Towards a Systematic Dynamic Calculation of Material Carbon Footprints Through Harmonized Material Taxonomies and Enterprise Resource Planning Data Integration

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***Abstract*—Industry makes up the largest contribution to Greenhouse Gas (GHG) emissions, with three-quarters of global GHG emissions derived from it. Industrial GHG emissions themselves have been growing faster since the 2000s than any other sector due to an increase in material extraction and production as its demand exceeds economic and population growth. A slight change in procurement could lead to a fluctuation in products' GHG emissions, especially in large, complex products or systems with a short cycle. This creates a problem, where additional effort is required in the data collection processes. At the same time, state-of-the-art technologies had been introduced to the manufacturing environment to capture more accurate data. In this paper, we incorporated an event-based architecture alongside the Enterprise Resource Planning (ERP) system to bring material and emission data into a dynamic visualization tool. This method enables the calculation of material GHG emissions based on each order from the ERP system, providing a more accurate and detailed estimation and result.**

***Keywords*—material emission, Dynamic Life Cycle Assessment (LCA), event-based architecture**

I. Introduction

Despite efforts to reduce material consumption and the threat of resource scarcity, global resource consumption continues to increase [1]. The growth itself exceeded the population and economic development within the same time frame [2]. Even in regions where material consumption has decreased, such as the EU, the level of current consumption as well as the waste derived is still unsustainable, and the allocation of the natural resources to their most efficient use is still far from ideal [1, 3, 4]. Increase in basic material extraction and production is the main driver of the growing increase in GHG emission from industrial activities, which also make up the largest contributors to worldwide GHG emission [2, 5]. This has prompted several calls for action, such as the UN Sustainable Development Goals and the EU Green Deal, with a focus on reducing material consumption [6, 7].

As a result of the acknowledgment and the urgency to reduce product-adjacent and industrial environmental impact, several organizations are conducting assessments to estimate their systems' environmental footprint. One method that is widely recognized and applied is the Life Cycle Assessment (LCA). Despite its popularity and replicability, LCA still dwells on several limitations. LCA methodology is based on the average performance of a process and does not consider slight changes that might have impacted its input flow [8]. It considers the impact of a system that has happened in the past to assess the potential pathways of the said system. This leads to the limitation of the methodology in which practitioners have to make hypotheses of the system and rely on static data input [9, 10]. Dynamic LCA (DLCA) is proposed as a solution to this problem by accounting for the system dynamically and incorporating the temporally induced changes that affect the result and interpretation of the system [9, 11].

The comprehensiveness of LCA itself relies on extensive data collection across both upstream and downstream processes in conjunction with advanced data analytics [12]. DLCA has also gained more relevance due to the integration of state-of-the-art technology into the manufacturing environment to collect data in real-time with high reliability [10].

This paper aims to deliver a methodology for dynamically calculating a product's material carbon footprint based on its material characteristics derived from real-time data in the ERP system. The result of the assessment is as well visualized dynamically using a dashboard tool that allows temporal, product- and plant-related elements to be adjusted based on users' queries. The integration of various dynamic elements could result in a more reliable and detailed assessment of the material carbon footprint. This methodology was then applied in a case study of calculating the material footprint of a truck trailer.

II. Significance of Dynamic Material Footprint Calculation

A. Raw Material Contribution in Product Environmental Impact

Material footprint is a consumption-based measure of material use [1]. It accounts for the amount of primary materials required to satisfy a country's final demand, such as household, government consumption, and capital investment, across the entire global supply chain network [1, 4]. Thus, the indicator is robust against outsourcing [1].

Materials with carbon-intensive extraction and manufacturing processes, such as iron, steel, and concrete, contribute significantly to the total GHG emissions derived from material consumption [2, 13]. Worldwide iron and steel production accounted for 20 percent of the GHG emissions from industry [14]. This is due to their high energy

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consumption in the manufacturing process, combined with a high reliance on carbon-intensive energy sources such as coal. Additionally, iron and steel have various alloying profiles and elements, some of which are considered critical to the EU, as a result of their low abundance and reliance on certain regions [7, 14, 15]. Different alloying elements could have an impact not only on the steel's carbon footprint but also end product that is constructed by it [15].

Iron and steel are not the only raw materials where different chemical or physical characteristics could lead to discrepancies in both the material and end product GHG emissions. Other materials with a large GHG contribution, namely concrete, its mixture, grade, and cement class, could affect its environmental impact [16]. It is also recommended that systems with complex chemical structures, such as polymer-based products, must be estimated based on their chemical components [17].

B. Dynamic Life Cycle Assessment

A traditional LCA calculation is currently still performed using specialized software without any conjunction to other systems integrated into a manufacturing process [18]. This leads to a data collection process that is time and effort-consuming, especially in large, complex systems as well as products with a short model change cycle [19]. By incorporating real-time data and adaptive management practices, DLCA could enhance the accuracy, relevance, and applicability of environmental assessment as well as alleviate the complex data collection process [10]. This is compounded by a study by Perau *et al.* [18], which found that by integrating firms' IT systems into LCA calculations, it could lead to higher data reliability, as 20 percent of carbon accounting information is available in the system, with simple modifications can increase the information availability, so the gap after modification is 51 percent.

Most of the studies concerning DLCA incorporated dynamic systems during its inventory phase [11]. This is due to a more widespread implementation of automatic data collection technologies in Industry 4.0 and 5.0 environments, such as sensor and IoT, as well as manufacturing information systems [10, 20]. The concept of Industry 5.0 lies around the consolidation of such technologies into a conventional industrial set-up and allows machines to conduct more complex tasks and aid in decision-making problems with human-provided insight and knowledge that the machine is not able to perform [21].

Among the manufacturing information systems, ERP is one of the widely used IT systems in the manufacturing sector as it is responsible for numerous activities, including management, planning, documentation, and control of business processes, as well as the enterprise's resources [18]. An ERP system could also process and store data centrally, thus allowing an optimized use of human and physical resources [19].

Despite the increasing prominence of DLCA, the integration of dynamism in the interpretation phase is still overlooked [9, 11]. Temporally dynamic interpretation methods, such as dashboards, enabled real-time data updates, which allow agile decision-making and proactive measures. It is also able to induce complexity, thus capable of analyzing and evaluating trends, identifying patterns, deriving insights for continuous performance, and allowing different strategies to communicate results [9, 22].

III. Methodology

The method is based on the preceding study by Davila [23]. In this study, the calculation follows the ISO 14067 standards as per guidelines provided by the European Sustainability Reporting Standards (ESRS). Based on the guidelines, a calculation based on LCA methods was performed. LCA started with a goal and scope. The objective of this study is to calculate the material carbon footprint in a more detailed and dynamic manner, and thus covering only the emissions from material procurement activities. This assessment is classified as a retrospective dynamic LCA, as it used previously collected dynamic life cycle inventory data, therefore already fully available at the time of the assessment [9].

A. IT Architecture

In order to simplify the data collection process, we incorporated the information systems of industrial manufacturing companies. The material management module of the ERP system is responsible for managing material flows in the companies. It covers all essential processes from demand planning and purchasing to inventory management and warehouse management, and thus forms the basis for logistics as well as product composition. Based on this information, the individual parts of an end product can be precisely determined. For this purpose, parts lists can be used, from which the materials and weights of the individual parts can also be accessed. Together with the required quantity per individual part for the respective end product, the total quantity of a material per product can thus be determined.

The underlying study relied on the use of an event-based architecture to integrate this logic into the information flow and enable it to be automatically scaled up for a large number of individual product units. To this end, the material and quantity information for each product is summarized via the material management module in the ERP system and transferred to a broker via an interface. At the same time, a database is created based on the information from Ecoinvent and connected to the broker. Then the broker is linked to a data visualization platform, such as a dashboard, using Logstash. In this study, SAP and its SAP PI act as the ERP system, and its interface with Kafka is utilized as the broker. The IT infrastructure is described in Fig. 1.

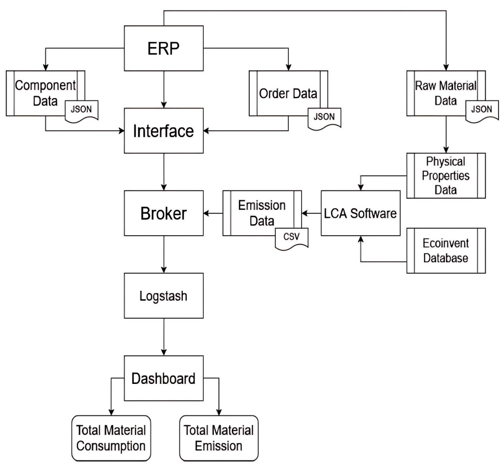

Fig. 1. IT architecture.

B. Material Carbon Footprint Calculation

The Life Cycle Inventory (LCI) Analysis was conducted using the collected data from the ERP system, including its standardized raw material classification. Using additional data from the Ecoinvent 3.11 database, the emission factor was be able to be estimated using openLCA. As previously stated, the chemical composition, grades, classes, and treatment of raw materials could affect their environmental impact; thus, standards, such as DIN steel grades, were incorporated into the calculation. These grades provide standardized information on chemical and physical compositions. Furthermore, each raw material was then treated as its own flow with a modified input composition based on these standards and process information based on the Ecoinvent database.

Then the EF 3.1 standard was adopted as the impact assessment method. The impact category that was evaluated was the Global Warming Potential (GWP) in kg CO_2-eq. The material and emission factor data were then gathered into a single CSV file and uploaded into the broker. Besides the customized emission factor based on standardized grades, this CSV file also contains information on the treatment or form of the raw materials and the calculated total emission factor based on this two information.

The Life Cycle Impact Assessment (LCIA) was dynamically performed in Grafana, which also served as the visualization and interpretation platform for the analysis. This was done by combining two data sets: one is the dynamic raw material data from ERP, and the other is the static modified emission data from Ecoinvent. The data structure is described in Fig. 2.

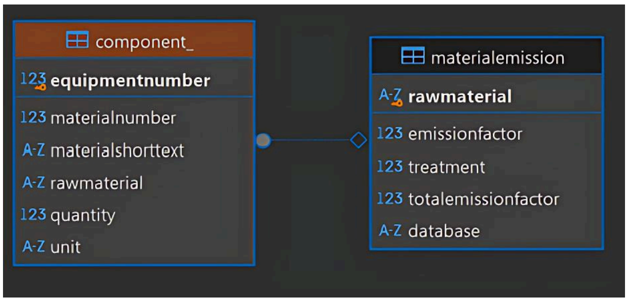

Fig. 2. Database structure for material emission calculation.

Grafana is able to perform mathematical calculations as well as simple database manipulation on its platform, thus eliminating further IT integration and additional effort for the maintainers and users. In order to calculate the material carbon footprint, the raw material emission is multiplied by the quantity of the raw material procured. Subsequently, they were grouped based on their materialNumber from the ERP system to calculate the total material carbon footprint. This calculation is based on a previous study on the tool by Davila [23] and therefore follows the same logic. In this tool, the material reduction efficiency was ignored, and therefore ER = 0. The resulting equation is described in Eq. (1).

$$Em = \sum Er \times M \times \frac{1-ER}{100} \quad (1)$$

Similar to the LCIA, the interpretation phase was conducted using Grafana. As a tool, it is capable of providing dynamic visualization by allowing users to adjust the temporal aspect of the data. It could also filter based on users' requirements. In this context, product and plant-oriented parameters could be adjusted, such as which products are being assessed or which plant does the manufacturing occur in. This allows the users to access the carbon footprint data instantly and eliminates complicated IT and communication processes as well as allowing users to recognize hotspots and apply more direct improvement measures based on parameters set. The material carbon footprint is incorporated into the greater Product Carbon Footprint (PCF) dashboard developed by Davila. [23], which allows dynamic visualization of PCF and its various components.

IV. Case Study

The method was applied to calculate the material carbon footprint for truck trailer production in the Northern Part of Germany. The base year of measured and calculated data was 2024/2025. Due to the complexity of the construction and data availability, simplification techniques were integrated into the calculation. The screening method was applied following the similar logic implemented by Howe [24] in calculating the environmental footprint of passenger aircraft. With the screening method, only processes or components that contribute significantly are considered [25].

In the case study, the operating and non-structural components were eliminated from the assessment. These components were considered insubstantial as they consist only for less than 2 percent of the total weight. Using the technique, a more detailed calculation was assessed for the components that have a significant contribution to the total mass. This includes modifying the contribution of raw materials that made up the component based on DIN standards, as previously mentioned in the methodology.

In trailers, 86 percent of the total weight is made of components derived from steel, with 90 percent of them in the form of sheet or bar. During the preliminary study to decide the granularity of the material emission factor, it was concluded that the form in which the steel is incorporated to the end product has a significant influence on the material carbon footprint. Therefore, in this study, the GHG emission of steel components was calculated based on their raw material composition and their form. Though this logic did not apply to smaller components derived from steel, such as bolts and screws. This method is applied due to their insignificant contribution to the total mass of the end product; thus, their emission factor is based on unchanged steel data from Ecoinvent. Another material group that contributes significantly is the wood plate. Similar to steel plates, the wood plates were grouped and calculated based on their wood origin. Thus, for the total emission factor, we integrated the emission from the treatment process into the calculation, as described in Eq. (2).

$$Er = EF \times Et \quad (2)$$

In order to perform a thorough assessment of the material carbon footprint, more robust and detailed data need to be presented to the users. In a case where the total mass of the products consists mainly of carbon-intensive raw material, both the total mass consumption and total material emissions must be introduced to allow a comparative assessment between mass and emissions. The visualization of material consumption and carbon footprint is presented in Fig. 3. and Fig. 4.

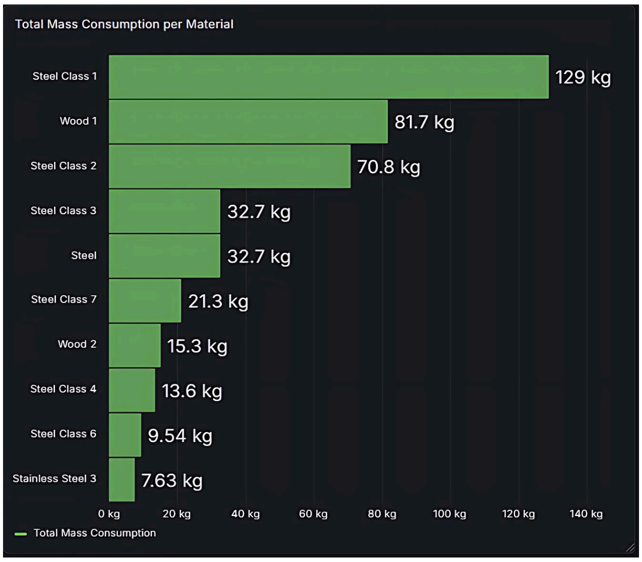

Fig. 3. Visualization for total mass consumption within the PCF dashboard.

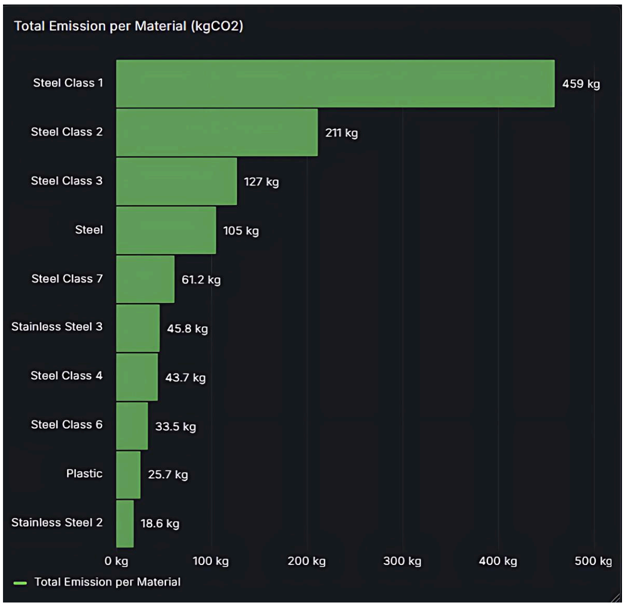

Fig. 4. Visualization for material carbon footprint within the PCF dashboard.

Based on this visualization, the discrepancy between the true consumption in units of mass and the material footprint could be observed. In this case study, wood has a large contribution to the total mass, but is absent when considering the material with the largest contribution to the carbon emissions. Meanwhile, several steel grades, especially stainless steels and plastics, make a significant contribution to the total emissions. Using a comparable unit, determining the carbon emission per mass unit of material is also feasible.

V. Conclusion

Material carbon footprint plays a pivotal role in assessing product-related environmental impact. Various characteristics, may it be temporal, chemical and physical composition, as well as pre-processing activities, could have a critical impact on the reliability of the estimation. Additionally, the carbon footprint of large, complex products is difficult to measure as they require an even more complex and time-consuming data collection process.

In many manufacturing organizations, these data are located within the ERP system. But this system needs a certain expert and is difficult to navigate for non-users. Thus, in order to simplify the data collection process, event-based architecture was incorporated alongside the ERP system to bring the inventory data into a more user-friendly and simpler interface. Additionally, using this tool, a more streamlined LCA estimation could as well be conducted. Furthermore, the dynamic visualization enables a more accurate and reliable hotspot identification, as a result of the feasibility of temporal and product-related adjustment.

Material emission is only one aspect that comprises the PCF and Corporate Carbon Footprint (CCF). Therefore, other flows, such as energy usage and transportation, need to be integrated into the dashboard. The estimation of other flows must also be conducted by incorporating dynamic temporal and spatial components during its inventory process. With a fully dynamic PCF and CCF, a more reliable estimation could be presented.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Naila Rana Andira: Conceptualization, Methodology, Writing—Original draft, Visualization. Philipp Sander: Methodology, Writing—Original draft. Alexandra Pehlken: Supervision, Writing—Reviewing and Editing; all authors had approved the final version.

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