage, and end-of-life processes.

The materials and manufacturing phase of the bicycle accounts for over 70% of the total Global Warming Potential (GWP). The production phase of bicycles, particularly the extraction and processing of materials like aluminum, has a significant environmental impact. Aluminum components are identified as having the highest environmental burden (67.3%) due to energy-intensive processes involved in their production (Roy *et al*., 2019) [22].

The study by Roy *et al*. highlights the need for working with the Aluminum supplier in order to understand how to decarbonize the material using renewable energy. To apply the approach highlighted in this paper, the ecoinvent process *"Global market for wrought aluminium alloy"* was chosen. Using SPA analysis with the method as defined in the pyspa package, the electricity related GWP contribution of Aluminum is 40% of the total GWP. It is estimated that the emission factor associated with electricity generated from renewable resources is approximately 5% of that from fossil fuel-based sources. This suggests that the GWP of Aluminum can be reduced by 38% by replacing the fossil based electricity with renewable electricity in the supply chain.

This example implementation shows the potential of using SPA to determine the reduction in embodied emissions of materials through the use of renewable electricity. This approach can be employed within any industry for any products highlighting its versatility.

Conclusion

In conclusion, the integration of Life Cycle Assessment (LCA) and structural path analysis (SPA) presents a robust framework for understanding and mitigating the environmental impacts associated with supply chain activities, particularly in the context of decarbonization efforts. By systematically evaluating the entire life cycle of products and identifying hotspots for carbon emissions, companies can implement targeted strategies to reduce their carbon footprints. The application of Ecoinvent data through SPA allows for the disaggregation of electricity-related emissions, providing valuable insights into the potential for replacing fossil-based electricity with renewable sources. This approach not only aids in achieving net-zero emissions targets but also enhances the overall sustainability of industrial operations. As demonstrated through the bicycle manufacturing example, the collaboration with suppliers to transition towards renewable energy can lead to significant reductions in the global warming potential of materials, thereby contributing to a more sustainable and low-carbon economy. The findings underscore the importance of a comprehensive approach to supply chain decarbonization, emphasizing the need for innovative methodologies and collaborative efforts across all stages of the product life cycle.

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