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Assessing the Environmental Performance of Municipal Solid Waste Collection: A New Predictive LCA Model

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Abstract: Most existing life cycle assessment models of waste management have so far underplayed the importance of the waste collection phase, addressing it only in a simplified fashion, either by requesting the total amount of fuel used as a direct user input or by calculating it based on a set of input parameters and fixed diesel consumption factors. However, if the main purpose of the study is to improve the efficiency of the collection system itself, a more detailed analysis of the collection phase is required, avoiding oversimplified and potentially misleading conclusions. The new LCA collection model presented here relies on a large number of parameters (number and type of containers, collection frequency, distances for the various legs of transport, etc.) and allows the detailed predictive analysis of alternative collection scenarios. The results of applying this newly developed model to a number of experimental case studies in Portugal are analyzed, discussed, and compared to those produced by a selection of pre-existing, more simplified models such as ORWARE and MSW-DST. The new model is confirmed as being the most accurate and, importantly, as the only one capable of predicting the consequences of a range of possible changes in the collection parameters.

Keywords: LCA; waste management; waste collection; predictive model

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1. Introduction

LCA was originally developed to analyze the environmental performance of product systems; however, since the end of the 1990s, this methodology has also been used for the analysis of waste management systems [1]. Since then, hundreds of scientific papers on this topic have been published. Proof of this sharp increase all over the world is the review of 222 LCA studies comparing waste management systems before 2013 performed by Laurent et al. in 2014 [2]; the review of 153 worldwide studies after 2013 performed by Khandelwal et al. in 2019 [3]; and the even more recent reviews of 79 papers performed by Iqbal et al. in 2020 [4] and of 45 studies by Zhang et al. in 2021 [5], both of which included selected case studies from developing and developed regions. Until 2013, the majority of studies were performed in Europe, whereas from this date on, there has been a remarkable increase in the use of LCA in China and also a progressive extension to other low-income or less developed countries such as India, Brazil, or Pakistan.

In all these studies, LCA was used to compare different alternatives for the treatment of a specific waste flow such as paper [6–9], plastic [10–12], or organic waste [13–15]; to compare or improve different technologies [16–20]; and also to compare more complex systems such as complete integrated waste management systems, including all waste fractions [21–33]. The benefit of using LCA in this context is that it helps to expand the scope of the analysis and to obtain a complete view of the entire system, including all processes and associated environmental impacts. This approach can avoid the unintentional shifting of environmental loads between different stages of the waste management system, geographic areas, environmental compartments (air, land, and water), or impact categories (e.g., global warming, acidification, etc.).

In this context, LCA has gained importance in recent years as a tool to assist decision making for waste management policy and planning in Europe [34,35]. Although some authors performed their studies using conventional LCA software and databases such as Simapro and Ecoinvent [14,28], the methodological development of LCA for waste management has gone hand in hand with the development of models and specific software tools to facilitate its implementation by non-LCA experts. These models have been developed almost independently, and mainly in Europe and North America, from the mid-1990s onwards by a wide range of universities, consultancy firms, and environmental protection agencies (Table 1).

Table 1. The most widely known, used, and complete waste LCA models.

Software	Country	Launch Time	Reference
ORWARE (a)	Sweden	1997	[36,37]
EPIC/CSR (b)	CA	1999	[38–40]
MSW-DTS (c)	USA	1999	[41,42]
WIZARD (d)	UK, FR, NZ	1999	[43]
IWM-2 (e)	United Kingdom	2001	[44]
SSWMSS (f)	Japan	2004	[45,46]
LCA IWM (g)	European Union	2005	[47–49]
WRATE (h)	United Kingdom	2007	[50,51]
EASEWASTE ((i)	Denmark	2008–2009	[52]
EASETECH (j)	Denmark	2013	[53]
SWOLF (k)	USA	2014	[54]

Notes: (a) ORWARE (ORganic WAste REsearch) was initially focused on organic waste but extended afterwards to other waste fractions. (b) EPIC/CSR is an Integrated Waste Management model produced by the Environment and Plastics Industry Council (EPIC) and Corporations Supporting Recycling (CSR). (c) MSW-DST (Municipal Solid Waste Decision Support Tool). (d) WIZARD (Waste-Integrated Systems Assessment for Recovery and Disposal). (e) Integrated Waste Management (IWM), first version launched in 1995 [55]. (f) SSWMSS (Strategic Solid Waste Management Supporting Software). (g) LCA IWM (Life Cycle Assessment-Integrated Waste Management) software was developed under a research project financed by the European Commission between 2002 and 2005. It also includes a prognostic tool for estimating the future generation of waste in European Cities. (h) WRATE (Waste and Resources Assessment Tool for the Environment) software is an evolution of the older WIZARD. (i) EASEWASTE (Environmental Assessment of Solid Waste Systems and Technologies). (j) EASETECH (Environmental Assessment System for Environmental TECHnologies) is an evolution of the older EASEWASTE. (k) SWOLF (Solid Waste Optimization Life-Cycle Framework). Information extracted from Gentil et al., 2010 and updated [56].

All these software packages have in common the inclusion of specific datasets for a wide range of unit processes (waste collection, sorting, recycling, incineration, landfilling, composting, or anaerobic digestion), and the possibility for users to build their own waste management systems by combining these unit processes and specifying waste generation, waste composition, and/or recovery rates to arrive at specific results for their system(s) of interest.

In-depth reviews of the existing models were carried out by Björklund et al. [57] and Gentil et al. [56]. Both studies featured comparisons based on methodological issues, input parameters, and modeling assumptions, and concluded that there are substantial differences in the models, often linked to the date of development and the level of knowledge at that time. Along the same lines, other authors evaluated the same management systems or waste management processes using different models to check if the results were comparable. Examples of such comparative work are those by Hansen and Christensen [58], comparing organic waste treatments; Winkler and Bilitewski [59], comparing the entire management system of the city of Dresden in Germany; and Rimaityté et al. [60], comparing the outcomes of waste incineration using different models and also vs. experimental data.

However, no comparative meta-analyses of the results of applying different LCA models to the waste collection phase were found in the literature. This is probably due to the fact that, while this latter phase of the management system accounts for a major part of the total costs of modern waste management systems [61], several LCAs have shown that its overall effect in terms of energy demand and emissions of CO_2, SO_2, and NO_x remains comparatively small, provided that the collection and transport systems are reasonably efficient [62–65]. In fact, the recent review by Iqbal et al. of the use of LCA for WMS revealed that about 16% of the studies excluded waste collection and transport altogether, assuming that their contributions would be insignificant compared to the rest of waste management chain [4]. The general validity of these findings in relative terms, i.e., that the waste collection stage is the smallest contributor to the overall environmental impacts of the entire waste management chain, is not questioned. However, in many cases, waste collection is in fact the one process that can be most directly controlled and optimized by actors such as local municipalities and waste management companies, and its impacts can still be rather large in absolute terms. Therefore, the lack of a detailed predictive tool capable of accurately estimating the environmental consequences of a range of specific collection alternatives represents a significant gap in the existing LCA knowledge base.

The drive for implementing a source-separated collection system for different waste fractions rests on the assumption that the amount and quality of the waste collected in such a way are sufficient to overcompensate for the additional environmental burdens entailed by the more complex collection system (thanks to the environmental credits arising from the recovered materials and/or energy), or, in other words, that the collection and transport systems are reasonably efficient. The national implementation of the Directive 2008/98/EC of the European Parliament and the Council on waste [66] led many countries to introduce a legal obligation of establishing a source-separated collection for plastics, glass, paper and cardboard, metals, and also organic waste. However, in countries like Spain or Portugal, where many of the municipalities are very small (under 5000 inhabitants) and scattered around the territory, whether source-separated collection is really environmentally sound and effective in all cases remains to be carefully assessed.

Some authors have questioned the premise of collection efficiency and pointed out that this stage of the waste management system can have a major influence on the overall outcome, depending on how it is implemented. For instance, Klang [67] states that in rural and sparsely populated areas of Sweden, it is "more difficult to transform their waste systems in a more sustainable direction", due to small waste volumes, long collection routes, and distant treatment facilities. Along the same lines, Tanskanen and Kaila [68] pointed out that the increasing complexity of the collection systems in terms of the amount of different waste fractions collected separately, and the associated transport and fuel consumption, may increase the relevance of this stage. Salhofer and colleagues [69] demonstrated how transport distances may affect the environmental benefit of recycling a range of waste flows (refrigerators, waste paper, polyethylene films, and expanded polystyrene). In the same way, Aryan et al. in India [70] and Ahamed et al. in Singapore [14] demonstrated that the collection and transport of PET and PE in the former and food waste in the latter may have a high contribution to the global warming potential of the systems, ranging from 23% for food waste up to 40% for PET, due to the large distances to recycling facilities. All this calls for a better focus on the collection phase to assess whether (or the extent to which) the additional environmental burdens associated to the source-separated collection of municipal solid waste are in fact offset by the attainable higher recovery rates of materials and energy from waste.

The aim of this paper is thus two-fold. Firstly, it provides a careful review of existing models for the LCA of waste management systems and looks at whether or not they do a satisfactory job of estimating the fuel consumption and the associated impacts in the waste collection phase. Secondly, it introduces a new, more complete and detailed model to predict the environmental performance of the waste collection phase, in which changes in the operational parameters of the system (such as, e.g., the number or volume of waste containers, changes in the distances between containers or between the collection area and unloading site, etc.) have a direct effect on the modeled fuel consumption and emission rates.

2. Review of Existing Models

When dealing with the environmental performance of the waste collection phase, three different levels of complexity can be found among the LCA software packages listed in Table 1. The first level comprises those models that require that the user input the total amount of fuel (e.g., diesel) consumed directly (such is the case of IWM-2), and then apply fixed emission factors associated to the combustion of this fuel. Second level models require the input of fuel consumption (or efficiency) rates (e.g., in terms of km traveled per liter of diesel, liters of diesel consumed per ton of collected waste, or liters of diesel consumed per hour of service) and the input of the amount of waste and/or km traveled and/or the overall collection time in order to calculate the total fuel consumption. Then, corresponding emission factors are also applied. Within this second type of model, a distinction can be made between models in which the user is required to specify their own consumption factors (for instance, IWM-Canada and EASEWASTE/EASETECH), and others in which default values are provided, which may be changed by the user either manually or by selecting different truck types from a database (WRATE and LCA-IWM). Third level models are those in which the distances or time spent in the collection stage are not directly entered by the user but instead calculated by means of a set of operational parameters like travel speed, distances between individual collection points along the route, time spent in different operations, etc. Such km or hours spent are then multiplied by fixed consumption factors (L/km, L/h, or L/(t.km)), either introduced by the user or provided by default (as in MSW-DST and ORWARE). Like in the previous cases, emission factors are then applied to convert the diesel consumption into airborne emissions in order to evaluate the environmental impact of the collection stage.

It is worth noting that, in the end, existing simplified models (both level 2 and 'level 3′ types) are still similarly limited in assuming a straightforward direct correlation between the distance traveled, waste collected or time spent collecting (in the case of MSW-DST), and the fuel consumed. These models may be regarded as arguably sufficient only for a quick estimate of the environmental impacts of the collection phase within the framework of a broader analysis of a complete waste management system, especially when the average collection performance (in terms of L (fuel)/t (waste), L (fuel)/km, or total fuel consumption) is already known. However, they fail to provide a sufficient level of detail if the focus of the analysis is on the optimization of the waste collection system itself. Questions like the following cannot be answered using such simplified models if no real data are available: "what if rear-loading trucks were replaced by side-loading trucks, using fewer larger containers?" or "what if the number of containers were reduced and the collection frequency were doubled?". In order to answer these types of questions, more sophisticated models are needed, which must be able to predict the ensuing changes in the performance of the waste collection system. The original model presented in this paper is aimed squarely at filling this knowledge gap.

3. Materials and Methods

The steps followed in order to achieve the aims of this research are summarized in Figure 1. The materials and methods used are described in the following subsections.

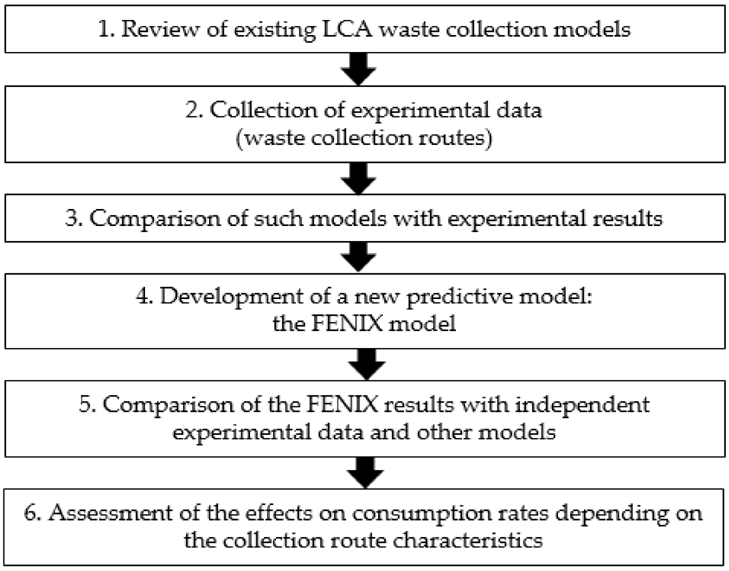

Figure 1. Research steps.

3.1. Selection of Pre-Existing Models for Review and Comparison

The scope of this review and comparison will be restricted to level 3 models, plus the stock model for waste collection trucks included in Ecoinvent, since the latter is arguably the most widely-used life cycle inventory database used by LCA practitioners. The selected models are described below.

- ORWARE: This model is based on the calculation of fuel consumption and emissions for waste collection trucks, considering two different situations: while collecting waste and while traveling from the collection area to the unloading site. Data on average load, average speed, etc. are used as input parameters. Data on energy consumption (MJ/(t.km)) were obtained from average data provided by the Uppsala Public Service Work in 1994 and emissions from a simulation of an average bus tour in an urban area with many stop-and-go cycles and a rather low average speed. The author explicitly mentions that this model is only valid for the collection of waste in urban areas. Data for energy consumption (converted to the international system of units (SI)) are shown in Table 2. A complete description can be found in [71].

Table 2. Default diesel consumption rates used in the analyzed models.

	Units of Energy Consumption	Waste Truck, in Collecting Route	Waste Truck, from the Collection Area to the Unloading Point	Waste Truck, Idling
ORWARE [(a)]	L/(t.km)	0.24	0.13	
MSW-DST [(a)]	L/km	1.18	0.47	
	L/h			0.26
Ecoinvent	L/(t.km)	0.42		

Notes: (a) original consumption rates were transformed to international system (SI) units.

- MSW-DST: This model includes a set of equations to calculate the time required for the individual activities of the collection vehicles in a typical working day (driving to the collection area, driving in stop-and-go cycles, and idling at the stops). These times are then used to calculate the associated fuel consumption, based on corresponding fixed consumption factors (gallons per mile and gallons per hour)—see Table 2 for the values converted to SI. A complete description of the model and equations can be found in [72].

- Ecoinvent dataset for collection trucks ("CH: transport, municipal waste collection, lorry 21 t"): This dataset is based on five case studies for German and Swiss municipalities, from which an average consumption rate of 4 L/t was obtained. The (fixed) transportation distance was estimated from the standard transport distance to municipal solid waste incineration plants in Ecoinvent, i.e., 10 km. From these values, an average fuel consumption factor expressed as L/(t·km) was derived—also included in Table 2. For further details, the reader is referred to Doka [73].

3.2. Experimental Data Collection

Weekly experimental data from 14 different curb-side collection routes were gathered in 2012 in Portugal (Lisbon and surrounding areas). These routes refer to the source-separated collection of different waste fractions, namely: mixed municipal solid waste (MSW), light packaging waste (LPW), paper and cardboard (P), and glass (G). All the routes correspond to more residential areas, except routes (LP2 and P2) that correspond to more commercial areas. For all routes, specific data were gathered, including total amount of waste collected, number of containers, distances between different parts of the collection route, and total fuel (diesel) consumption.

3.3. Development of a New Model: The FENIX Model

Within the EU Life+ project "FENIX", a new predictive LCA model for the assessment of the environmental performance of the waste collection stage (hereinafter, the FENIX model) was developed. In this model, the collection stage includes both the effective collection leg of the route (within urban areas) as well as other distances traveled by the collection trucks, from the moment they leave the parking until they return to it (the latter distances collectively referred to as "transportation" in the model) (see Figure 2).

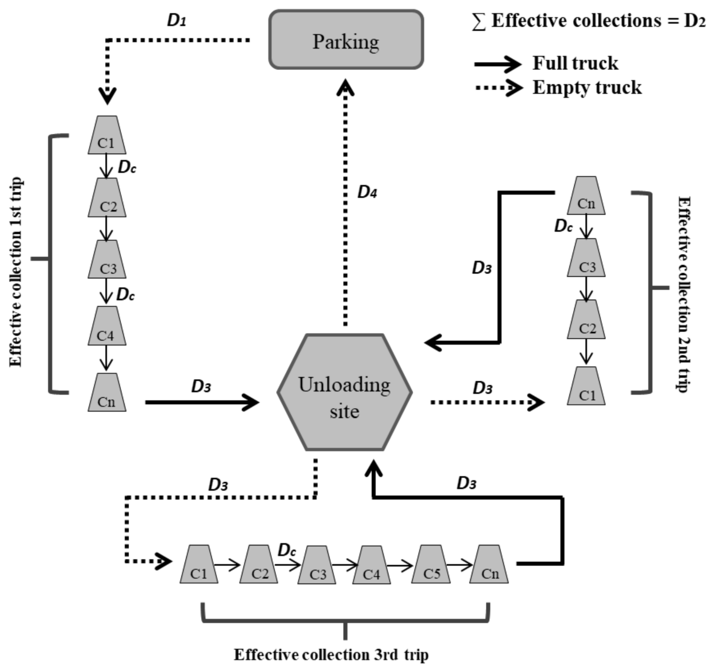

Figure 2. Simplified diagram of the collection model to calculate distances, share of km in each type of service, and utilization ratio.

The development started by modifying a pre-existing model for a conventional transport truck to factor in the additional fuel consumption due to the specific stop-and-go drive cycles and other intrinsic characteristics of the waste collection truck, as well as to lifting the waste containers and compacting the waste. Finally, a detailed model for the calculation of the needed input parameters to run the modified collection truck model was developed based on a set of operational parameters and limiting factors.

3.3.1. Starting Point: A Conventional Commercial Truck

The FENIX model is based on the parameterized truck models developed by Sphera and available in the built-in database of the GaBi LCA software package, as well as in the (now discontinued) European Reference Life Cycle Database (ELCD). Essentially, those models calculate variable fuel (diesel) consumption and emission factors (CO_2, CO, N_2O, NH_3, NMVOC, CH_4, NO_x, SO_2, Toluene, Xylene, and PM) in terms of mass units per (kg·km) of transport. The fuel consumption factors are computed according to Equation (1):

$$Diesel_{cf} = \sum_{j=1}^{3} \left[\alpha_j \times \left(A_j + \left(B_j - A_j \right) \times U_r \right) / \left(P_l \times U_r \right) \right] \tag{1}$$

where $Diesel_{cf}$ is the diesel consumption factor (kg(diesel)/(kg·km)); j is the type of road (1 = urban; 2 = extra-urban; 3 = motorway); α_j is the share of km traveled in each type of road (-); A_j is the diesel consumption of the empty truck, depending on the type of road (speed and driving conditions) (kg(diesel)/km); B_j is the diesel consumption of the full truck, depending on the type of road (speed and driving conditions) (kg(diesel)/km); P_l is the maximum payload capacity of the truck (kg); and U_r is the utilization (fill) ratio of the truck by mass (-).

Then, the total amount of diesel consumed to transport goods is calculated as detailed in Equation (2):

$$Diesel \ = \ Diesel_{cf} \ \times \ Load \ \times \ D_T \tag{2}$$

where $Diesel_T$ is the total diesel consumption (kg(diesel)); *Load* refers to the total transported mass (kg); and D_T refers to the total distance traveled to transport the load (km).

In such base models, Equations (1) and (2) are formulated in the same way for calculating the emissions of CO_2, CO, NMVOC, CH_4, NOx, Toluene, Xylene, and PM. The only difference is that factors Aj and Bj refer to the correspondent mass of substance emitted per km. The remaining emission factors, namely those for N_2O, NH_3, and SO_2 are calculated according to Equations (3)–(5), respectively.

$$N_2O_{ef} = \sum_{j=1}^{3} \left[\alpha_j \times E_j / \left(P_l \times U_r \right) \right] \tag{3}$$

$$NH_{3_{ef}} = E / \left(P_l \times U_r \right) \tag{4}$$

$$SO_{2_{ef}} = PPM \times 2 \times Diesel_{cf} \tag{5}$$

where E_j is the emission factor, depending on the type of road (speed and driving conditions) (mg/km); E is the average emission factor (mg/km); *PPM* is the proportion of sulfur in diesel (ppm), and *2* is the ratio of the molecular mass of SO_2 to that of S (kg(SO_2)/kg(S)).

3.3.2. Adaptation of the Conventional Truck to Waste Collection Vehicles

Waste collection vehicles differ from conventional trucks in their performance because they have different intrinsic characteristics. First of all, waste collection vehicles continuously carry the additional load of the heavy box and equipment used to collect and compact the waste. Moreover, their operation entails more stop-and-go cycles in comparison to conventional trucks, since they have to stop and start again every time they collect the waste at each collection point. Additionally, while the trucks are stationary, the engines still operate at high revolutions per minute (RPMs) in order to lift the waste containers from the curb and compress their content. Another important difference is related to the utilization ratio (U_r) of the truck. Whereas the U_r of a conventional truck would remain constant, from the loading site all the way to the unloading site, the same parameter for a waste collection truck varies along the collection route (increasing as more and more waste is collected). For all these reasons, it was necessary to modify the basic truck model described above in order to incorporate the additional diesel consumption and related emissions.

The additional consumption due to the heavy box and equipment, the additional stop-and-go cycles, and the variable utilization ratio were considered by including a correction parameter (β_j), which is the ratio of consumption/emission factor of a waste collection truck to that of a conventional one (Equation (6)).

$$\beta_j = Diesel_{cf}{}' / Diesel_{cf} \quad (6)$$

where $Diesel_{cf}{}'$ is the diesel consumption factor (kg(diesel)/(kg·km) of the collection truck.

$$Diesel_{cf}{}' = \sum_{j=1}^{2} \left[\alpha_j \times \left(A_j{}' + \left(B_j{}' - A_j{}' \right) \times U_r{}' \right) / \left(P_l{}' \times U_r{}' \right) \right] \quad (7)$$

where α_j is the share of km traveled in each leg of the collection route (respectively, $j = 1$ for transport and $j = 2$ for effective collection), $A_j{}'$ is the diesel consumption of the empty collection truck (including the box) in each leg [kg(diesel/)km]; $B_j{}'$ is the diesel consumption of the full collection truck (including the box) in each leg, also depending on the number of additional stops per trip (kg(diesel)/km); $U_r{}'$ is the utilization (fill) ratio of the collection truck by mass (-); and $P_l' = (P_l - W_{box}))$ is the maximum effective payload capacity of the truck (discounting the weight of the box) (kg); and W_{box} is the weight of the box used to store and compact the waste (kg).

The share of km travelled during the effective collection and the transportation legs or the route (α_j) and the total distance per collection trip (DT) are calculated as detailed in Equations (8)–(11).

$$\alpha_2 = 1 - \alpha_1 \quad (8)$$

$$\alpha_1 = (D_T - D_2) / D_T \quad (9)$$

$$D_T = [D_1 + D_2 + (N-1) \times 2D_3 + D_3 + D_4] / N \quad (10)$$

$$D_2 = (C-1) \times D_c \quad (11)$$

where, again α_2 is the share of km travelled during the effective collection (-); α_1 is the share of km traveled the rest of the collection route (-); C is the number of containers (or collection stops) (-); D_1 is the distance between the parking lot and the collection route (km); D_2 is the total distance while collecting waste (effective collection) (km); D_3 is the distance from the collection area to the unloading site (km); D_4 is the distance between the unloading site and the parking lot (km); and D_c is the average distance in between individual containers or collection stops (km).

All calculations were carried out in an Excel worksheet. The number of trips per truck (N) was calculated taking into account the following limiting factors in an iterative way: (1) the maximum number of containers in the collection route, (2) the maximum volume or weight capacity of the truck, and (3) the maximum duration of the working day. These and other default parameters and intermediate calculations needed to obtain the output data are described in Table 3. It was first assumed that, after collecting all the waste from the curb-side waste containers, if neither the volume, mass, nor time limits have been reached, then the truck will travel to the unloading site, unload its content there, and then go back to the parking area. If, however, during the collection route the truck reaches its maximum capacity either by weight or volume, then it will also go to unload its content, and then the algorithm in the model evaluates whether there is still enough time (the third limiting factor) to go back and continue the collection. If yes, the same truck is then assumed to return to the collection area and continue collecting—this iterative process is allowed to occur up to 3 times.

Table 3. Main operational data included in the model to calculate model key parameters.

Input Data	Default Parameters and Intermediate Calculations
W_T: total amount of waste collected (kg)	β_j: consumption truck correction factor (-)
dens: waste density (kg/m^3)	P_l: maximum payload capacity of the truck (kg$_{load}$)
Freq: collection frequency (year-1)	A_j: diesel consumption of the empty truck, depending on the type of road (kg$_{diesel}$/km)
C: number of containers (-)	B_j: diesel consumption of the full truck, depending on the type of road (kg$_{diesel}$l/km)
V_c: average volume per container (m^3/C)	F_{comp}: diesel consumption factor while the truck is lifting containers and compacting waste (kg$_{diesel}$/h)
V_t: volume capacity of the truck (m^3/truck)	W_{box}: weight of the box truck (kg)
D_1: distance between the parking lot and the collection route [(a)] (km)	$Fill_c$: average container fill ratio (%)
D_3: distance from the collection area [(a)] to the unloading site (km)	cr_t: compaction ratio of the truck (-)
D_c: distance in between individual containers (km/C)	*ef*: collection efficiency in number of containers collected per hour (C/h)
D_4: distance between the unloading site and the parking lot (km)	S_{col}: average speed while collecting (km/h)
T_T: duration of the working day (h)	S_{transp}: average speed while transporting (km/h)
Output Data	T_{comp}: time spent loading and compacting waste (h)
α_j: share of km traveled in each type of road (-)	T_{unload}: time spent unloading waste (h)
U_r: utilization (fill) ratio of the truck by mass (-)	T_{luch}: time for lunch break (h)
D_T: distance of one full trip of the waste collection truck (km)	T_{transp}: total time spent while transporting (h)
	T_{col}: time spent collecting (h)
	D_2: total distance spent while collecting waste (effective collection distance) (km)
	N: number of trips per truck (-)

(a) This distance is modeled as the weighted mean distance to the different collection points within the collection area.

If adopting the same basic model as for a conventional truck, the utilization ratio may be calculated as:

$$U_r = W_T/(N \times P_l) \tag{12}$$

where W_T is the total waste mass collected per year and N is the number of trips per year.

A variable utilization ratio of the collection truck could instead be calculated as described in Equation (13):

$$\begin{gathered} U'_r = \left(\frac{WT}{N(P_l - W_{box})} \times \frac{(D_1 + D_4 + (N-1)D_3)}{D_T} \times r_1\right) \\ + \left(\frac{WT}{N(P_l - W_{box})} \times \frac{ND_3}{D_T} \times r_2\right) + \left(\frac{WT}{N(P_l - W_{box})} \times \frac{D_2}{D_T} \times r_3\right) \end{gathered} \tag{13}$$

where D_T is the distance of one complete trip (km); N is the number of trips (-); r_1 is the effective load while the truck travels empty (-); r_2 is the effective load while the truck travels full (-); and r_3 is the effective load while the truck is collecting waste (-).

Taking into account the values for the effective load of the truck in each individual leg of the route (r_1 = 0, r_2 = 1 and r_3 = 0.5), Equation (13) may be simplified as described in Equation (14).

$$U'_r = \left(\frac{WT}{N(P_l - W_{box})}\right) \times \left(\frac{ND_3}{D_T} + \frac{D_2}{2D_T}\right) \tag{14}$$

However, based on the experimental fuel consumption values obtained for a number of collection routes in the north of Spain (Galicia), it was found that in virtually all cases, the resulting βj factor for a truck of 20–26 t of maximum authorized weight and 17.3 of payload capacity (in relation to the corresponding collection truck) was invariably around 2. It was therefore decided to refrain from implementing this additional level of complexity in the model, and instead settle for using the simpler Equation (12) for the calculation of Ur, and then applying a fixed parameter βj = 2 throughout.

The additional fuel consumption to lift the containers and compress the waste (*Add_diesel*) was modeled assuming that the truck uses the same amount of fuel per hour as when traveling on urban roads, since it was impossible to obtain the additional fuel consumption due to these operations from experimental sources:

$$Add\_diesel = C \times * T_{comp} \times F_{comp} \quad (15)$$

where C is the number of containers (or collection stops) (-); T_{comp} is the average time spent in emptying one container and compacting the waste contained therein (or the correspondent amount spent at a collection stop) (h), which depends on the type of container used; and F_{comp} is the diesel consumption factor while the truck is lifting containers and compacting waste (kg(diesel)/h), which was set by adopting the average fuel consumption of conventional trucks when traveling on urban roads at a speed used of 27 km/h.

Finally, the total fuel consumption of a waste collection vehicle ($Diesel_{TCT}$) (kg(diesel)) results from Equation (16):

$$Diesel_{TCT} = \left(\sum_{j=1}^{2} \beta_j \times Diesel_{cf} \right) \times W_T \times D_T + Add\_diesel \quad (16)$$

where WT is the total amount of waste collected (kg) and DT refers to one complete trip of the waste collection truck (km).

In the same way, the formulae to calculate the emissions of substances associated to diesel consumption were corrected using adapted β_j factors and additional emission amounts.

4. Results

This section is divided into three main parts. Firstly, the performance of the existing methods (ORWARE, MSW-DST, and Ecoinvent) in predicting the performance of the collection trucks in terms of fuel (diesel) consumption in comparison to the experimental data from the known collection routes in Portugal (see Table 4) is presented. Secondly, the performance of the FENIX model in comparison to the aforementioned methods as well as experimental data are shown. Finally, the FENIX model's ability to accurately estimate the environmental performance of the collection phase when selected changes are made to the operational parameters is discussed.

Table 4. Average experimental data of different curb-side collection routes in Portugal.

Waste Fraction Collected	Route Code	Amount Collected (t/year)	Annual Distance (km/year)	Annual Diesel Consumption (L/year)	Performance Indicators	
					L/100 km	L/t
Glass	G1	189	5996	1716	28.6	9.1
	G2	124	2637	755	28.6	6.1
MSW	MSW1	2039	22,919	24,935	108.8	12.2
	MSW2	3015	47,265	30,216	63.9	10.0
	MSW3	1990	35,078	23,475	66.9	11.8
Light Packaging Waste	LP1	76	3877	1956	50.4	25.6
	LP2 [(a)]	139	2990	1765	59.1	12.7
	LP3	165	5347	4390	82.1	26.6
	LP4	92	2147	2335	108.8	25.3
Paper and Cardboard	P1	144	2773	1606	57.9	11.2
	P2 [(a)]	248	2584	1525	59.1	6.2
	P3	293	6747	5540	82.1	18.9
	P4	201	2651	2884	108.8	14.4
	P5	332	5788	3873	66.9	11.7

(a) Correspond to the more commercial routes, which are more efficient in environmental performance (L/t).

4.1. Comparison of Experimental Data to Results of Existing Models

Average experimental data from the 14 curb-side collection routes in Portugal are presented in Table 3. The experimental data on total fuel consumption were then compared with the results obtained by multiplying the default consumption rates assumed by ORWARE, MSW-DST, and Ecoinvent by the experimental data gathered in terms of total amount of waste (t), transport and effective collection distances (km), number of containers (-) and idling time while stopped to lift up the containers (h). Results of this comparison are shown in Figure 3. Vertical axes are expressed in a base-2 logarithmic scale.

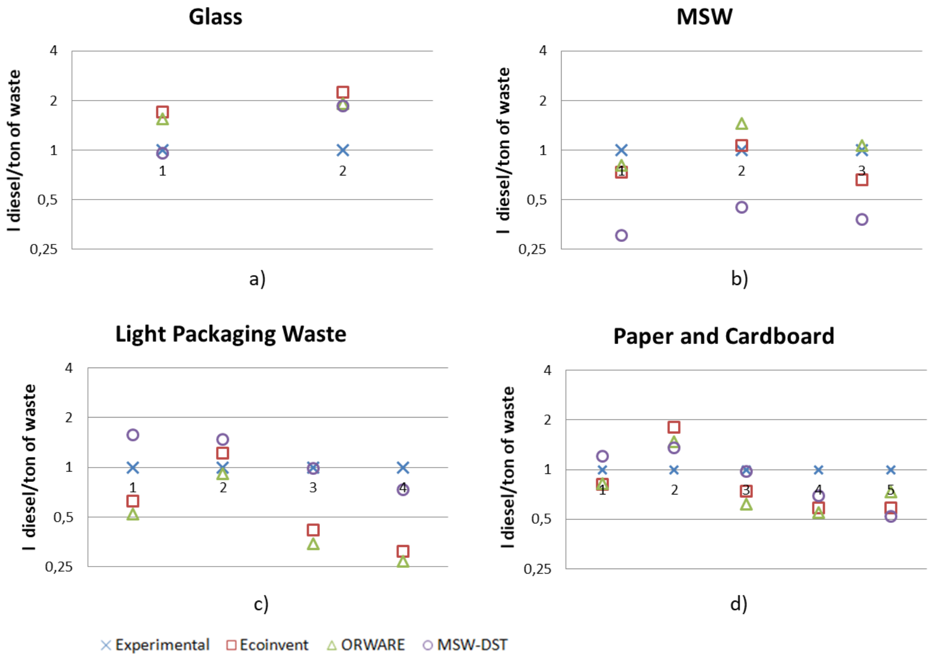

Figure 3. Comparison of the results of experimental data with the results using Ecoinvent, ORWARE, and MSW-DST model for (**a**) glass; (**b**) mixed waste; (**c**) light packaging waste; and (**d**) paper and cardboard.

An analysis of the results reveals that, overall, none of the total fuel consumption figures produced by these models match the experimental data. Only in those cases in which the characteristics of the experimental routes happened to coincide somehow with those of the calibration routes on which the average fuel consumption rates used in the models are based, were the results any better. In other cases, for instance for light packaging waste, the model estimates were found to be low by a factor of 4, when using Ecoinvent and ORWARE. In general, it was confirmed that if the objective of an LCA is to predict the potential impacts of a specific waste collection option, or to compare and choose among different alternatives, the use of models based on fixed 'average' fuel consumption factors may lead to rather inaccurate results.

4.2. Comparison of FENIX Model Results to Those Produced by Previous Models and to Experimental Data

The results produced by the FENIX model were also checked against the experimental data from the 14 curb-side collection routes in Portugal, for which all required input data included in Table 4 were gathered. The results of this comparison are shown in Table 5. This revealed that, on average, the FENIX model produces much more balanced and accurate results than all other models, and for all waste routes. This is quantitatively proven by the sum of the squared deviations of the results of each individual model vs. the experimental data.

Table 5. Comparison of FENIX results with experimental and existing models.

Waste Fraction Collected	Route Code	Experimental(L/t)	Relative Deviation from Experimental Data			
			FENIX	ORWARE	MSW-DST	Ecoinvent
Glass	G1	9.1	−0.34	0.54	−0.04	0.70
	G2	6.1	0.20	0.92	0.85	1.25
MSW	MSW1	12.2	0.44	−0.19	−0.69	−0.26
	MSW2	10.0	−0.11	0.46	−0.55	0.07
	MSW3	11.8	0.63	0.06	−0.62	−0.34
Light Packaging Waste	LP1	25.6	−0.11	−0.48	0.57	−0.38
	LP2	12.7	−0.13	−0.09	0.48	0.22
	LP3	26.6	−0.25	−0.66	−0.01	−0.58
	LP4	25.3	0.26	−0.73	−0.27	−0.69
Paper and Cardboard	P1	11.2	−0.01	−0.17	0.20	−0.19
	P2	6.2	0.12	0.48	0.36	0.80
	P3	18.9	−0.11	−0.38	−0.02	−0.26
	P4	14.4	0.19	−0.45	−0.31	−0.42
	P5	11.7	0.65	−0.27	−0.48	−0.41
Sum of the squared deviations			1.41	3.27	3.01	4.35

4.3. Sensitivity to Model Parameters

The main reason for developing the FENIX model was the identified need for a model which would be able to predict changes in the environmental performance of the waste collecting phase before changes in operational parameters are applied in real life, in order to help decision makers to make environmentally and economically sound choices.

Table 6 presents some illustrative examples in which the potential effects of the variation of some of these operational parameters are assessed. Specifically, the following aspects were analyzed: the total number of containers (scenarios 1–2), the collection frequency (3–4), the length of the working day (5–6), and, finally, the collection in more rural areas (7–8). The latter was parameterized by increasing the distances between the parking area and the collection area, between the collection area and the unloading point, and from the unloading point back to the parking area, as well as increasing the distance between the individual collection sites within the collection area (a distance along which no effective waste collection is carried out).

As it can be seen, by reducing the number of containers in scenario 1 from 449 to 269 (the latter being the minimum number of containers calculated by the model as necessary for this particular route), or by increasing the number of containers by 10% (scenario 2), the performance of the collection phase (L/t was respectively improved by ~25% or worsened by ~17%. Increasing the collection frequency by 25% (scenario 3), or doubling it (scenario 4), produced a worsening in the performance by ~41% and ~120%, respectively. Changes in the duration of the working day (the new limiting factor included in this model) also had a large effect on the results. Reducing the available time by 2 h (scenario 5) or by one half (scenario 6) led to a worsening in the performance by ~32% and ~46%, respectively. Finally, collecting the same amount of waste with the same operational parameters but in more rural areas, exemplified by doubling the distances in the collection route and also considering 25 (scenario 7) or 50 (scenario 8) additional km traveled to reach the collection site, produced a worsening of the performance by ~68% and ~87% respectively.

Table 6. Effects of selected operational parameters of the route on the waste collection performance.

	INPUT DATA										CALCULATED DATA					
	Waste (t)	**Working Day (h)**	**Yearly Freq.**	**N. Cont**	**Container Volume (m^3)**	**Truck Volume (m^3)**	**Dist Parking-Fist Cont**	**Dist End Coll-Unloading**	**Dist Unloading Point -Parking**	**Dist between Collection Areas**	**Performance (n.cont/h)**	**(kg diesel/(t.km))**	**Annual km Traveled**	**km/trip**	**l/year**	**l/t**
Baseline	92.2	8	55	449	0.25	22	1.7	10.2	10.7	0	41.2	0.86	3462	31	2928.48	31.76
1	92.2	8	55	**269**	0.25	22	1.7	10.2	10.7	0	41.2	0.49	2184	40	2171.13	23.55
2	92.2	8	55	**494**	0.25	22	1.7	10.2	10.7	0	41.2	1.00	3462	31	3419.55	37.09
3	92.2	8	**70**	449	0.25	22	1.7	10.2	10.7	0	41.2	1.20	4406	31	4123.59	44.72
4	92.2	8	**110**	449	0.25	22	1.7	10.2	10.7	0	41.2	1.88	6923	31	6435.03	69.79
5	92.2	**6**	55	449	0.25	22	1.7	10.2	10.7	0	41.2	1.20	4739	29	3853.33	41.79
6	92.2	**4**	55	449	0.25	22	1.7	10.2	10.7	0	41.2	1.44	6016	27	4280.64	46.43
7	92.2	8	55	449	0.25	22	**3.4**	**20.4**	**21.4**	**25**	39.3	0.67	7257	66	4915.81	53.32
8	92.2	8	55	449	0.25	22	**3.4**	**20.4**	**21.4**	**50**	37.5	0.64	8602	78	5469.50	59.32

Note: Changes with respect to the baseline scenario are marked in **bold**.

5. Discussion

When performing LCAs of waste management systems, the environmental benefits of recycling must often be balanced against the additional environmental impacts arising from increased transportation [74]. As has been demonstrated by experimental results, using fixed consumption factors may lead to some serious shortcomings in calculating the environmental impact of the collection phase, especially when the characteristics of the real collection routes do not coincide with those that were used to derive the default consumption factors. In particular, the effects of changes in operational parameters of the waste collection route on the fuel consumption rates have been discussed in the previous section and shown in Table 6. However, the effect of time (in terms of the overall duration of the waste collection trip) merits special attention and additional discussion.

In the guidelines for conducing LCA of waste management systems developed in the last decades [65,75], time is not given any consideration, and only the overall volume and weight of the waste are mentioned as limiting factors to be considered for the calculation of the environmental impacts of the collection and transport of waste. In addition, other studies evaluating the significance of the collection and transport phases in LCAs of integrated waste management systems indicate that "time is not relevant for assessing the environmental loads of waste collection" [57,76]. However, this assertion appears to be questionable based on the results illustrated in Table 6, where changes in the duration of the waste collection journey were found to have an important effect on the results. In fact, once the maximum allotted time for the collection of waste is reached, it no longer matters whether there is any capacity available left in the truck, since the truck will still return to the parking area and another truck will resume the collection on the following day from where it was interrupted. In so doing, the total cumulative distance traveled to collect the same overall amount of waste will increase, thereby negatively affecting the average collection performance in terms of L(diesel)/t(waste collected). The time factor may not have a significant influence in urban areas, but it does have a larger influence in more rural areas, where long distances are driven so waste collection is less efficient to begin with.

This is particularly relevant for countries like Spain and Portugal, where the performance of the waste collection phase is often far from optimal. In these countries a large percentage of municipalities under the obligation of implementing source-separated collection systems have less than 5000 inhabitants. Moreover, collection frequencies are much higher than in other countries. Whereas in Denmark, for instance, collection for paper and glass waste is carried out once or twice per month [76], in Spain the collection frequency is typically once per week and in Portugal twice per month. In the case of MSW, the situation is even more extreme. In Denmark, MSW is collected from 2 to 4 times per month, whereas in Spain and Portugal, MSW is typically collected every 1 to 3 days. This situation leads to higher fuel consumption rates, in terms of liters of diesel per ton of collected waste, than in other countries. The higher intensity in collection frequency may be due to specific climate conditions with result in a more rapid decomposition of organic waste (especially in the summer), which causes undesirable odors and inconvenience to citizens, but may also be partly due to perceived citizen demand.

6. Conclusions

As discussed in the previous sections, it is safe to conclude that the fixed consumption rates included in some LCA tools or databases for waste management to calculate the environmental performance of the waste collection phase are to be used warily. If the aim of the study at hand is to evaluate the environmental performance of the currently implemented waste collection system, real fuel consumption data should be used instead, while adjusting the characteristics of the route on which the average parameters are based to match the characteristics of the real-world system under analysis. Conversely, for some applications, especially if the focus of the study is the optimization of the collection phase itself, and where predictive results are needed before implementing changes in the system, it is arguably necessary to use a more complex model (such as the FENIX model presented here), duly taking into account many more characteristics of the collection scheme and the associated operational parameters in the model itself, in which consumption and emission factors depend on the characteristics of the route and are not fixed. Specifically, one parameter which has been identified as particularly relevant in the development of the FENIX model, but which had hitherto been neglected in most previously available models, is the duration of the working day. The recommendation is thus made to pay special attention to this parameter in all future LCA modeling of waste collection.

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