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Article (Accepted version) (Refereed)

Original citation:
Ferreira, S., Cabral, M., De Jaeger, Simon, da Cruz, Nuno F., Simões, P. and Marques, R. C. (2015) *Life cycle assessment and valuation of the packaging waste recycling system in Belgium.* Journal of Material Cycles and Waste Management, online. pp. 1-11. ISSN 1438-4957

DOI: 10.1007/s10163-015-0383-x

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Abstract

This study analyses the packaging waste management system in Belgium. Waste management operations involve a significant number of processes associated with energy consumption and emission of pollutants to air and water. In order to assess the impact to the environment of the several waste management operations, a Life Cycle Assessment was developed. The operations of selective and refuse collection, sorting, recycling and incineration of packaging waste were considered. A comparison between two scenarios was developed. The first scenario comprised the packaging waste management system in operation in 2010. This system comprises the waste management operations that envisage the recycling of the packaging materials. The second scenario was developed based on the hypothesis that there was no recycling system and all packaging waste would be collected in the refuse collection system. An environmental valuation was performed to convert the environmental results into a common unit (EUR). In order to accomplish this valuation, three methods were used: Ecocost, Ecovalue and Stepwise. These methods were developed in Europe and follow different methodologies. The environmental results were compared using the three methods and they were consistent with the conclusion that the recycling scenario (i.e. the 2010 situation) is more environmentally sound.

Keywords: LCA; packaging waste; recycling; waste management; incineration; valuation

1. Introduction

Life Cycle Assessment (LCA) is a methodology used to assess the environmental outputs of activities. It is a tool used to assess all environmental exchanges (resources, energy, emissions, waste) occurring during all stages of the activities' life cycle. The steps for performing a proper LCA have been described and standardised in the recent

ISO 14040 standards. LCA can be used for comparisons of alternative options and can be integrated to a general decision-making process covering the environmental implications of a decision. It is also commonly used to quantify the environmental impacts of different waste management options. The studies can focus on single sections of the waste management (e.g. collection schemes) or compare different treatment options.

Some of the few studies that analyse the whole management systems have concluded that reducing landfilling in favour of increasing energy and material recovery leads to lower environmental impacts and resource savings [1-4]. Some LCA studies focus on a specific waste fraction. For instance Rigamonti et al. [1] conducted an environmental analysis on the recyclable materials from municipal solid waste (MSW) including the organic fraction. Massarutto et al. [5], on the other hand, used Life Cycle Costing (LCC) on a number of fractions of MSW. In this paper, the focus is on packaging waste. Wada et al. [6] used LCA and LCC to compare types of waste incineration systems.

The LCA of waste management systems is not a simple task since it involves a considerable amount of variables and extensive information. However, some international databases (e.g. Ecoinvent) have been developed to provide data about the emissions and energy consumption of several waste management operations. This study intends to perform a LCA to the Belgian packaging waste management system in 2010.

2. Case study

In Belgium, the MSW management is, to a large extent, carried out by 36 inter-municipal associations (called *intercommunales*): 28 inter-municipalities in Flanders, seven in Wallonia and only one operator in Brussels-Capital [7]. MSW services encompass several operations such as refuse and selective collection, sorting, composting and incineration. In Belgium, the direct landfilling of several flows was banned. For instance both the Flemish as the Walloon region imposed a landfill ban on unsorted municipal waste and waste collected separately for recycling or recovery purposes (due to the absence of landfills, the legislation in the Brussels Capital region is less specific on this topic).. This constraint, along with the high gate fees, led to the closure of many landfill sites. In fact, the rate of landfilled municipal waste in Belgium is with its 8 kg per capita in 2010 among the lowest in the EU [8]. Table 1 presents the existing infrastructures for treating the MSW in the three Belgian regions in 2010. Regarding municipal packaging waste, this flow is selectively collected by two main systems:

- Kerbside collection for paper/cardboard, PMD (plastic bottles and flasks, metallic packaging and drinks cartons) and, depending on the agreement with the Belgian green dot company, also glass;
- Collection of glass via bottle banks (differentiating coloured and clear glass).

[Insert Table 1]

Selectively collected paper/cardboard and glass waste are sent directly to recycling. The PMD flow must be sorted by material at sorting facilities before it can be sent for recycling. The quantities of packaging waste rejected in the sorting process are incinerated with energy recovery [12]. The quantities of packaging waste selectively collected are shown in Table 2.

[Insert Table 2]

In practice, the 36 *intercommunales* organize selective collection and sorting of household packaging waste in their territory. However Fost Plus, the Belgian Green Dot company, manages the household packaging waste flow by firming contracts with the *intercommunales*. In the financial perspective, Fost Plus reimburses the costs incurred by the *intercommunales* (for a standard level of service) with selective collection and sorting of packaging waste and pays additional fees for extra collection of glass waste, for metal packaging waste recovered in the incineration facilities, etc. In addition to the financial costs and benefits, municipal packaging waste management operations will also have environmental costs and benefits. For instance, waste collection and sorting activities comprise environmental costs mainly related to the consumption of diesel and electricity. In recycling and incineration (with energy recovery) activities, the environmental costs could be compensated by the benefits of saving raw materials and energy.

3. Methodology

3.1 Life cycle assessment

The LCA methodology was used for the evaluation of the environmental impacts associated with the packaging waste collection, sorting and recycling. This methodology was developed using the SimaPro software (version 7.3.3), according to the ISO 14040:2006 requirements [13]. The data used was collected from the Belgian national and regional environmental and waste authorities Fost Plus, Ovam, VMM, the independent research organisation VITO and directly from the operators.

3.2. Goal definition

The main goal of this assessment is to quantify the positive and negative environmental impacts of the several packaging waste management operations (including the recycling activity conducted by private processors). The expansion of the system boundaries technique was adopted [4]. With this approach, the environmental impacts resulting from the waste management operations are compared with the savings in terms of energy and raw materials consumption avoided with the recycling process.

According to [14] the system model for a waste LCA can be described as two sub-systems: (1) foreground system (that includes the waste management activities from collection to recycling/disposal) and (2) background system (systems that interact with the foreground system supplying energy and materials, including the avoided energy and primary material's production in the recycling process). The background data was taken from the Ecoinvent and BUWAL database while the foreground data was collected from the waste management operators. The assumptions made include the following aspects:

- The secondary materials produced through the recycling of packaging waste replace the corresponding primary materials (i.e. those produced from virgin raw materials). The savings in energy, raw materials and emissions released from the avoided production were considered in the recycling process;
- The electricity produced from waste incineration is supposed to substitute the same amount of electricity produced in Belgium (considering the different energy sources). This energy corresponds to the real energy mix production in 2010 (average approach) since we were able to gather the exact data. The Belgian energy mix in 2010 was composed by nuclear (45%), natural gas (29%), biomass (3,4%), coal (2,8%), other fossil fuels (5,1%), other renewable sources (3,2%) and imported (12%).

Taking into account the goal of the study (i.e. to analyse the impacts of packaging waste management operations in 2010) an attributional approach was used. For 2010 the information used related to the emissions released and the energy and materials consumption avoided with the recycling processes and energy production from the incineration.

3.3. Functional unit and reference flow and system boundary

In this analysis, the functional unit is the total amount of packaging waste selectively collected (and non-packaging paper)[1] in Belgium in 2010 corresponding to 1.237.362 tonnes. According to the ISO [13], the system boundary defines the unit processes to be included in the system. The waste management operations performed by the waste operators were defined as unit processes in the LCA. The unit processes included in our system are indicated in Figure 1.

[Insert Figure 1]

[1] Printed paper is collected together with packaging paper.

Considering the objectives of the study and also due to the lack of information available, the following processes were excluded from the analysis:

- The cleaning of packaging waste by the householders.
- Packaging waste materials transport from its local production (mainly households) to its delivery in the respective containers;
- Manufacturing and maintenance of drop-off containers;
- Composting process.

3.4. Life cycle inventory analysis

The data required for modelling the unit processes included in the system boundary was gathered through questionnaires sent to the operators in charge of collection, sorting and incineration. Regarding the recycling of packaging waste materials, data from the literature was used. All the assumptions made, in order to fill the missing information required, were taken based on the relevant literature. In the absence of information, some processes included in the software databases were also used with the appropriate adjustments to the case study. The various unit processes are described below.

Waste collection

The selective collection of the several packaging waste materials, refuse waste collection and the transport of the sorted waste to the recyclers was considered in the analysis. The transport entails several environmental impacts, mainly related to air pollution. However, the construction, maintenance and material disposal of vehicles also comprise emissions and energy and raw materials consumption that were considered in the Life Cycle Inventory (LCI). The LCI from these activities were calculated from the Ecoinvent database.

The emissions concerning the operation of the vehicles are mainly from fuel combustion and tire abrasion. The Tier 1 methodology from [15] uses fuel as the activity indicator, in combination with average fuel-specific emission factors (EF). This approach for exhaust emissions uses the following general equation:

$$E_i = \sum_j \left(\sum_m \left(FC_{j,m} \times EF_{i,j,m} \right) \right) \tag{1}$$

Where, the E_i is the emission of pollutant *i* (g), $FC_{j,m}$ is the fuel consumption of the category *j* vehicle using fuel *m* (kg), $EF_{i,j,m}$ is the fuel consumption-specific emission factor of pollutant *i* for vehicle category *j* and fuel *m* (g kg-1). Carbon dioxide (CO_2) and sulphur dioxide (SO_2) emissions are directly derived from the fuel consumption and carbon content or sulphur content of the fuel used. To determine the CO_2 emissions an EF of 3,14 g CO_2 kg-1 fuel [15] was adopted. To calculate the SO_2 emissions, it is necessary to take into account the sulphur present in the fuel used. Hence, the EF for SO_2 is 100 mg kg-1 fuel (diesel). Methane emissions (mg/km) were calculated from emission factors provided in [15]. The emission factors ($EF_{i,j,m}$) provided by [15] for HDV diesel vehicles were used. To calculate the emissions of lead and mercury we used the emission factors provided in [16]. Other exhaust emissions included nitrous oxide (N_2O), ammonia NH_3 and polycyclic aromatic carbons (PAH). To estimate PAH we used the EF provided in [17]. For heavy duty vehicles the emission factor is 1,0E-06 g (vkm)-1 but it may range between 0,02E-06 to 6,2E-06 g (vkm)-1 [18]. The emission factors for non-exhaust abrasion particle emissions and the emissions from vehicle manufacturing, maintenance and disposal, are calculated through the Ecoinvent (2007) database. The emissions relative to vehicle manufacturing, maintenance and disposal concern one vehicle unit. To calculate the emissions regarding the functional unit, we considered a kilometric performance of each vehicle of 5,40E+05 Km [18]. The waste collection diesel consumption is indicated in Table 3.

[Insert Table 3]

The composition of the PMD flow is represented in Figure 2.

[Insert Figure 2]

Sorting facilities

This unit process is the (further) separation of the selectively collected packaging waste by material in a sorting station. In Belgium, only the PMD (plastic, metal and drink packaging) flow is effectively sent for sorting. The paper/cardboard and glass packaging waste is sent directly to recyclers. The sorting process of PMD was modelled in SimaPro, considering the rejected material and all main consumptions related to the operation, as shown in Table 4.

[Insert Table 4]

The rejected material is usually sent for incineration. This process is described later and is included in the sorting process.

Incineration facilities

Incineration is defined as the combustion of MSW in controlled facilities. The reference flow was one tonne of different packaging waste materials incinerated. The data used was collected from the several incineration facilities and OVAM (Public Waste Agency of Flanders). Since incineration is a multi-input-output allocation process where several inputs (different packaging waste fractions) and outputs (energy recovery, ash, slag and scrap generation and emissions) coexist, the allocation method was adopted. According Margallo et al. [20], different types of allocation must be applied to calculate the impacts for each packaging waste material, depending on the parameter considered, as it is shown in Table 5.

[Insert Table 5]

Mass allocation was applied when there is no relation between the inputs and the waste composition. Regarding the emissions of specific pollutants such as nitrogen compounds, they depend on the technology rather than on waste composition, so the mass allocation was also applied.

The CO_2 emissions were calculated based on an estimate of the fossil carbon content in the waste incinerated multiplied by the oxidation factor and converting the product (amount of fossil carbon oxidised) to CO_2, according to the Intergovernmental Panel on Climate Change [21].

Since the incineration of waste is carried out for energy production, both fossil and biogenic (combustion of biomass materials) emissions were calculated. The contribution of each material for energy production during the process was determined based on the heating value of each material and the total energy produced by the MSW combusted in 2010, according to the following equation (the heating value allocation as it was described before, [22]):

$$E_{fractionj} = \frac{Etheo_{fractionj} \times E_{MSW}}{Etheo_{MSW}} \tag{2}$$

where:

$E_{fractionj}$ is the energy produced by component *j*, (in MWh);
$Etheo_{fractionj}$ is the theoretical energy produced by component *j* (calculated based on the heating value of component *j*), in MWh;
$Etheo_{MSW}$ is the theoretical energy produced by the MSW (calculated through the sum of theoretical energy produced by each component *j*), in MWh;

E_{MSW} is the total energy actually produced by the combustion of MSW in 2010. The waste characteristics, assumed from the literature, are indicated in Table 6.

[Insert Table 6]

An average incineration process for each packaging waste material was modelled in SimaPro, using the Ecoinvent 2.2 database and changing the values collected from the Belgian operators (through questionnaires).

It was considered that the reject from the sorting and recycling operations was also treated in incineration facilities.

Recycling facilities

After the sorting and incineration processes, the several packaging waste materials are transported to recyclers. The transport to recyclers was considered and analysed based on the distance travelled and quantities transported. The packaging materials recycling allows for replacing (partially or totally) the primary raw materials in the manufacture of new packaging or other products. Hence, in the recycling processes, the avoided materials production was considered, assuming a substitution ratio of 1:1. The paper/cardboard packaging waste was the exception with a substitution ratio of 1:0,83, because the paper fibres degrade in the recycling process, so they cannot be reused indefinitely [1]. The plastics recycling process consists, in general, in a mechanical recycling process, in which the waste plastic is shredded and extruded to form recycled granulate to be used in new plastic products. The glass (cullet) is transported to the glass industry and it is used in the kilns together with raw materials. The metals, separated into ferrous (steel) and non-ferrous (aluminium), are smelted in the respective industries. The LCI of the primary production and recycling of materials was obtained from Ecoinvent 2.2 (2007) database and the relevant literature [1, 25]. The reference flow was one tonne of different packaging waste materials transported and recycled. We considered the savings in the production of a new material but also the energy and resources consumption in the recycling process [26]. Table 7 presents the unit processes analysed and the recycling efficiencies assumed.

[Insert Table 7]

Energy

Several of the unit processes previously described present a common input: the consumption of electricity. Regarding this input, we assumed the electricity mix production of Belgium using an existing process in the Ecoinvent 2.2 (2007) database and based on the relevant literature. The electricity sector in Belgium was characterized for the year 2010 with data from Spitzley and Najdawi [27] and Eurostat [28,29]. The electricity sector in Belgium was characterized for the year 2010, as shown in Table 8.

[Insert Table 8]

3.5. Environmental Valuation

During a LCA, the Life Cycle Impact Assessment (LCIA) is developed in two steps: "characterization" and "weighting". In the later the impact categories are expressed in the same unit using weighting systems. The objective of the valuation methods is to convert different impacts to a common unit in order to compare the impacts from different projects. In this study, we intend to convert the impacts achieved in the characterization step in EUR. Three monetary valuation methods were used: Eco-costs2012 [30, 31], Stepwise2006 [32] and Ecovalue08 [33] and the results were compared. The Eco-costs2012 and Stepwise2006 were developed for Europe while Ecovalue08 was developed for the case of Sweden. Since the reference year is 2010, the monetary values obtained were converted into EUR2010, assuming the European (EU27) inflation rates [34]. The eco-costs technique is based on the "marginal prevention costs", or in other words, the costs for repairing the environmental impacts to a sustainable level. The stepwise method converts all impacts in monetary units (EUR2003) or QALYs (Quality Adjusted Life Years),[32]). The monetary value of a QALY is based on the budget constraints, assuming that "the average annual income is the maximum that an average person can pay for an additional life year" [32]The Ecovalue08 method [27]uses a weighting database based on stated preference methods (in particular, contingent valuation).

In order to compare the results obtained by each method, only the impact categories shared by all the methods were analysed, namely: Climate change, Acidification, Human toxicity, Aquatic eutrophication and Photochemical Oxidant formation.

4. Results and discussion

Valuation of environmental impacts

The results of the LCIA of the packaging waste management operations were converted into monetary values (EUR) for three valuation methods. The operation “recycling” include the transport of the sorted materials to the recycling infrastructure. The results for the environmental valuation for of several packaging waste management operations achieved with the Ecovalue08 method are indicated in Table 9.

[Insert Table 9]

The impact categories analysed are expressed in EUR. In this analysis only the minimum values of the weights were considered. The negative values consist in avoided impacts meaning that they can be considered as a benefit for the environment. The positive values represent the environmental costs for each impact category considered. Recycling packaging waste avoids the release of emissions, energy and raw materials consumption. For this packaging waste operation all the results are negative. The energy production from the packaging waste incineration contributes for some environmental benefits, achieving some negative results for the impact category “Acidification”. The results for the environmental valuation for the several packaging waste management operations achieved with the Stepwise method are indicated in Table 10. Similarly to the Ecovalue08 method, the packaging waste recycling achieved negative results for all the impact categories. The incineration also achieved a negative result for the impact category “Acidification”.

[Insert Table 10]

The results for the environmental valuation for the several packaging waste management operations achieved with the EcoCosts2012 method are indicated in Table 11.

[Insert Table 11]

The values achieved with this method are higher than the previous ones. As it was mentioned before, the methods use different LCIA techniques and weighting systems that cause the differences in the results. However, they are consistent in the negative results achieved with recycling and in the negative results achieved for the impact category “Acidification”. Nevertheless, with this method the impact “Aquatic eutrophication” also achieves a negative result in the incineration process. Figure 3 indicates the benefits and the costs in EUR of the packaging waste recycling. The results are expressed for each waste management operation. The environmental benefits are related with the opportunity costs and recycling activities. The remaining waste management operations consume energy and release emissions, consequently the results are expressed as costs.

We considered as benefits the environmental results of recycling and also the opportunity costs of avoiding the incineration. If there was no recycling system implemented, the packaging waste would have to be incinerated with the refuse waste. In Belgium the contribution of the population in the recycling process has been crucial in the diversion of the packaging waste from the incineration facilities, contributing to lower environmental burdens. However, among the waste management operations involved in the recycling system there are energy consumption and emissions released that lead to some disamenities. The costs considered in the analysis were obtained from the LCIA results achieved for the operations of selective collection, sorting and the transport for the recyclers. For the three methods used we conclude that the benefits of the recycling system clearly outweigh the costs.

Scenarios

The scenarios analysed correspond to the “2010 scenario” and the “Incineration scenario”. The first scenario assumes the level of recycling observed in 2010. This scenario considered the environmental burdens associated with the packaging waste selectively collected and sent to the several material recycling processes. The operations involved were selective collection, sorting and recycling. The incineration of the packaging waste rejected from the previous processes was also considered.

[Insert Figure 3]

The second corresponds to a hypothetical scenario in which the same quantity of packaging waste collected in the previous scenario is sent directly to incineration. In Belgium the landfill of the (untreated) municipal waste is not allowed, meaning that the packaging waste is either selectively collected to be recycled or, if collected in the refuse collection system, incinerated. In the incineration scenario selective collection is not provided, but rather there is packaging waste collected in the refuse collection system. These scenario only comprises the refuse collection and the incineration processes. The two scenarios were compared and the results are shown in Figure 4. The results are compared based on the contribution of each scenario to each impact category (in percentage of the sum of both scenarios in absolute value).The results show that the “2010 scenario” encompasses lower environmental impacts comparing to the “Incineration scenario” for all the impact categories and all methods used.

[Insert Figure 4]

5 Conclusions

This study encompasses a LCIA of the waste management system of Belgium, in particular the recycling system of packaging waste material. Analysing the packaging waste management system in 2010, this study intends to evaluate the environmental sustainability of the recycling scheme, identifying the respective burdens and benefits. The packaging waste, after being discarded by the citizens, can be collected together with the refuse waste or by the selective collection system. With data collected from the packaging waste management operators an extensive LCI was obtained. The results from the LCA were obtained for all the packaging waste management operations: refuse collection, selective collection, sorting, recycling and incineration. With these results, a comparison between two scenarios was developed. The first scenario consisted of the waste management system in operation in 2010 ("2010 scenario"). The second scenario consisted of a hypothetical scenario where no selective collection, sorting or recycling was implemented ("incineration scenario"). The first scenario proved to be more environmentally favourable for all the impact categories and valuation methods analysed. Although the monetary values differ significantly according to the valuation method used, the results consistently suggest that the packaging waste recycling system brings an important contribution to the environment. Moreover, even if energy recovery from the incineration of packaging waste in the second scenario is taken into account, the energy savings are less beneficial compared to the savings resulting from the recycling of the packaging waste materials.

AKNOWLEDGEMENTS

This paper had the financial support of the European Investment Bank University Research Sponsorship (EIBURS) Program. The findings, interpretation and conclusions presented in this article are entirely those of the authors and should not be attributed in any manner to the EIB.

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Figure Legends

Fig. 1. System boundary

Fig.2. Composition of PMD flow in 2010 [19]

Fig. 3. Environmental benefits and costs of the Belgium packaging waste recycling system.

Fig. 4. Comparison of the environmental valuation results for the “2010 Scenario “and “Incineration” scenario.