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Real-Time Carbon Data Collection Based on the Duty of Care: A Case Study of an Aluminum Processing Plant

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Abstract

With international brands enforcing strict Extended Producer Responsibility (EPR) requirements, aluminum processing manufacturers must fulfill their Duty of Care to meet end-customer expectations, particularly in urgently reducing carbon emissions during production. Accurate real-time carbon data collection enables aluminum processing plants to immediately enhance carbon efficiency and fulfill their Duty of Care obligations demanded by end users.
This study explores a real-time carbon data collection system designed to precisely assess the carbon footprint of each production batch. Through the case study of an aluminum processing plant, we demonstrate how real-time data technologies can be applied to improve carbon efficiency, reduce emission errors, and continuously optimize production processes. The results show that real-time data collection significantly enhances carbon management in aluminum processing and supports better control of carbon emissions across different stages of the product life cycle.

JEL classification numbers: L0, L7.
Keywords: Real-Time Carbon Data, Product Life Cycle, Duty of Care, Carbon Efficiency.

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1. Introduction

Within the principle of Duty of Care, due to the high carbon intensity of its raw materials, the aluminum processing industry has emerged as a critical focus for carbon reduction initiatives. Conventional methods of calculating carbon footprints predominantly rely on annual data, limiting their ability to capture real-time production variations and thereby impairing decision-making efficiency. The integration of real-time carbon data collection with product life cycle management can enhance data transparency and enable companies to formulate more precise carbon reduction strategies, supporting aluminum producers in meeting the evolving demands of end customers.

The aluminum processing sector plays a pivotal role within the global supply chain, with its production processes characterized by substantial energy consumption and significant greenhouse gas emissions. Accordingly, improving the accuracy of carbon emission data and implementing effective mitigation measures are essential for advancing the industry's sustainable development. Real-time data collection allows enterprises to continuously monitor carbon emissions throughout the production process, facilitating the prompt adjustment of production parameters to reduce both energy consumption and environmental impact. Additionally, enhanced data transparency can strengthen the trust of governments, consumers, and investors in a company's environmental commitments, thereby bolstering its competitiveness in the marketplace.

Furthermore, Duty of Care emphasize corporate ethical responsibilities in environmental governance, including information transparency, employee engagement, and collaboration with supply chain partners to establish a sustainable operational model. This study aims to explore how real-time carbon data technology can be combined with Duty of Care to further promote the balanced development of enterprises in terms of environment, society and economy.

2. Literature Review

2.1 Carbon Emission Coefficient of the Aluminum Industry

Although aluminum is abundant in the Earth's crust, the extraction of pure metallic aluminum requires a substantial amount of energy. Consequently, the carbon emissions associated with primary aluminum production are approximately seven to ten times higher than those of cement and steel production (Ding et al., 2024).

2.2 Definition of the Duty of Care

The obligation of The Duty of Care refers to corporate executives should be carefully evaluate when making decisions, ensuring that no negligence occurs in areas that require attention. Decision-makers are expected to fulfill their responsibilities with the highest degree of diligence. The precautions of Duty of Care refers to the precautions that people in society who are generally honest, diligent and have considerable experience should have. In Taiwan, the courts believe that the general social concept is that people with considerable knowledge and experience can pay attention to a certain event, and the standard is objectively determined. (Hsu, 2016).

2.3 The Importance of Real-Time Carbon Data

Currently, domestic enterprises predominantly rely on consulting firms to conduct carbon inventories. These consultants typically perform carbon assessments based on their professional experience, with records often maintained through Excel files or digital tools. However, due to the lack of regulatory verification mechanisms, digital tools developed by information service providers have encountered difficulties in achieving widespread adoption (Wang, 2024).

Building a sustainable supply chain is a critical path toward achieving broader societal sustainability goals, supporting both carbon reduction targets and environmental protection commitments. For enterprises, as directly bound stakeholders under the global trends of net-zero emissions and sustainable development, it is imperative to actively align with market demands. This includes closely monitoring the development of relevant industry mechanisms, strengthening cooperation with suppliers, and implementing thorough supply chain due diligence, where the importance of real-time carbon data becomes increasingly evident.

Real-time carbon data not only serves as a crucial foundation for internal corporate decision-making but also enhances management efficiency and transparency. It enables companies to rapidly monitor carbon emissions across various stages, including production processes, logistics, and raw material sourcing. Through real-time data analysis, enterprises can promptly identify carbon-intensive hotspots, make adjustments, and optimize operations. This leads not only to reduced carbon footprints but also contributes to energy conservation, efficiency improvements, and cost control. Furthermore, real-time carbon data provides a solid basis for communication with stakeholders, enhancing corporate credibility and competitiveness in sustainability reporting and carbon disclosure efforts.

With advancements in digital technologies and carbon management tools, an increasing number of companies are adopting various solutions to achieve real-time monitoring and intelligent decision-making regarding carbon emissions. This shift is driving supply chains toward a low-carbon and high-efficiency model. Therefore, the establishment of real-time carbon data systems has become a fundamental pillar for realizing sustainable supply chains, achieving carbon neutrality, and enhancing international competitiveness.

3. Research Methodology

3.1 Factory Background

This study adopts case study approach, selecting an aluminum processing plant in Taiwan as the research subject and introducing a real-time carbon data collection system.

The selected facility is a medium-sized aluminum processing factory whose primary production processes include aluminum ingot smelting, rolling, extrusion, and surface treatment of aluminum products. Historically, the factory relied on annual data to calculate the carbon footprint of its products, making it difficult to accurately identify specific sources of carbon emissions and to track changes over time.

To address this limitation, a real-time carbon data collection system (accessible via both app and web platforms) was installed. Dynamic monitoring was implemented for each batch of the production process, enabling more precise tracking and analysis of carbon emissions at each production stage.

3.2 Design of the Real-Time Data Collection System

The data collection system utilized in this study is based on mobile application technology, integrated with an Energy Management System (EMS) and a Production Data Management System. The system is capable of recording real-time data on electricity consumption, fuel usage, material consumption, and waste generation. Production data for each batch is automatically recorded and uploaded to a central database, where carbon footprint calculations are performed using specific algorithms in compliance with ISO 14067 and ISO 14064-3 standards (ISO, 2018; ISO, 2019).

The key components of the system include:

- Sensor Network: Sensors are installed on major equipment such as melting furnaces, extrusion presses, and rolling mills to monitor energy consumption and emissions in real time.
- Integration and Visualization: A data integration platform aggregates information from production equipment and the energy management system, presenting it through visualized dashboards to facilitate real-time analysis.
- Carbon Footprint Calculation Model: A calculation model designed in accordance with the ISO 14067 standard is employed to compute the carbon footprint of each product batch in a stage-by-stage manner.

3.3 Life Cycle Assessment (LCA) Configuration

The product Life Cycle Assessment (LCA) in this study is structured into four stages to evaluate carbon emissions:

1. Raw Material Extraction: This includes the extraction of bauxite ore and its initial refining into aluminum.
2. Manufacturing: This stage encompasses the primary production processes such as smelting, extrusion, and rolling.

3. Transportation and Distribution: This covers the transportation processes associated with delivering aluminum products.
4. Use and End-of-Life Treatment: This includes the service life of aluminum products in their end-use applications and their subsequent recycling or disposal processes.

The application of the real-time data system enables dynamic monitoring of carbon emissions across all stages, facilitating the immediate identification of carbon-intensive hotspots and providing actionable insights for management to implement timely improvements.

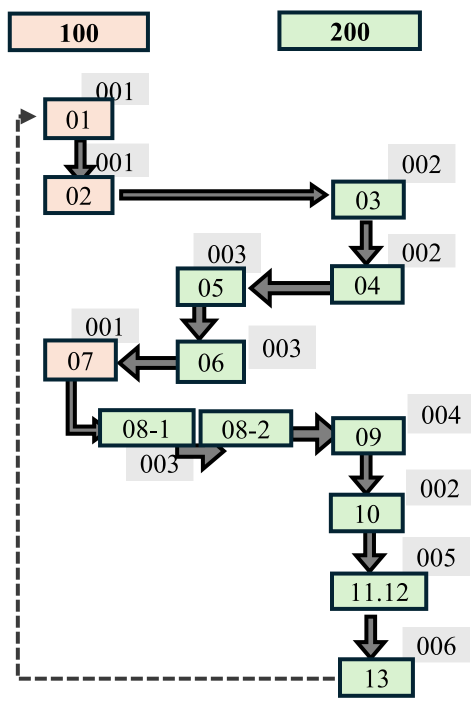
Process Flow Diagram	Code Description	
	100. Factory 200. Remanufacturing 01. Label 02. transfer 03. Reply transfer request 04. Transport order 05. Transportation 06. Load 07. Factory 08-1. Shipping 08-2. Deliver	09. Warehouse confirmed 10. Reproduction 11. Material requisition 12. Produce 13. Traceability 001. Administer 002. Supervisor 003. Driver 004. Warehouse 005. Production 006. Manager

Figure 1: System Deployment Flowchart Source: Compiled by this research

4. Results and Discussion

4.1 Application Effects of Real-Time Data

The real-time data collection system significantly enhanced the accuracy of carbon footprint measurements in aluminum processing operations. Compared to traditional annual data methods, the use of real-time data enabled more precise capture of carbon emission variations at the batch level. Particularly in factory operations, where energy consumption, equipment efficiency, and production conditions often fluctuate between batches, the real-time system effectively reflected these dynamic changes.

The results indicate that the margin of error associated with real-time data was 12% lower than that of traditional methods, demonstrating a greater capacity to accommodate production process variations.

4.2 Improvement in Carbon Efficiency

Through the implementation of real-time data collection, factory management was able to respond more rapidly by adjusting production processes based on real-time energy consumption and carbon emission data. For instance, when energy consumption for a particular batch exceeded the set threshold, the system immediately issued an alert, prompting optimization of smelting or extrusion processes to reduce carbon emissions in subsequent batches.
This capability for real-time adjustments led to an improvement in the factory's overall carbon efficiency by approximately 8%.

4.3 Optimization Potential in the Production Process

The collection of real-time carbon data also revealed several potential issues within the aluminum processing operations. For instance, certain equipment exhibited higher carbon emissions during low-load operation, whereas their energy efficiency improved significantly under high-load conditions. Based on these findings, the factory was able to optimize equipment operation strategies to minimize idle energy consumption and reduce inefficient operations.
Moreover, the real-time data indicated that carbon emissions during the surface treatment process were abnormally high in certain production batches. This finding highlighted the need for improvements in surface treatment techniques or the adoption of new technologies to further reduce emissions.

4.4 Batch-Level Carbon Footprinting

Through the implementation of the real-time data collection system, this study achieved the quantification of batch-level product carbon footprints. The availability of batch-specific data significantly enhanced the transparency and accuracy of carbon emission calculations, enabling the factory to better meet compliance audit requirements.
The high traceability and frequent updates of the data provided strong support for compliance management, allowing the factory to respond swiftly to regulatory changes. This capability is particularly critical in the aluminum processing industry, where emission standards are becoming increasingly stringent, especially in regions with active carbon trading markets and tighter governmental regulations.

4.5 Impact of Real-Time Data on Cost Efficiency

The application of the real-time carbon data collection system not only improved carbon efficiency but also enhanced overall cost efficiency. Specifically, real-time data enabled the factory to allocate energy and resources more precisely, thereby reducing unnecessary waste. For example, during the extrusion and rolling processes, real-time energy consumption data allowed for dynamic adjustments of equipment operating parameters, leading to lower electricity and fuel usage.

This approach not only reduced carbon emissions but also decreased production costs. According to our calculations, the factory achieved approximately a 5% reduction in energy costs within the first year of implementing the real-time data system.

4.6 Data Transparency and Decision Support

The transparency enabled by real-time data provided a powerful decision-support tool for management. Through real-time reporting and data visualization tools, the factory could quickly identify and rectify high-emission stages within the production process, while continuously improving operations based on batch-level data.

Moreover, the availability of transparent data facilitated more open communication with external stakeholders, such as customers and regulatory authorities, thereby strengthening the factory's environmental compliance and sense of corporate social responsibility.

4.7 Continuous Improvement and Future Applications

The real-time data system not only facilitated short-term optimization but also supported long-term continuous improvement within the factory. Following the implementation of the real-time data system, the aluminum processing factory in this study gradually established an automated, data-driven continuous improvement process.

Looking ahead, with further advancements in Industrial Internet of Things (IIoT) technologies, data analysis tools such as machine learning can be applied to the collected datasets to enable more refined process optimization and predictive maintenance. These developments are expected to further enhance carbon management efficiency within aluminum processing operations.

5. Conclusion

This study explored the application of real-time carbon data collection systems in the aluminum processing industry and demonstrated how this technology can enhance carbon efficiency across the product life cycle. Compared to traditional annual data collection methods, real-time data collection enables more precise capture of carbon emission variations during each production batch and allows for dynamic adjustments based on real-time information.

The results indicate that the implementation of a real-time data system not only improved carbon efficiency but also enhanced production cost efficiency and management transparency. With the ongoing advancement of technology, real-time carbon data collection systems are poised to become essential environmental management tools in the aluminum industry as well as other energy-intensive sectors.

Compared to primary aluminum, recycled aluminum significantly reduces energy consumption and carbon emissions during production, making it a crucial element in green supply chains. However, to ensure the credibility of recycled aluminum sources and the transparency and low-carbon nature of the recycling process, the establishment of a comprehensive and traceable product carbon footprint record is vital. This traceability further provides an important foundation for corporate leaders to fulfill their Duty of Care in environmental management.

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