Container-Based Microservices Application for Product Carbon Footprint Calculation in Manufacturing Companies

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Abstract: Regulations like the Corporate Sustainability Reporting Directive (CSRD), require companies to report their carbon footprints. However, many manufacturing companies struggle to calculate precise product carbon footprints due to the complexity of integrating data from various systems, or lack of time to develop the tools necessary, which leads to high uncertainty in their reports. This paper introduces a highly customizable Open-source tool for calculating product carbon footprints based on ISO 14067 and CSRD guidelines using a container-based microservices architecture. The tool ensures scalability, ease of use, and data security, working with existing manufacturing digital tools and providing clear carbon footprint visualizations to enhance companies' sustainability efforts.

Keywords: Product carbon footprint, microservices architecture, sustainable manufacturing, environmental informatics

1 Introduction

Companies must report their carbon footprint due to the Corporate Sustainability Reporting Directive (CSRD) [EU23]. Initially, these regulations addressed only large companies, but they are increasingly becoming mandatory for more companies each year. This aligns with the European Green Deal's [EU20] goal to make Europe climate-neutral by 2050.

Companies use digital tools like Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP) systems to manage their operations. Despite these tools, calculating the carbon footprint of individual products is complex, requiring combining the data from MES, ERP, IoT sensors, and Supply Chain Management (SCM) systems.

Companies often lack the expertise, budget or time to meet these reporting standards. They recognize the benefits of detailed carbon footprint reports but struggle with the complexity and costs involved. Many companies calculate their total resource consumption and then divide it by the number of products they produce, making many assumptions in the calculation. This introduces a high level of uncertainty, which complicates the comparison and improvement of sustainability of the process [He18].

This paper addresses these challenges by providing two contributions: (i) it outlines a procedure for calculating the product carbon footprint based on ISO 14067 and the CSRD guidelines, and (ii) it presents an Open-source tool[4] that simplifies this calculation, making it accessible even for companies with limited resources. This tool helps companies get a clearer picture of their carbon footprint with minimal effort, paving the way for more sustainable manufacturing practices.

2 Related Work

The main related work are other tools for product carbon footprint calculation. Commercial examples include those developed by BearingPoint and SAP [SF24], Cority [Co24], and Siemens [Si24]. These tools, while effective because they are custom-made, are often costly and may lack flexibility for small to medium-sized businesses.

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Notable free tools are the 2030 calculator [Do24] by Doconomy and MINDFUL [La24]. 2030 calculator allows users to define products, materials, and energy sources. It is user-friendly and free, but requires account creation, runs on their server, has limited categories of products, and offers minimal customization. MINDFUL [La24] is a proof-of-concept tool using machine learning to estimate product carbon footprints from Comma-Separated Values (CSV) file inputs, claiming to improve calculation accuracy. However, it is not publicly available.

Our tool is an Open-source base code that offers full customization and integration with any MES, ERP, or sensor data. It runs locally to ensure data security and supports user contributions for continuous improvement. It also aligns with the CSRD and uses the standard it recommends to build the methodology, ISO 14067[IS18]. It uses a container-based microservices architecture, making it scalable, user-friendly, and transparent.

The CSRD expanded sustainability reporting requirements, replaced the Non-Financial Reporting Directive (NFRD), and requires companies to report on their environmental, social, and governance (ESG) impact. ISO 14067 provides guidelines for assessing the carbon footprint of products, ensuring consistent greenhouse gas emissions reporting throughout a product's lifecycle.

3 Methodology

In order to design the tool, we follow the guidelines provided the European Sustainability Reporting Standards (ESRS) [Es23], which recommends to follow the ISO 14067 [IS18]. We design our tool as follows:

1. **Goal and Scope:** Our Open-source tool calculates a product's CO_2 emissions from the local supply of materials to the end of the manufacturing process, called *gate-to-gate*, addressing all three scopes of the Greenhouse Gas Protocol [WB04]: direct emissions, energy-related emissions, and transportation emissions.
2. **Life Cycle Inventory (LCI) Analysis:** Our tool allows users to create their product inventory by populating the input tables (in CSV format) with their information about the product components and the amount of resources consumed during production. Details on the data collection are shown in Section 3.1.
3. **Life Cycle Impact Assessment (LCIA):** The tool calculates the CO_2 equivalent using emission factors and the data from the LCI. Emission factors are also called Global Warming Potential (GWP) factors [WB04] and they quantify the environmental impact of resources by estimating the average emission rate of a specific source. They are typically expressed as $kg\ CO_2e/kWh$, meaning the number of kilograms of carbon dioxide equivalents (CO2e) emitted per kilowatt hour of energy consumed, or $kg\ CO_2e/kg$ per kg of material, or $kg\ CO_2e/tkm$ per ton transported a number of kilometers [LS14].
4. **Interpretation:** The tool includes a dashboard that displays the calculated product carbon footprint, clearly showing key emission sources and areas where improvements can be made. This is not based on extra calculations but uses the dashboard's visual design to help users identify potential opportunities for optimization.

3.1 Calculation Schema for the LCIA

Figure 1 shows the calculation procedure of the product carbon footprint, detailing the three main internal sources of information: `Orders`, `ProductComponents`, and `ProductProductionProcess`.

- **Orders:** This table, from the ERP system, includes order numbers, product types, and production date. It helps allocate emissions to the appropriate product.

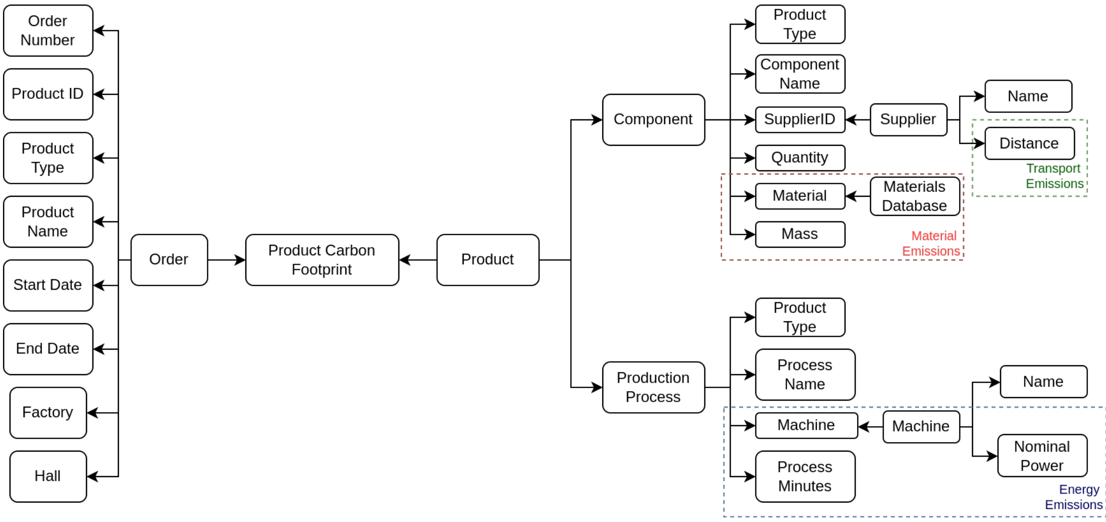

Fig. 1: Schema for the product carbon footprint calculation

- **Product Components:** Part of the ERP system's Bill of Materials (BOM), this table lists component quantities, materials, mass, and origin (in-house or supplier). It helps determine the material mass per component ($M_{material}$).
  - **Supplier:** Contains supplier details, including distance and transport method. Using the $M_{material}$ and the distance from the company to the supplier, one can calculate the tons per kilometer per supplied component ($M_{transported}$).
- **Product Production Process:** Part of the MES system, it details per product type, the components, machine use, and production time.
  - **Machine:** Lists machines, their locations, and nominal power, helping calculate energy consumption per production step and per component ($E_{process}$).

3.2 Emissions Calculation

The tables above are the basis for the emissions calculation, but the tool also needs two external sources of information: a `MaterialsDatabase` to determine the emission factors of the resources, and a `EnergyMixDatabase` to determine the energy source at the time of production and therefore calculate the energy emission factors.

Equation 1 [EPA90] is the main equation to calculate emissions, where E are the calculated emissions, A is the activity rate, as explained below, EF is the emission factor, and ER is the emission reduction efficiency, which accounts for the percentage of emissions reduced through control technologies. In our tool, we assume no emission reduction technologies are in place, so we set $ER = 0$.

$$E = A \times EF \times \frac{1 - ER}{100} \tag{1}$$

In order to calculate material emissions, we need to use the sum of the mass of material used per component ($M_{material}$) and the resulting equation looks like Equation 2.

$$E_{material} = \sum M_{material} \times EF_{material} \tag{2}$$

To determine the $EF_{material}$, we use a materials database, such as (i) Probas[P24], a database by the German environmental agency, (ii) Ecoinvent [Eco2424], a commercial database for LCA, (iii) the report from the federal office for economic affairs and export control in Germany [BA24], (iv) OpenCO2Net [Open24], a free database. The factors used for our public tool (Section 4) are shown in Table 1.

Tab. 1: Material emission factors used during the tool development. For factors only available in commercial databases, a dummy value and source is used for the public repository.

Material	Emission Factor	Unit	Source	Date
Cast Iron	1.5	kgCO2/kg	Probas [P24]	1999
Steel	1.569	kgCO2/kg	Probas [P24]	2005
Plastic	3.0	kgCO2/kg	Avg-Probas [P24]	2005
Electronics	189.9	kgCO2/kg	Avg-Probas [P24]	2005
Cables	4.2	kgCO2/kg	Avg-Probas [P24]	2005
Polybutadine	3.29	kgCO2/kg	Probas [P24]	2000
Glass Fiber	2.54	kgCO2/kg	BAFA [BA24]	2024
Aluminum	9.274	kgCO2/kg	Probas [P24]	2001
Leather	46.9	kgCO2/kg	OpenCO2	2019
Carbon Fiber	20.0	kgCO2/kg	Dummy	0000
Stainless Steel	4.529	kgCO2/kg	Probas [P24]	2004
Copper	2.874	kgCO2/kg	Probas [P24]	2000
Silicon	58.2	kgCO2/kg	Probas [P24]	2020
Gold	179	kgCO2/kg	Probas [P24]	2000
Lithium	18.344	kgCO2/kg	Probas [P24]	2001
Lead	1.36275	kgCO2/kg	BAFA [BA24]	2024
Tin	7.5	kgCO2/kg	Dummy	0000
Neodymium	50.0	kgCO2/kg	Dummy	0000
Nickel	6.06	kgCO2/kg	Probas [P24]	2005
Zinc	3.26	kgCO2/kg	Probas [P24]	2000
Platinum	138.916	kgCO2/kg	Probas [P24]	2002
Palladium	93.356	kgCO2/kg	Probas [P24]	2000
Tungsten	2.87	kgCO2/kg	Probas [P24]	2000
Magnesium	73.117	kgCO2/kg	Probas [P24]	2000
Titanium	27.373	kgCO2/kg	Probas [P24]	2000
Graphite	0.0273	kgCO2/kg	Probas [P24]	2000
Rubber	3.29	kgCO2/kg	Probas [P24]	2000
Polyethylene	2.59	kgCO2/kg	Probas [P24]	2005
Polypropylene	3.53	kgCO2/kg	Probas [P24]	2005
Polyvinyl Chloride (PVC)	1.905	kgCO2/kg	Probas [P24]	2004
Acrylic	3.7	kgCO2/kg	Dummy	0000
Polystyrene	14.0	kgCO2/kg	Dummy	0000
Polycarbonate	23.0	kgCO2/kg	Dummy	0000
Fiberglass	2.54	kgCO2/kg	BAFA [BA24]	2024
Chromium	26.261	kgCO2/kg	Probas [P24]	1999
Manganese	2.525	kgCO2/kg	Probas [P24]	2003
Bismuth	22.104	kgCO2/kg	Probas [P24]	2000
Cobalt	7.721	kgCO2/kg	Probas [P24]	2000
Molybdenum	8.634	kgCO2/kg	Probas [P24]	2000

In order to calculate transport emissions, we use the sum of the tons per kilometer of supplied components ($M_{transported}$) and the result is Equation 3. For the emission factor $EF_{transport}$, we used the value for a truck (LKW in German) from Probas [P24]. In future work, we plan to add a column to the transportation table that specifies the different modes of transport. This will allow us to calculate transport emissions more accurately based on the specific method used for transportation.

$$E_{transport} = \sum M_{transported} \times EF_{transport} \tag{3}$$

In order to calculate energy emissions, we need to use the energy consumption per component and product ($E_{process}$) and the result is Equation 4.

$$E_{energy} = \sum E_{process} \times EF_{energy} \tag{4}$$

The energy emission factors EF_{energy} depend on the energy mix, which is the percentage of energy generated per source at the moment of production. Each source has a different emission factor, as shown in Table 2.

Tab. 2: Energy emission factors used during the tool development. For factors only available in commercial databases, a dummy value and source is used for the public repository.

Source	Emission Factor	Unit	Source	Date
Biomass	27	(gCO2e/kWh)	BAFA [BA24]	2024
Hydropower	2.6	(gCO2e/kWh)	GASAG [G22]	2024
Offshore Wind	9.3	(gCO2e/kWh)	GASAG [G22]	2024
Onshore Wind	16.9	(gCO2e/kWh)	GASAG [G22]	2024
Photovoltaic (Solar Power)	55.7	(gCO2e/kWh)	GASAG [G22]	2024
Other Renewable	10	(gCO2e/kWh)	GASAG [G22]	2024
Nuclear Energy	12	(gCO2e/kWh)	GASAG [G22]	2024
Lignite (Brown Coal)	347	(gCO2e/kWh)	BAFA [BA24]	2024
Hard Coal	303.9	(gCO2e/kWh)	BAFA [BA24]	2024
Natural Gas	182.34	(gCO2e/kWh)	BAFA [BA24]	2024
Pumped Storage	4	(gCO2e/kWh)	Dummy	0000
Other Conventional	300	(gCO2e/kWh)	Dummy	0000

We use the publicly available energy database SMARD [S24] to determine the energy mix at the moment of production. In our real use case we used the information provided by the energy provider, however this is not always available. SMARD provides the energy mix with a 15-minute interval for Germany.

Finally, the total product carbon emissions $E_{product}$ are calculated as shown in Equation 5.

$$E_{product} = E_{material} + E_{transport} + E_{energy} \tag{5}$$

4 Use Cases

The tool was developed using a real-world use case, part of the EDNA [E24] project in northern Germany. The industrial partner in project EDNA is KRONE, which is an agricultural technology and commercial vehicle manufacturer. The emission factors used come from the commercial database Ecoinvent [Eco2424]. The data required to calculate the product carbon footprint is private, as it contains sensitive information about the products. For this reason, with the purpose of developing an Open-source tool, a fictional use case was created for the public repository.

The fictional company is a truck factory in northern Germany. Two trucks were produced with serials: C2192802 and C2176038, where C2176038 is the larger model. Artificial data was generated using GPT4.0 [O23]. For each table, we ensured that the generated information was realistic by providing text-based examples, such as explaining that the larger truck (C2176038) should have heavier components and require more materials. GPT4 then generated the corresponding tables based on this input. The emission factors used are shown in Table 1, and the energy mix information was replaced with the publicly available energy mix from SMARD [S24].

4.1 Proof of Concept

The tool was developed using containers because they create a separate and consistent space for applications to run, making sure the software works the same everywhere. This separation is key for keeping microservices stable, allowing each service to run on its own without affecting others, which improves the application's ability to grow, stay reliable, and be easy to manage.

We chose Docker [D24] and its tool Docker Compose because of its popularity and community support. It uses a YAML file to set up the application's services, networks, and storage, making it simple to build a complex system with connected microservices. This method not only makes development easier but also improves the deployment process, making it simpler to copy and expand the application in different environments. This high customization level was a requirement during our design of the tool.

The repository for the proof of concept is composed by the tool and the data folder. The data folder contains the input tables. The data about material emission factors and energy mix can be replaced by APIs because these provide real-time updates, making the system more efficient and responsive to changes. For materials, we used the commercial API from Climatiq [C24]. We configured SMARD using the public repository [Matz23].

The example is composed by three main services: (i) a website, (ii) a database, and (iii) a dashboard.

4.1.1 Website and Database

The website is the main service where users can see the method, tables, and dashboard all in one place. This integration makes it easy to access and use all parts of the system together. The website was built using Angular [A24], a popular tool for making web apps. Angular is advantageous because it allows apps to be built in modular pieces, making them easier to customize. No login is required on the proof of concept example but this can be easily added using the Dockerfile from the Github repository.

The database is designed using the schema in Figure 1 and is created using TimescaleDB [TS24], which is built on PostgreSQL. We chose a SQL database because it is a common and straightforward query language. The login details for the database are provided in the `docker-compose.yml` file and can be modified if necessary. In the Github repository, the data for the proof of concept is included, in order to show the user the results of the calculation. Figure 2 shows the website and database schema.

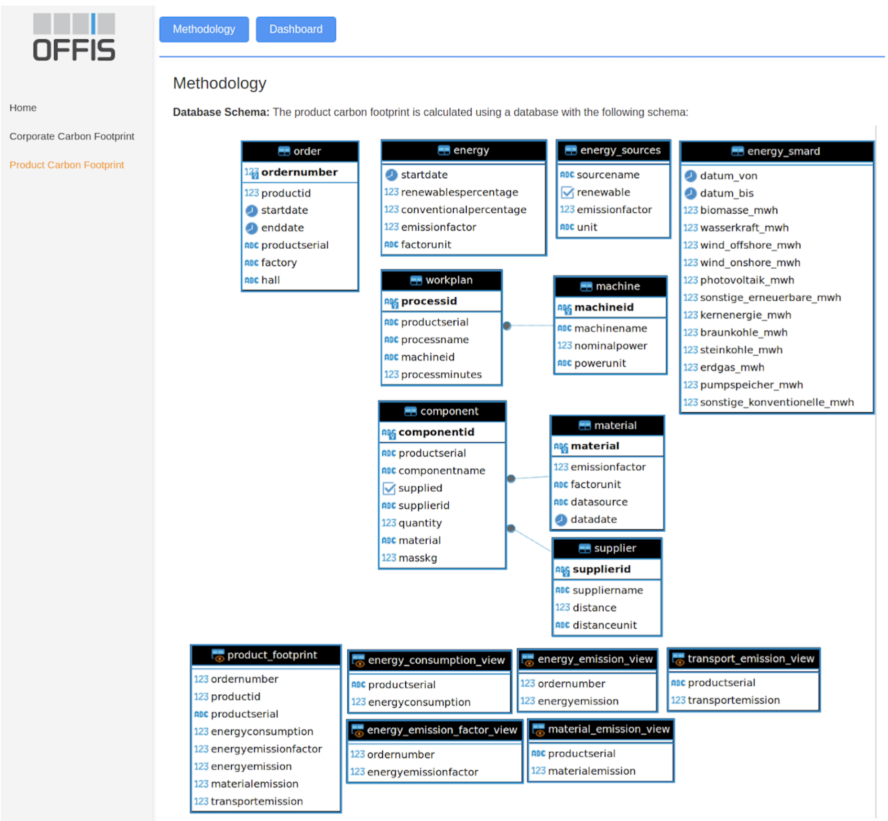

Fig. 2: Website of the tool, showing the schema of the database needed to calculate the product carbon footprint. This includes all the tables, the columns necessary and the relations between tables. The website can be accessed in `https://github.com/mafedavila/product_footprint.git`

4.1.2 Dashboard

The dashboard shown in Figure 3 is made with Grafana, a powerful Open-source tool for monitoring and visualizing data. Grafana is known for its customizable dashboards and it connects with many data sources. Our tool includes a dashboard showing the results for the product carbon footprint calculation and the user can create as many dashboards as needed. The login details for Grafana are specified in the `docker-compose.yml` file.

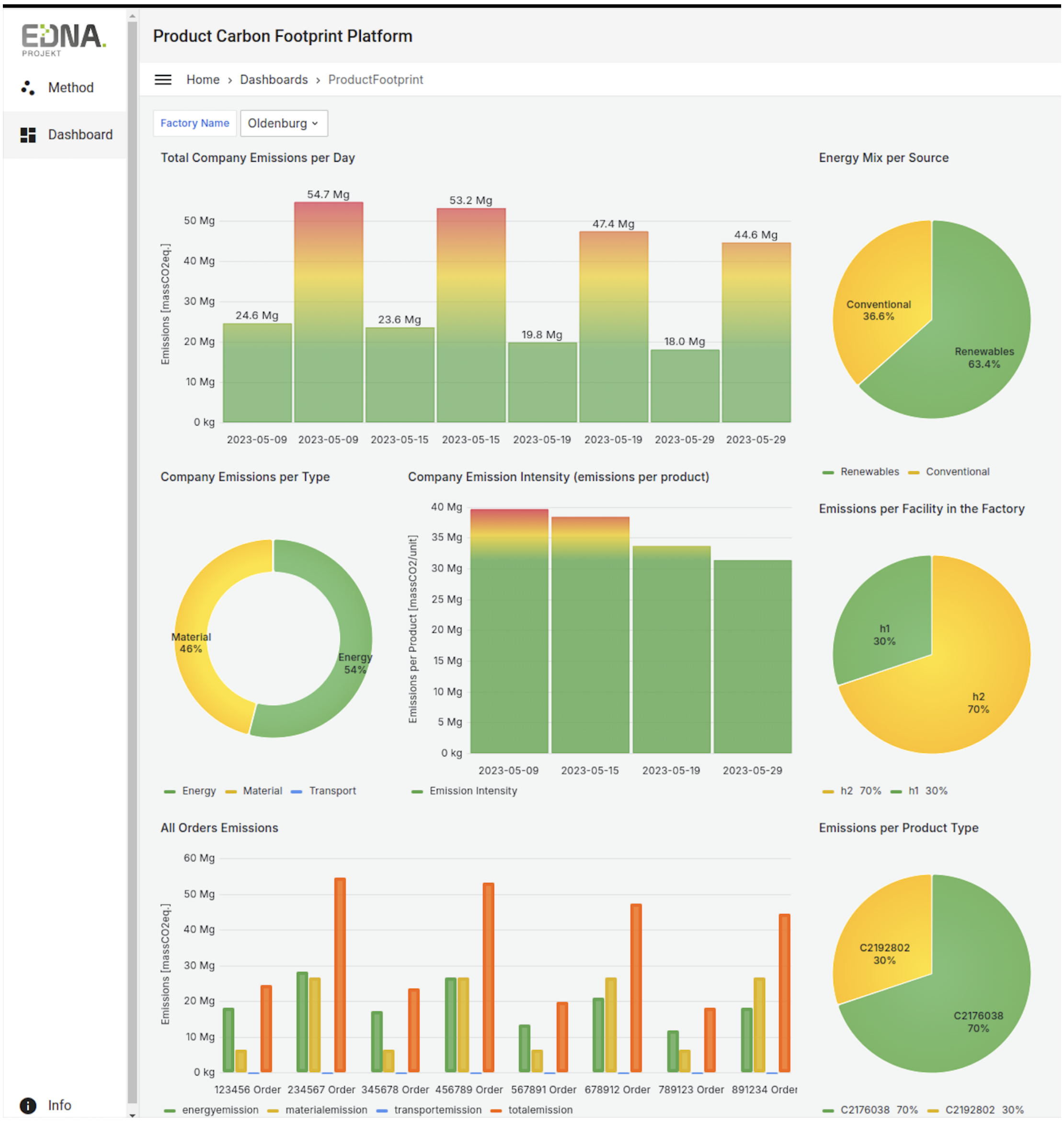

Fig. 3: Dashboard provided with the tool, showing the results of the product carbon footprint calculation for the company per energy source, the emission intensity per product, per facility and product type.

The dashboard in Figures 3 and 4 show the results of the calculation of the Product Carbon Footprint from the use case. The developed architecture is able to calculate the material, energy and transportation emissions and create useful visualizations where the results are filtered by facility in the factory, product type, material, and energy source.

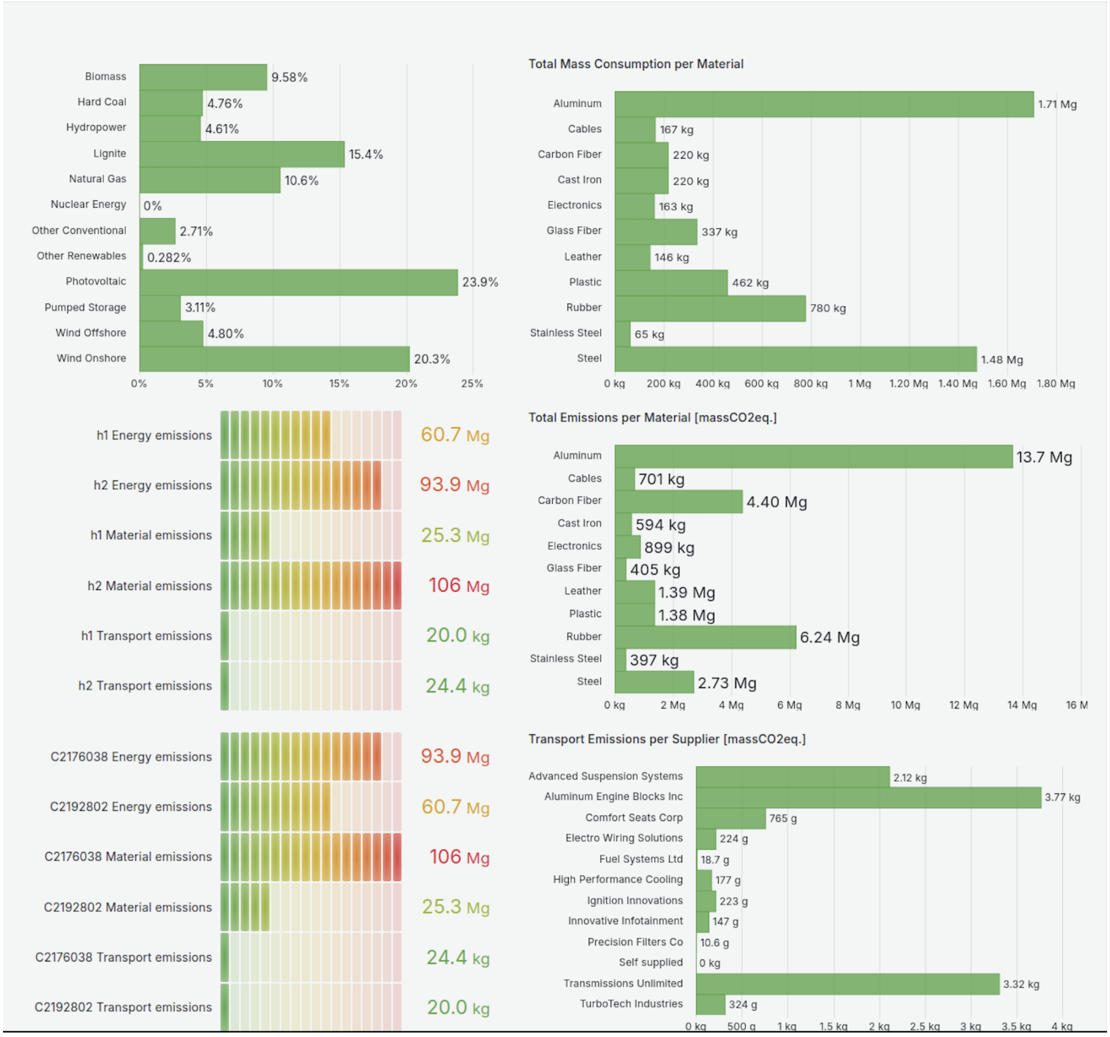

Fig. 4: Dashboard provided with the tool, showing the results of the product carbon footprint calculation for the company per energy source, the total mass consumption per material, the emissions per material and the transport emissions.

5 Conclusion

We developed an Open-source tool for calculating product carbon footprints, which helps manufacturing companies meet environmental rules like the CSRD. By following ISO 14067 standards and working with the existing systems in manufacturing companies, the tool makes it easier to track and lower their carbon emissions. Its Open-source design means it's available to all, even smaller companies with fewer resources. This not only improves the accuracy of sustainability reports but also supports the larger goal of reducing climate impact as part of the European Green Deal.

The setup includes tables for orders, product parts, suppliers, production steps, and energy consumption making it easier to calculate CO_2 emissions accurately. The user-friendly dashboard shows emissions data clearly, helping companies spot areas to improve in their processes. The successful implementation in the EDNA [E24] project and a sample case shows that the tool works well and could be widely used in the manufacturing industry.

Future work involves addressing additional requirements of the CSRD directive, which expands beyond product carbon footprints to include the environmental impact from an organizational perspective. To meet these needs, we are developing an enhanced tool that calculates emissions not only at the product level but also for specific processes, machines, and organizational units within production companies.

Additionally, future work will focus on a comprehensive analysis of the uncertainty in carbon footprint calculations. The goal is to ensure that this uncertainty is smaller than the percentage of any improvements or deteriorations in performance, allowing for accurate measurement of the effects of various optimization projects within manufacturing companies.

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