

Carbon Footprint Evaluation Tool for Packaging Marketplace

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Abstract – Businesses willing to reduce their carbon footprint embrace sustainability and positively impact the progress towards achieving climate neutrality. Well-prepared and presented information to the business customer before purchasing can be a strong driver for better decision-making towards less impactful product alternatives. This study presents the development of a tool for packaging products online marketplace that informs customers about the carbon footprint of packaging products and allows them to evaluate which of the select packaging alternatives is most preferable from an environmental perspective. The tool implements a life cycle analysis (LCA) approach, including the stages of raw material extraction, packaging production, and transportation to the customer. The impact assessment in the tool is performed according to Intergovernmental Panel on Climate Change (IPCC) 2021 methodology for assessing greenhouse gas (GHG) emissions based on information obtained from the Ecoinvent database. The final output of carbon footprint calculation is provided with an indicator marking the carbon footprint performance of customer-defined alternatives in a clear, simple, and consistent way. The tool aims to educate customers, foster informed purchasing decisions, and improve the environmental outcomes of their decisions.

Keywords – Climate neutrality; GHG; Life cycle analysis; online tool; packaging material.

1. INTRODUCTION

Global warming is one of the community's most prominent local, national, and global issues. An increase in the temperature is the most instant effect of global warming, which leads to climate change [1]. The Intergovernmental Panel on Climate Change (IPCC) identifies greenhouse gas (GHG) emissions as a primary contributor to global warming [2]. As a quantifiable representation of GHG emissions from activity, carbon footprint is useful for managing emissions and assessing mitigation strategies [3], [4]. Carbon footprint concept appeared in the 1960s with the growing interest in climate change [5]. According to the Kyoto protocol [6], carbon footprint refers to the total amount of GHG emissions in CO₂ equivalent and other GHG emissions caused by a product's life cycle stages, including production, storage, distribution, usage, and disposal. According to the European Parliament [7], one ton CO₂ equivalent is the total amount of GHG emissions expressed as the product of GHG mass in tonnes and their global warming potential.

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Carbon footprint reduction is one of the critical parts of sustainable development, representing a vital objective of the European Union (EU) sustainable development. The existing regulatory framework clearly shows the development and intensification of carbon footprint trends. In 2008, The European Parliament committed to reducing GHG emissions by 20 % by 2020 and 80–95 % by 2050 [8] in comparison to 1990 level. In 2015, the United Nations proposed 17 specific Sustainable Development Goals (SDGs) to improve the human well-being scale on a global level [9]. Moreover, European countries are actively working toward carbon neutrality following the European Green Deal regulations, which aim for zero GHG emissions from the EU by 2050 [10].

Carbon footprint is a crucial indicator to assess the degree of disturbance of human activities to the climate system [11]. To realize sustainable consumption, it is crucial to show consumers the GHGs of consumer behaviour or action, which shows the CO₂ visualization of the daily goods to the consumers while purchasing [12]. In other words, carbon footprint calculations are anticipated to make producers develop new products with reduced environmental impacts before switching to sustainable production within the cycle of “sustainable consumption and production” [13]. The importance of carbon footprint label reporting [14] carbon emissions is that they provide consumers with a straightforward quantity (kg CO₂) that allows them to immediately compare any two products, independent of their categories [15], [16].

The packaging market is a significant contributor to GHG emissions [17]. In 2009, plastic packaging waste generated 29 kg per capita in the EU. In 2010, global plastic waste production equalled 265 million tonnes [18]. Some packaging manufacturers aspire to measure, develop, and reduce the carbon footprint of their products. Companies have decided to reduce the carbon footprint of their products and educate customers about how their purchasing decisions influence GHG emissions [19]. Direct application of carbon footprint for companies includes several approaches, including [20]:

- Assessment of product lifecycle GHG emissions and their significant reduction;
- Emission impact on decision-making for suppliers, materials, product design, and manufacturing processes;
- Cost saving opportunities;
- Set a benchmark for measuring emission reduction;
- Comparison of GHG emission levels for a product.

In such a context, the Carbon footprint calculation can follow a specific framework called Life Cycle Analysis (LCA) [21]. LCA is an internationally standardized technique [22] for accessing products or systems environmental impacts under analysis. Carbon footprint estimation based on GHG emissions within the frame of LCA is performed according to the Global Warming Impact Assessment Method, which aligns with IPCC criteria [23], [24].

An example of an existing carbon footprint evaluation for packaging products is mentioned in [25], where polyethylene terephthalate (PET) packaging material to polylactic acid (PLA) and polystyrene (PS) are compared. A study by Pasqualino J. *et al.* [26] examined the carbon footprint of PET and glass bottles of various sizes. Another example of an integrated LCA-based approach to assessing the environmental impact of packaging material considering the different life cycle stages is shown in [27]. Carbon footprint evaluation of packaging films made from bioplastics, such as polylactic acid, low-density polyethylene, and polybutylene adipate terephthalate using the LCA database, can be found in [28]. In the study [29] carbon footprint assessment is applied to examine the environmental impact of cardboard box containers to store fruits and vegetables.

Apart from the packaging sector, other examples of carbon footprint tools include [24] a tool for the building design process, which assesses the CO₂ emissions from raw materials

and recycled materials through production and transportation, and a tool [30] to analyse carbon footprint or energy and environmental performance in small and medium-sized enterprises. The tool refers to carbon emissions related to the company’s operation field, electricity consumption from the operation field, and transportation. The carbon footprint tool for dairy production systems, including the CO₂ emissions from all feed crops, animal production, and manure handling, is presented in [31]. In the study [32] a carbon footprint evaluation tool for the industrial park includes in the carbon footprint calculation the impacts related to purchased electricity, heat, material, energy consumption, industrial process, and waste management. Lastly, the carbon footprint tool for supply chain management considers the economic sustainability of a product is presented in [33].

This study presents the development of a carbon footprint evaluation tool for packaging materials based on the LCA approach, which is designed for an online packaging marketplace. The tool aims to inform the customers about the carbon footprint of their selected packaging types, thus allowing them to select among existing alternatives the ones that have a minor environmental impact.

2. CASE STUDY

The carbon footprint evaluation tool is developed for a specific packaging product online marketplace case. The marketplace acts as a matchmaker for a desired packaging type customizing the standard packaging products according to the customer's choices. The overall process of the marketplace is presented in Fig. 1.

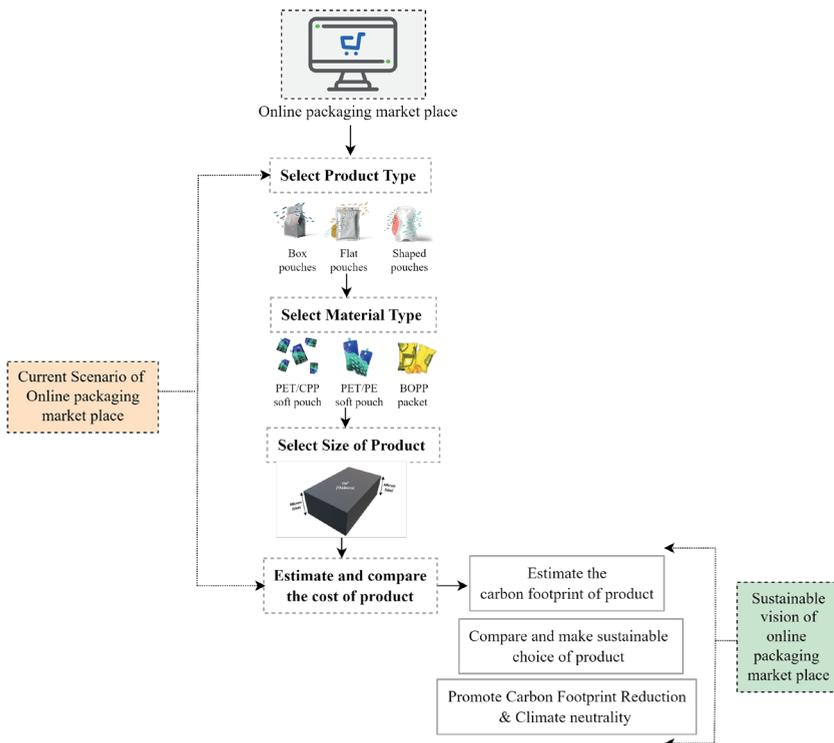


Fig. 1. Schematic presentation of packaging product online marketplace.

The online marketplace provides customers with options for selecting different packaging parameters, such as type of material and product, thickness, and size. After that, the comparison of the cost for selected alternative options is provided to the customer taking into consideration different transport modes and distances from the manufacturer; following the good practice examples found in the literature, the packaging product online marketplace aims to guide customers towards more environmentally friendly decisions by introducing the carbon footprint evaluation tool within their platform.

3. METHODOLOGY

The LCA is a methodology for evaluating a product's environmental impact by quantifying all associated inputs and outputs, such as materials, energy, waste, and emissions. The life cycle of a product considers all production processes, from raw material extractions to waste disposal. This study shows how the carbon footprint tool can be developed based on the LCA approach according to the ISO 14044 standard.

3.1. Goal & Scope Definition

The study aims to develop a carbon footprint evaluation tool for packaging materials in the online marketplace. The system boundary used in carbon footprint evaluation is defined from the “cradle to gate” with transportation to the customer, including the raw materials extraction stage, manufacturing of the packaging, and transportation scenarios to the customer. The system boundaries of the study are shown in Fig. 2.

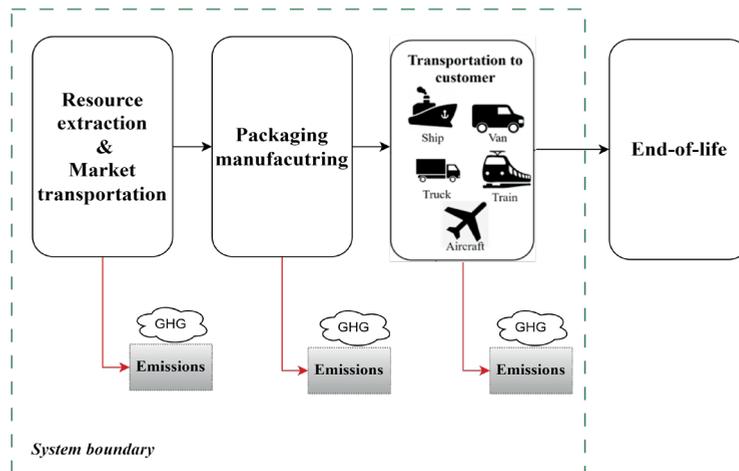


Fig. 2. System boundaries for the case study.

Data for study processes and products used within the defined system boundaries is obtained from the online marketplace company about the different packaging thicknesses and material density. The rest of the data regarding the manufacturing process of specific materials, resource extraction, GHG emissions, and possible transportation modes are obtained from the *Ecoinvent* database. A total CO₂ footprint is measured from the total GHG emissions associated with all activities. The functional unit (FU) in the study is 1 cm² of the

packaging, which serves as the reference unit for accounting for the impacts created during the lifecycle of packaging in the defined system boundaries.

The study's main limitation is a lack of data on packaging products in different regions. The data used in this study is based on the global average values for the manufacturing process of specific materials and transport modes as given in the *Ecoinvent* database. Moreover, at the tool's current development level, the impacts related to different packaging surface production and additional materials in the packaging (e.g., zipper, slider, and other additional options) are excluded from the scope of the study.

3.2. Life Cycle Inventory

The life cycle inventory quantifies inflows and outflows of the system, which must be normalized to the FU. Quantitative data for the material variations and parameters are provided by the online packaging marketplace. The inflow of the system includes different materials, their density, and their thickness. For the transportation scenario, different modes of transport are used to distribute packaging materials. Geographically, the global market was selected for all modes of transportation except for trucks. For truck transportation, the market was selected in the geography of Europe. The outflow of the system includes the GHG emissions, where CO₂ emission is considered for the environmental impact assessment. As stated in the ISO standards 14044, the data must ensure at least its validity regarding the geographical origin, representativeness, technological efficiency, and data sources. Summarizing:

- The background is from *Ecoinvent 3.7.1*, and the weight & specification of materials are according to the manufacturer;
- The geographical context of the system is considered for Europe;
- The data quality is generic;
- The year of data is 2022, and the representativeness per FU is for the year 2021;
- The technological characteristics concern the operations of resource extraction, market transportation, manufacturing, and distribution of packaging materials.

3.3. Impact Assessment Methodology

The carbon footprint is calculated based on the GWP100 using the IPCC 2021 methodology in the *SimaPro* software 9.4. IPCC 2021 is the successor of the IPCC 2013 method, developed by the IPCC [23]. It contains GWP climate change factors of IPCC with 100 years of timeframe. According to the method description, IPCC characterization factors for the GWP of air emissions are [34]:

- Including carbon cycle response;
- Not including the indirect formation of dinitrogen monoxide from nitrogen emissions;
- Not including radiative forcing due to nitrogen dioxide emissions, carbon monoxide, volatile organic compounds, black carbon, organic carbon, and sulfur oxides;
- Not including the indirect effects of carbon monoxide emissions;

The results can be calculated cumulatively as GWP100 or per category: GWP100 – fossil, GWP100 – biogenic, and GWP100 – land transformation [34].

4. RESULTS & DISCUSSION

A carbon footprint evaluation tool is developed for packaging products in the online marketplace to help customers to identify and evaluate different packaging alternatives from

the worst to the best scenario based on their carbon footprint. The created tool foresees carbon footprint evaluation among user-selected alternative packaging materials in five steps shown in Fig. 3.

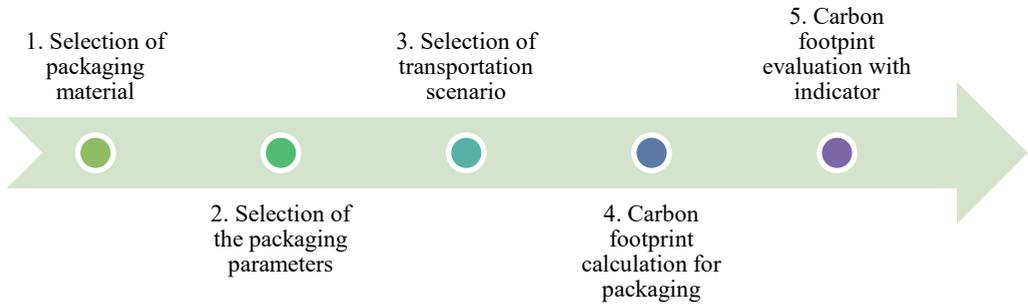


Fig. 3. Steps for carbon footprint evaluation.

The first step is the selection of packaging material alternatives, among which the online marketplace customer would like to make the carbon footprint evaluation. Once the packaging material has been identified from the list of alternative options, the second step is defining the packaging material's amount based on the size of the packaging and the thickness of the packaging material. Step three defined the transportation scenario, including information on transportation type and travelled distance to transfer the packaging. Step four is the carbon footprint calculation for selected alternative packaging scenarios. In this step, the calculation is made for the created GHG emissions in packaging production and transportation to the client based on the information provided in the previous steps. Finally, in step five, a colour indicator is assigned to every alternative indicating the worst, medium, and best options among the selected alternatives.

For the selection of packaging material, information from the packaging company is obtained for different packaging material parameters, including the density and thickness variation. The amount of material in the packaging area equal to 1 cm² is estimated based on density and thickness. The parameters of different packaging materials used for further estimations are given in Table 1.

TABLE 1. PARAMETERS OF PACKAGING MATERIALS INCLUDED IN THE TOOL

Material, <i>x</i>	Density, ρ , g/cm ³	Thickness variation, <i>Th</i> , μm	Material in packaging, σ_A , $\mu\text{g}/\text{cm}^2$
Polyethylene Terephthalate (PET)	1.4	12–30	1680–4200
Low-density polyethylene (LDPE)	0.91	40–120	3640–10 920
Polyethylene (PE)	0.95	45–142	4275–13 490
Recyclable Polyethylene (Recyclable PE)	0.95	25–142	2375–13 490
Kraft paper	1.201	45–80	5405–9608
Brown Kraft Paper	1.201	45–90	5405–10 809
Monoaxial-oriented Polyethylene Film (OPE)	0.95	15–20	1425–1900
Polylactic acid (PLA)	1.24	20–50	2480–6200

Polypropylene (PP)	0.9	15–70	1350–6300
Aluminium (AL)	2.705	7–9	1894–2435
Polyamide (PA)	1.14	50–150	5700–17 100
Paper	1.201	18	2162
Polyamide nylon (OPA)	1.14	15	1710
Wax (paraffin)	0.9	5	450
Biaxially oriented polypropylene (BOPP)	0.946	15–70	1419–6622
Cast polypropylene (CPP)	0.9	25–60	2250–5400

Note: The online marketplace provides density ρ , (g/cm³) and Thickness variations Th , (μ m).

The packaging size can differ depending on customer needs [35]. In the marketplace, the customer can select his preferred packaging p such parameters as packaging material x and size from the available option. This information will serve as input in carbon footprint evaluation. For packaging p of a specific size with an area A_p (cm²) and thickness Th (μ m) the mass of packaging m_p will be estimated in the tool by following Eq. (1):

$$m_p = A_p \cdot \rho_A, \quad (1)$$

where

m_p Mass of selected packaging p , g;
 A_p Area of selected packaging p , cm²;
 ρ_A Area density of material x ; μ g/cm².

To estimate transportation impact, the definition of transportation scenario must include two essential parameters: transport mode and transport distance.

The carbon footprint calculations for selected packaging can be performed by following Eq. (2).

$$CF_p = CF_{xp} \cdot CF_{tp}, \quad (2)$$

where

CF_p Total carbon footprint of packaging p ;
 CF_{xp} Carbon footprint of material x in packaging p ;
 CF_{tp} Carbon footprint of transportation scenario t of packaging p .

The variables CF_{xp} and CF_{tp} are estimated according to the following Eq. (3) and (4).

$$CF_{cp} = CF_x \cdot A_p, \quad (3)$$

where

CF_x Estimated carbon footprint for 1 cm² of packaging materials x ;
 A_p Area of packaging p .

The carbon footprint for the transportation scenario of packaging p is estimated as the sum of the multiplication of transportation distance, the carbon footprint of transport type used, and the mass of packing transported.

$$CF_{tp} = \sum_{i=t}^n D_t \cdot CF_t \cdot m_p, \quad (4)$$

where

D_t	Distance by transport type t ;
CF_t	Carbon footprint coefficient for transport type t ;
m_p	Mass of packaging p .

CF_x and CF_t are the carbon footprint values obtained for a single unit process from *Ecoinvent* by the IPCC 2021 impact assessment method. The CF_{tp} is calculated by selecting the global average datasets from *Ecoinvent*. The transport mode for specific delivery routes must be distinguished among Ship, Truck, Van, Train, and Aircraft based on information from the shipping company. The Carbon footprint coefficient for all transport modes is considering delivering the transportation service of 1 kg of material across a distance of 1 km.

To provide packaging products online marketplace customers with an explicit and simple way for compare of carbon footprint values among their selected alternatives, the colour indicators are assigned to the obtained carbon footprint values. The colour indicator is used for the three carbon footprint levels: low, medium, and high. The different carbon footprint levels can be calculated using Eq. (5) and (6).

$$I = \frac{\max(CF_p) - \min(CF_p)}{3}, \tag{5}$$

where,

I	Value that is used for distinguishing carbon footprint levels;
$\max(CF_p)$	Maximum value among CF_p of selected alternative options;
$\min(CF_p)$	Minimum value among CF_p of selected alternative options.

Eq. (6) is a logical function that assigns the indicator values to every alternative selected:

$$\begin{aligned} &\text{if } (CF_p) < \min(CF_p) + (I), \text{ then } (I_{\text{low}}); \text{ else (if } (CF_p) \geq \min(CF_p) + (2 \cdot I); \\ &\text{then } (I_{\text{high}}); \text{ else } (I_{\text{medium}})), \end{aligned} \tag{6}$$

where

I_{low}	Shows low levels of carbon footprint;
I_{medium}	Shows medium levels of carbon footprint;
I_{high}	Shows high levels of carbon footprints,

A simple evaluation of packaging alternatives can be performed by indicating three carbon footprint levels for packaging alternatives and their transportation scenarios: low, medium, and high.

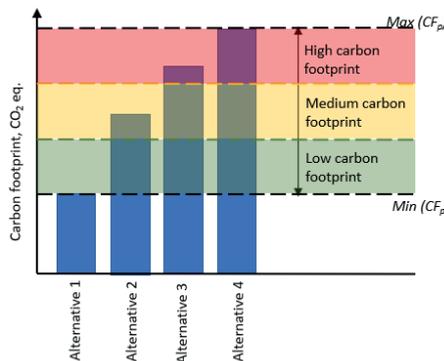


Fig. 4. Colour visualization of carbon footprint calculation for packaging alternatives.

The carbon footprint calculation results can be presented to the online marketplace client using colour indicators to distinguish these levels. As shown in Fig. 4, low, medium, and high carbon footprint levels can be visualized in green, yellow, and red colour indicators. It is noteworthy that the current tool may be developed further, including surface variation and more materials.

The carbon footprint calculation of the packaging, including the transportation scenario, not only shows numerical results and educates clients but also allows the different stakeholders to prioritize opportunities to reduce GHG emissions associated with the product supply chain. Therefore, product policies that promote implementing carbon footprint reduction schemes are worth considering. These policies should be standard and comprehensive, embracing the environmental assessment of products considering their life cycle. In the short term, companies are expected to incorporate carbon footprint schemes as a strategic measure for the competition in the market and decision-making. This goal can be achieved by following well-defined methods. As a long-term goal, policymakers should enforce to implement carbon footprint schemes for companies.

5. CONCLUSIONS

In this work, a simple and stepwise approach is applied to develop a CO₂ calculator to promote the reduction of the carbon footprint of packaging material. The developed carbon footprint tool is used as a strategy to enable CO₂ reduction of an online marketplace company for packaging products. The tool implemented an LCA-based methodology as a viable calculation approach toward the carbon footprint of packaging material using the IPCC 2021 method that provides the unique quantitative value for global warming potential estimation. The tool allows the customer to understand better aspects related to decreasing the carbon footprint, directly contributing to mitigating the intensity of carbon emissions by selecting potentially less impactful choices. Indirectly, the use of this tool promotes climate neutrality. It educates the clients about their purchases and arises as potential support for decision-making companies. The presented case study can be a great starting point for companies with similar packaging strategies and see whether their products are environmentally competitive in the market. Additionally, further research would be worth exploring the parameters, such as packaging surface and additional materials used in the packaging. Moreover, data availability on the regional scale could influence the precision of such tools in the future and, thus, the decision-making in the corporations regarding their sustainability strategies.

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