Towards a sustainable circular economy: a tool for carbon footprint assessment of waste management options

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Abstract: Reducing and recovering waste are the premises of circular economy, that requires the awareness of the flows to be recovered and of the available waste management solutions. It is also relevant to understand the impacts associated with circular strategies to avoid the "circular economy rebound effect". This condition arises when the environmental benefits of recovering value from waste are offset by the negative impacts of circular practices, for instance if the impact of waste transportation is higher than the benefits of waste recovery. This study addresses these elements by creating a tool with a comprehensive view on waste management, with the objective of offering visibility on waste flows and providing an overview of the transportation and management impacts associated with their recovery. This instrument also responds to the call of scholars to provide methods for the circular economy rebound effect at microeconomic level. The tool is built on a thorough assessment of GHG and IPCC protocols, to determine relevant waste management alternatives and related emission parameters. The developed calculation methodology can determine emissions with a customizable combination of primary and proxy data, enabling the effective use of the tool in case of missing data and encouraging data collection. Companies can employ the tool to map waste produced in each node of their supply chain and assess the related emissions considering the distance to the waste recovery plant and the consequent treatment. The tool represents a decision-making instrument that allows the development of what-if simulation scenarios (e.g., choosing an alternative treatment destination for waste management). The tool is validated with data from an Italian retailer, considering waste generated in distribution centres. The results show the ease of application of the tool and offer insights on how it can represent adequate support in the development of sustainable circular supply chains.

Keywords: Circular Economy; Carbon Footprint; Waste Management; Calculation Tool; Logistics.

I. INTRODUCTION AND THEORETICAL BACKGROUND

The per capita generation of waste in Italy is around 3 tons every year, of which more than 80% derive from industrial and economic activities [1]. Circular economy aims at designing out waste and pollution from industrial systems, by keeping products and materials in use [2]. The paradigm of circular economy aims at going beyond waste management, to recover a greater value from waste flows [3]. Despite this objective, proper waste management, which focuses on recycling and recovering and avoids landfill, is the first building block to then achieve circularity at a greater degree [4]. To successfully implement waste management schemes, companies need to be aware of the waste flows to be managed, thus measuring and visualizing such flows is the first step to become more circular [5]. Visualizing such flows can also be relevant when trying to improve the environmental sustainability of waste management, since it allows the estimation of emissions related to waste management [6]. The possibility to closely estimate emissions from waste management, related to waste treatment and transportation, allows companies to assess how these emissions would change when less polluting waste treatment options are considered. This is particularly relevant to avoid the so called "circular economy rebound effect". This condition arises when the environmental benefits of recovering value from waste are offset by the negative impacts of circular practices, for instance if the impact of waste transportation is higher than the benefits of waste recovery [7]. The possibility to qualify and quantify emissions can help avoid the circular economy rebound effect. Scholars highlighted the need for methods for the circular economy rebound effect at the microeconomic level, which are not yet available for companies [8].

Starting from these premises, a tool to estimate emissions from waste management was developed. The model allows visualizing waste flows in the network and assessing the carbon footprint of both waste treatment and transportation. The model has been created to be easily employed by companies, and to guarantee usability even in case of incomplete or missing data. The remainder of the paper discusses how the model was conceptualized and built; the functionalities are presented by applying the tool to the case of an Italian retailer.

II. METHODOLOGY

The development process of the carbon footprint assessment model is shown in figure 1. The tool is composed of two modules, one devoted to the estimation of emissions related to waste treatment, while the second focuses on the transportation of waste to the treatment site. The developed tool can be employed to determine emissions with a customizable combination of primary and proxy data, enabling its effective use in case of missing data and encouraging data collection. The proposed calculation methodology has general validity, but parameters and proxy data need to be referred to a specific geographical area, designating the geographical scope of the tool. In the version of the model presented in this manuscript secondary data and parameters were collected for Italy.

A. Waste model

The development process of the waste model is shown in the blue section of figure 1; it started with the definition of the relevant waste treatment processes to be mapped, together with the identification of appropriate standards to be employed to structure the model. The IPCC Protocol [9] and the GHG Protocol [10][11] were identified as reliable sources. IPCC stands for Intergovernmental Panel on Climate Change, whose members are countries belonging to the United Nations or to the United Nations Environmental Programme. The objective of the IPCC is to provide guidance to governments in the development of climate policies, by offering scientific information and reporting methodologies [12]. The GHG protocol, created in 1998 by the World Resources Institute and the World Business Council for

TABLE I. WASTE TREATMENT PROCESSES INCLUDED IN THE MODEL AND RELEVANT EMISSION SOURCES

Waste treatment process	Positive emissions	Negative emissions
Anaerobic digestion	·Biogas leakages	·Digestate production ·Energy production ·Biomethane production
Composting	·CH_4 emissions ·N_2O emissions	·Compost production
Recycling	·Material recycling	·Material recovery
Mechanical-biological treatment	·All from composting and anaerobic digestions	·All from composting and anaerobic digestions
Incineration with energy recovery	·CO_2 fumes ·CH_4 fumes ·N_2O fumes	·Energy production
Landfill	·CH_4 leakages	·Energy production
Wastewater treatment	·CH_4 emissions ·N_2O emissions	·Energy production

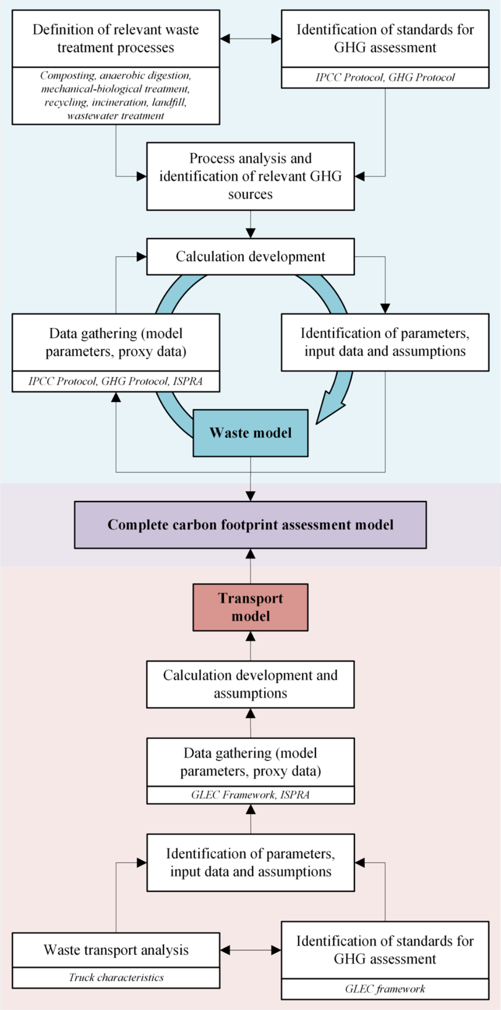

Figure 1. Development process of the carbon footprint assessment model – detail on waste model in blue, on transport model in red

Sustainable Development, has established global standardized frameworks to measure and manage emissions from the public and private sector [13]. Based on the guidelines provided in the standards, we identified the following waste treatment processes: composting, anaerobic digestion, mechanical-biological treatment, recycling, incineration with energy recovery, landfill, and wastewater treatment. Each process has been studied and analysed in detail to define the relevant sources of greenhouse gases. Table 1 details the positive and negative emission sources considered for all the processes considered in the calculation tool. Positive sources include for example methane, carbon dioxide, and nitrous dioxide emissions, while negative flows consider energy production from waste or material recovery. A thorough assessment of IPCC and GHG protocols has then allowed defining calculation methodologies for each of the relevant emission sources, and identifying required parameters, input data and assumptions. The following step was the retrieval of parameters and input data from several data sources (IPCC Protocol, GHG Protocol, and ISPRA, the Italian Institute for Environmental Protection and Research). These references provide rich documentation on waste management, allowing us to extrapolate all the data required for the model [9][10][14][15][16]. These last steps were iterated several times, to refine the model based on available proxy data and parameters and ensure methodological consistency.

Figure 2 shows how the waste treatment processes was conceptualized and consequently modelled. The developed methodology allows estimating the total emissions of each process in CO_2 equivalent terms. The calculation output provides an indication on both positive and negative emissions, that consider all the greenhouse gas sources relevant for the process. The only input data always required for estimating emissions is the total waste produced by the company in a certain node of its network, for instance, in one of its warehouses. The emission calculation is performed based on the availability of other data regarding waste (e.g., composition, treatment type, treatment site…). If primary data are not sufficient, the estimation if performed by also considering proxy data and parameters from international protocols. The final output is obtained by translating the greenhouse gas streams into CO_{2e} emissions through the global warming potential values suggested in the GHG protocol [17].

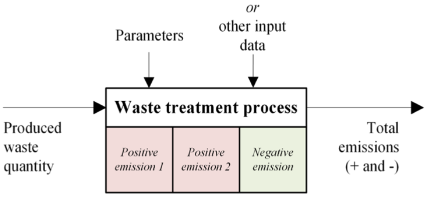

Figure 2. Generic waste treatment process modelling, with input data and output information

B. Transport model

The development process of the transport model is shown in the red section of figure 1, which started with analysing how waste is transported (vehicle type, capacity). Simultaneously, the identification of the most appropriate standards for calculation development led to the selection of the GLEC framework. GLEC stands for Global Logistics Emissions Council and is the main protocol for the reporting of logistics-related emissions [18]. GLEC is part of the Smart Freight Centre, which has developed this framework for harmonizing reporting of logistics emissions and informing business decisions in the effort to reduce transport-related emissions [19]. The framework is compliant with the GHG protocol and in 2022 has been certified by ISO with the standard 14 083 [19][20]. Thanks to the analysis of the GLEC framework we defined the required input data and parameters for the calculation, together with the assumptions to be included in the modelling. Consequently, parameters and proxy data were retrieved from relevant sources: emission factors from the GLEC framework and the location of waste treatment sites from ISPRA [14]. The information provided by ISPRA does not include waste recycling sites, thus in this version of the model these nodes have not been mapped and will be implemented at a later stage. The final step of the transport model development was the construction of the calculation methodology based on gathered information and data.

A detailed modelling of transport is presented in figure 3. The required input data are the quantity of waste to be transported and the location of the node where the waste is generated, in geographical coordinates. The total emissions are calculated by

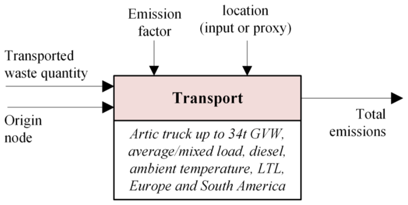

Figure 3. Transportation modelling, with input data, assumptions, and output information

considering the distance to be travelled and the emission factor of the default vehicle (Artic Truck up to 34t GVW, average mixed load, diesel, ambient temperature, less than truck load, Europe and South America) [18]. In this version of the model the used vehicle has been set as default to ease calculation; this truck has been selected since it well represents a truck for waste transport and is very frequently employed in logistics networks. This model parameter can be easily adjusted when more punctual data on transportation mode are available. The travel distance is estimated based on the location of the node where waste is generated and of the treatment site (input or proxy data). The model includes some assumptions on the location of the treatment site in case this is unknown. At first, the node where waste is generated is considered and the distance between the node and all the treatment sites is calculated (regarding a specific treatment type). Considering the spatial distribution and density of waste disposal sites on the Italian territory, the sites within 60km from the origin node are picked. The model finally estimates the travel distance by calculating the average distance of the selected nodes, weighted on the annual treated waste. This procedure allows an estimation of the emissions of waste transport in case of missing data.

III. RESULTS

The developed carbon footprint assessment model was applied to the case of an Italian retailer, specifically to its distribution centres located in Toscana, Lazio, and Sardegna (see figure 4). The retailer provided data for the year 2021 regarding the generated waste and in most cases about its composition and treatment destination (available in appendix A). No information was provided on the specific site where waste is treated, except for the case of incineration presented in paragraph III.E.

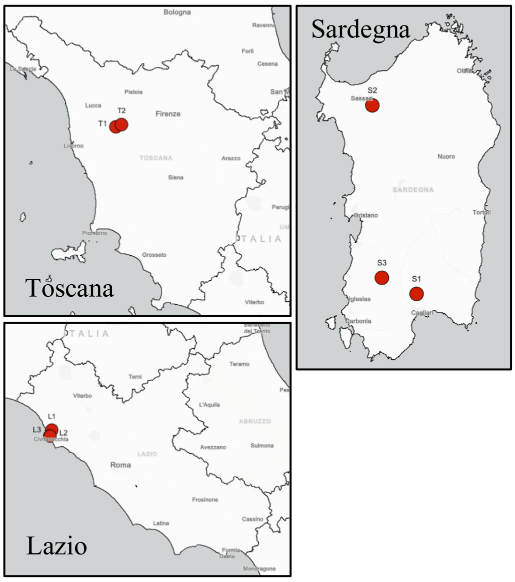

Figure 4. Location of the considered distribution centres in Toscana (T1, T2), Lazio (L1, L2, L3), and Sardegna (S1, S2, S3)

This section reports some illustrative examples of how the model can be applied and the related outputs (in green in appendix A).

A. T1 – Recycling

In node T1 part of the waste is destined to recycling, and information is provided on the composition of the generated waste.

Equation 1 and 2 show how to estimate positive emissions related to waste recycling and negative emissions linked to material recovery. The formulas require as only input data the generated quantity of waste per type of material. In both cases it is necessary to then match the emission factor (EF) to the considered waste fraction *i*, multiply the terms, and repeat the calculation for all the considered waste fractions.

$$(1)\quad +CO_{2e} = \sum_i waste_i\ [kg] \cdot EF_i\ [\frac{kg\ CO_{2e}}{kg}]$$

$$(2)\quad -CO_{2e} = \sum_i waste_i\ [kg] \cdot EF_i\ [\frac{kg\ CO_{2e}}{kg}]$$

This is an example of a calculation entirely based on primary data since the emission factors are model parameters and the quantity of waste per type of material is given. The calculation does not introduce approximations based on proxy data.

B. S1 – Recycling

In the distribution centre S1 part of the waste is destined to recycling. The information provided on the composition of such waste is incomplete, since for a portion of the waste the type of material is not defined.

The emissions for recycling can be estimated with equation 1 and 2, which require as input the waste composition.

In this case proxy data on waste composition are required for the calculation of emissions. The undefined flow to recycling is thus decomposed into fractions considering the average percentage composition of municipal waste destined to recycling (referred to Italy, year 2021) [14]. The obtained values are then associated to the appropriate emission factors to estimate emissions. The presented case is an example of a calculation based both on primary and secondary data, which shows how proxy data can be employed to estimate emissions.

C. S3 – Recycling

In distribution centre S3 waste is destined to recycling. The information provided on waste composition is incomplete, since it is only stated that the waste is “Packaging”.

This data is insufficient for the calculation since packaging can be made of different materials, which will have different emission factors (see equation 1 and 2).

The model in this case follows the same approach as in the previous example, but the average percentage composition specifically refers to municipal packaging waste destined to recycling (Italy, year 2021) [14]. This case exemplifies how it is possible to employ different proxy data to better contextualize the calculation and provide more accurate results.

D. S1 – Composting

In node S1 composition data for waste flows destined to composting are available. The composting process has negative emissions related to the production of compost from material degradation; compost can be used in place of fertilizers or peat, but information on the use of compost is not provided. It can be challenging for companies to collect this type of information, since they typically do not own or directly control waste treatment plants.

The negative emissions of compost use can be calculated with equation 3, where compost use describes how much of the compost is destined to the *i*-th use, associated to the *i*-th emission factor.

$$(3)\quad -CO_{2e} = \sum_i waste\ [kg] \cdot compost\ use_i\ [\%] \cdot EF_i\ [\frac{kg\ CO_{2e}}{kg}]$$

Proxy data are employed for compost use, expressing the portion of compost used in place of fertilizers or substituting peat; the related emission factors are parameters of the model [21]. This case highlights the importance of proxy data in the estimation of some emissions sources since the collection of primary data on waste treatment can be difficult for companies.

E. S2 – Incineration

In distribution centre S2 the residual mixed waste is destined to incineration, treated in the incinerator of Capoterra. Destination, composition, and treatment site are available for this waste flow.

The model can calculate some emission sources based on site-specific data, available through secondary sources [14]. In case of incineration with energy recovery, such information can be used for the estimation of avoided emissions related to energy production. The calculation methodology can be found in equation 4, where i and j represent electric and thermal energy, produced in different shares in different plants ($energy_{i,j}$), and associated to different emission factors.

$$(4)\quad -CO_{2e} = waste\ [\%] \cdot (\sum_i \sum_j energy_{i,j}\ [\%] \cdot E_{prod}[kWh] \cdot EF_{i,j}\ [\frac{kg\ CO_{2e}}{kWh}])$$

Site-specific data can be employed to estimate the proportion between thermal and electric energy and to assess the annual energy production (E_{prod}). The waste is expressed in percentage as it considers the share of the company waste treated in the site with respect to the annual treated waste. This data is available from secondary sources and is required to relate the company waste to the produced energy, to consequently allocate emissions. The case of S2 highlights how the model can adjust to include site-specific data and provide a more precise estimation of waste treatment emissions.

F. L1 – Destination not defined

L1 reports some waste flows with undefined destination, providing information on the composition of such flows.

The type of waste treatment is an important information for the functioning of the model since it defines which emission sources will be relevant for the calculation.

The model has been built to make emission estimation for such flows possible, to give a rough indication of the emissions related to waste treatment and encourage further data collection. To estimate the quantity of waste to be allocated to each destination, the model employs the average percentage municipal waste treatment in Italy for 2021 [14]. The calculated quantities are then used as input data to assess emissions for all the treatment processes available in the model. The L1 case highlights the flexibility of the model, with the possibility to allocate emissions to flows with undefined treatment. This functionality of the model allows avoiding an underestimation of overall emissions since the data would otherwise be discarded and emissions for these flows would not be estimated.

G. Transport

The treatment site is unknown for most of the nodes and destinations, thus the approximated methodology presented in paragraph II.B was applied in most cases. Transport emissions were not calculated for the flows with undefined destination, since it is not possible to determine which plant processes the waste. Only in node S2 there is a specific site for incineration of waste, hence in this case the exact distance between the points was used for emission estimation.

H. Model outputs

The first relevant output provided by the model is the distribution of waste in the network (see figure 5), which can be employed to raise attention on the most wasteful nodes.

Figures on emissions provide a multifaceted perspective on the waste recovery network, thanks to the granularity of the analysis. Starting from the network level, it is possible to assess emissions related to the different waste treatment options (figure 6). Emissions from waste treatment are also reported for each node, as shown in figure 7, to provide a more punctual understanding of emissions sources related to the chosen treatment destinations, along with transport emissions.

IV. CONCLUSIONS

The application of the developed model to the case of an Italian retailer shows its ease of application and flexibility. The reliance on proxy data allows the application of the model even in case of missing data, fostering data collection, and allowing a more complete reporting. Proxy data are effective also when the treatment site is known, to obtain a more punctual estimation of emissions. Beyond its simplicity and versatility, the carbon footprint assessment model can provide significant insights on waste management. The first contribution is the possibility to visualize waste flows in each node of the network since the awareness on the flows to be recovered is a first important step towards the development of a sustainable waste recovery network. Moreover, the information derived from figures 6 and 7 offer an overview on waste treatment at node and at network level, and this data can be combined with transport emissions to report the overall impact of waste management.

Altogether, emission estimations regarding waste management and transport can guide informed decision-making about sustainability and circular economy. This aspect will be pivotal in the further developments of the model, which will include the possibility of creating what-if scenarios based on the results of the emissions assessment. The simulations will be based on the analysis of model outputs, and will include, for example, the reduction of the waste flow or the change of waste treatment. Transport emissions will be decisive for simulations, since changing the waste treatment will entail transporting waste towards a different and maybe more distant site, potentially contributing to the circular economy rebound effect.

The presented model has some limitations that can guide its further development. The geographical scope is limited to the Italian context, thus influencing its applicability and reliability in other countries. The reliability of the model can be compromised if the input data are too scarce, requiring a high reliance on proxy data.

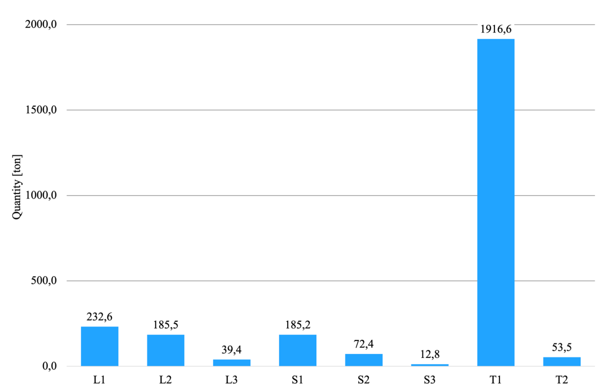

Figure 5. Waste produced in each node of the network, in tons

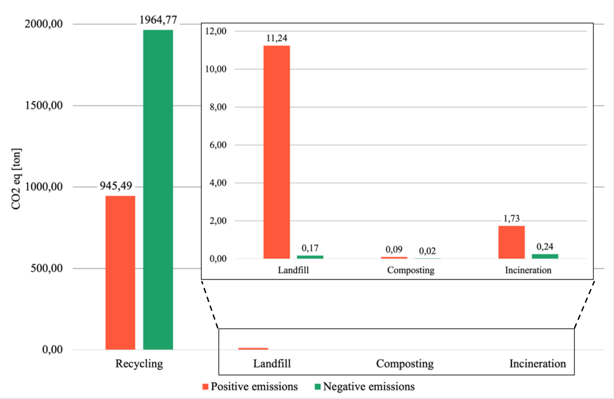

Figure 6. Network emissions for each waste treatment destination

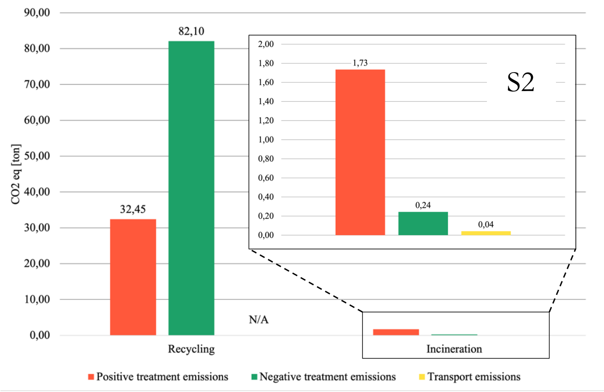

Figure 7. Emissions overview in node S2

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Appendix A. Input data, quantities in kg. Examples discussed in the paper in green.

DC	Treatment	Waste	Quantity
T1	Recycling	Cardboard packaging	237 110
		Wood packaging	865 260
		Plastic packaging	164 444
		Metal	33 500
	Landfill	Packaging	272 780
		Organic waste	8 090
T2	Landfill	Packaging	53 500
L1	Recycling	Hazardous waste	325 874
		Plastic packaging	37 140
		Wood	1 420
	Landfill	Packaging	4 590
	nd	Residual waste	32 640
		Organic waste	65 280
L2	Recycling	Cardboard packaging	30 285
		Wood packaging	26 150
		Plastic packaging	43 650
		Metal packaging	8 310
		Paper and cardboard	30 285
	Landfill	Packaging	18 320
		Organic waste	28 490
L3	Landfill	Organic waste	8 200
		Packaging	21 790
		nd	9 370
S1	Recycling	Cardboard packaging	102 800
		Plastic packaging	66 820
		Packaging	4 220
		Metal	7 480
		nd	1 281
	Composting	Organic waste	1 056
S2	Recycling	Cardboard packaging	32 380
		Plastic packaging	35 080
		Metal	2 780
	Incineration, Capoterra	Residual waste	2 200
S3	Recycling	Packaging	12 820