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## LCA OF RECYCLING CHAINS: INFLUENCE OF TRANSPORT MODELLING

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**Abstract:** Transport is an inherent activity of recycling chains. In LCA studies of e-waste recycling, the transport during the end-of-life management is either not considered or the distances are estimated and are not in accordance with reality. When transport is comprised in LCA boundaries, depending to the type of product then material, there is no consensus of its influence on the results. Some authors stressed that logistic chain accounts for a significant amount of impacts, but there are studies that concluded that the impacts are negligible in comparison to treatment activities. In this context, the goal of the study was to identify the contribution of transport (varying both distance and loading rate) in LCA results of e-waste recycling. A tablet treated in France was used as a case study. Life cycle inventory is based on the inventories available in Ecoinvent database and adapted with literature and primary data. In order to assess, spatialize and quantify the distances between the different stakeholders of the recycling chain, transport inventory was performed with a geographic information system (GIS) and LCA coupling approach. Impact assessment results were calculated at midpoint level with several impact categories. Depending on the impact category, transport contributes between 10 to 30% of the total impacts related to end-of-life treatment. This result stresses the need for assessing more realist scenarios for e-waste treatment.

**Keywords:** Transport; Recycling chains; GIS-LCA coupling; End-of-life

### Introduction

Considered the waste stream growing the fastest, waste electrical and electronic equipment (WEEE), also known as e-waste, has become a global concern in terms of environmental improvement and resource recycling. E-waste contains toxic materials (such as mercury, lead, and brominated flame-retardants), which can cause environmental and health issues if not properly treated (RUCEVSKA et al., 2015). Conversely, it also contains high-value materials (such as gold, copper, nickel, indium and palladium), and formal recycling of e-waste, can result in positive environmental, resources and economic benefit (ZENG et al., 2017).

Aiming to assess the environmental impacts related to the life cycle of electrical and electronic equipment (EEE), in the past ten years, life cycle assessment (LCA) studies have been published mainly in Europe, North-America and Asia (ARDUIN et al., 2017). Many studies assess the whole life cycle of EEE: raw materials extraction, manufacturing, transport, use and end-of-life (EOL). Studies focusing on EOL of WEEE are relatively rare and they often focus on waste management as it is intended to happen. However, the reality is that recycling may not proceed exactly as intended in best practice (BAXTER et al., 2016).

In LCA studies of e-waste recycling, transport during the EOL is either not considered or the distances are estimated and not in accordance with reality (BARBA-GUTIÉRREZ; ADENSO-DIAZ; HOPP, 2008). When transport is comprised in LCA boundaries, there is no consensus of its influence on the results. According to Menikpura et al. (2014), the logistic chain accounts for a significant amount of greenhouse gas emissions in EOL of e-waste in Japan depending on the type of WEEE treated. Choi et al. (2006) also identified significant impacts for WEEE collection in the EOL of a computer in Korea, as well as Grimaud et al. for cables recycling in France (2016). Conversely, Baxter et al. (2016) concluded that whilst transport aspects are normally very significant in terms of cost, from the environmental impact standpoint its effects are relatively insignificant. Similar conclusions were addressed in a study of WEEE chain in Italy (BIGANZOLI et al., 2015).

Transport is an inherent activity of recycling chains. In France, transport sector is the main source of GHG emissions (27.8% of the total GHG) producing 136.4 Mt CO<sub>2</sub> eq in 2012 (FRANÇOIS et al., 2017). In this context, this study aimed to identify the contribution of transport in LCA results of e-waste recycling. A tablet treated in France was used as a case study. In order to assess, spatialize and quantify the distances between the different stakeholders of the recycling chain, transport inventory was performed with a geographic information system (GIS) and LCA coupling approach. Besides considering the real distances between e-waste channel actors, the study assessed the impact of loading rate of lorries.

## French WEEE end-of-life chain

Household WEEE collection and treatment in France is organized in six separate waste streams: large cooling appliances; large household appliances (except for cooling appliances); screens; other small appliances; lamps and photovoltaic panels. Before e-waste arrives at the treatment center, it is transported among different stakeholders of the end-of-life chain, as presented in Figure 1.

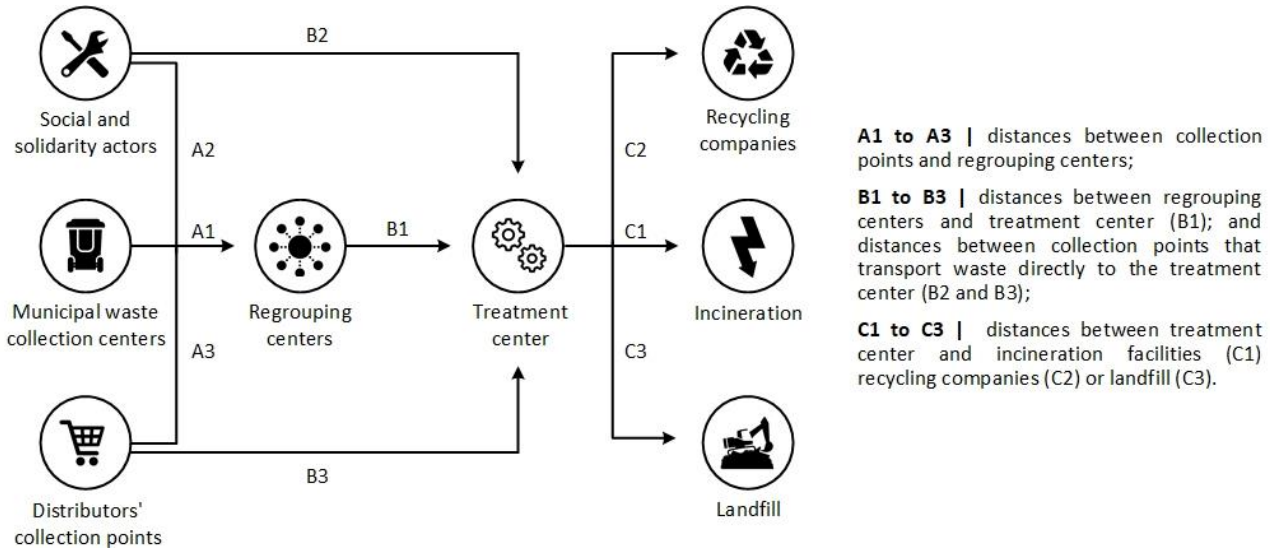


Figure 1 – WEEE recycling chain in France

French take-back schemes responsibility for waste treatment begins at the different collection points located across the country – these include distributors' collection points and municipal waste collection centers. Social and solidarity actors transfer to the recycling channel equipment and or its components that could not be repaired. (VADOUDI et al., 2015; ADEME, 2017). After collection, e-waste can be transported directly to a treatment center (distances B2 and B3), but most of the time it is transferred to a regrouping center (distance A1 to A3) where the e-waste from different sources is weighted and stored per waste streams.

Finally, the WEEE is transported to a treatment center where it undergoes different operational steps, according to the nature of the WEEE. The WEEE Directive requires the removal of polluting and hazardous materials (decontamination or depollution) before it can undergo any further form of treatment – for example liquid crystal displays (LCDs) and printed wiring boards with a surface area greater than 100 cm<sup>2</sup> must be removed (EUROPEAN PARLIAMENT, 2012). After depollution, the WEEE is dismantled (separation of the different components) in a manual or mechanical process. For some WEEE with components of high added value a manual dismantling is prioritized in order to reduce process losses (TESFAYE et al., 2017). The subsequent steps are shredding and sorting the different types of materials considering the technology available in the treatment center (ZHANG; XU, 2016). After sorting, the different fractions (ferrous, nonferrous, plastics, printed wiring boards, etc.) can be directly recovered or undergo other treatment steps (e.g. printed wiring boards sent to specialized recovery of precious metals) (YAMANE et al., 2011).

## Method

The goal of the study was to identify the contribution of transport in LCA results of collection and treatment of tablets in France. The reference flow is 1 ton of tablet. The composition of the tablet was determined based on manufacturer declaration (APPLE INC., 2011). After a first analysis of the French recycling channel, a conservative scenario that considers only the best-referenced recycling channels was selected. Table 1 presents the tablet components and the waste scenario considered for each component.

Life cycle inventory (LCI) was developed based on the inventories available in Ecoinvent database (version 3.2) and adapted with literature and primary data obtained in discussions with specialists and recyclers. Further information about the treatment modelling can be assessed in Arduin et al. (2017). The territory under study was modeled in Q-



GIS software. Data regarding roads' lengths and type and locations were obtained from ROUTE 120® database available in IGN website (Institute of Geographic and Forest Information). Primary data regarding the location of the EOL stakeholders was obtained with Ecologic (French take-bake scheme), and one treatment center was selected as a case study.

Table 1 – Tablet composition and EOL scenario

Components	Tablet mass (%)	WEEE treatment
LCD	41,5	Landfill
Aluminum alloy	22,9	Shredding, sorting and recycling
Battery Lithium-ion	22	Manual sorting and recycling
Printed Circuit Boards (PCB)	6,4	Manual sorting, recycling of precious metals and plastic incineration with energy recovery
Other metals	4,2	Shredding, sorting and recycling
Plastics	2,9	Shredding and treated with the sorting losses
Sorting and recycling losses	-	Landfill

Frequently the same lorry collects waste in different collection points before going back to the regrouping center. However, due to lack of data, it was not possible to take into account the logistics optimization. To minimize the errors of not taking these into account, distances from collection points to regrouping centers were calculated as the most direct path between two points (distances A). Distances between regrouping centers and treatment center, as well as distributor's collection points and social and solidary actors that transport waste directly to the treatment center were calculated based on highway network (distances B). Same assumption was considered to the distances between the treatment center, recycling companies and landfill (distances C). The percentage of e-waste collected from the different collection points in 2015, as well as the mass of different fractions after shredding and sorting were taken into account to calculate the weight transported per kilometer.

In Ecoinvent database, lorry processes describe the transport services with average load factors that include the average share of empty return trips. Considering the types of lorries used for transport in the WEEE chain, we selected "transport lorry 7.5-16 ton" (Ecoinvent average load = 3.29t) for distances A and C and "transport lorry 16-32 ton" (Ecoinvent average load = 5.79t) for distances B. The French lorry fleet in 2015 (Euro emission standard) was taken into account in the modeling (MINISTÈRE DE LA TRANSITION ECOLOGIQUE ET SOLIDAIRE, 2017). In order to assess the influence of loading factor, it was calculated the diesel consumption and emissions associated with fuel consumption for loading factor of 4.5t and 7.5 for the same types of lorries previously mentioned.

According to Rodrigues-Garcia and Weil (2016), the life cycle impact assessment (LCIA) methodologies more widely used in LCA of WEEE are CML 2001 and Eco-Indicator (95 or 99). Considering that these methods are superseded and that the European Commission released a methodology for LCIA in the European context, the LCIA results were calculated at midpoint level by using the ILCD 2011 adapted with the IPCC version 1.02, Pfister water scarcity method version 1.02 and USEtox version 2.02.

## Results and discussion

The locations of e-waste actors considered in the case study are presented in Figure 2. As mentioned previously, the case study presents one of the several treatment centers in France, and to treat less than 5% of the total amount of e-waste generated in 2015, more than 600 different stakeholders participated in the reverse logistics. For the treatment center selected in the case study, in 2015, 98% of the e-waste treated was collected in different collection point and regrouped in several regrouping centers. The distances between the different actors were calculated in QGIS software considering the assumptions previously described. The total mass transported per kilometer for each type of lorry is presented in Table 2.

As presented in Figure 3, the influence of transport in LCA results of e-waste recycling depends on the impact categories taken into account. The impact categories most relevant for transport are linked to air pollution (e.g. climate change, ozone depletion and photochemical ozone formation), acidification and terrestrial eutrophication. The transport impacts are mostly due to diesel emissions during transport, as well as related to its production. Avoided impacts with the tablet recycling were not taken into account in the study.

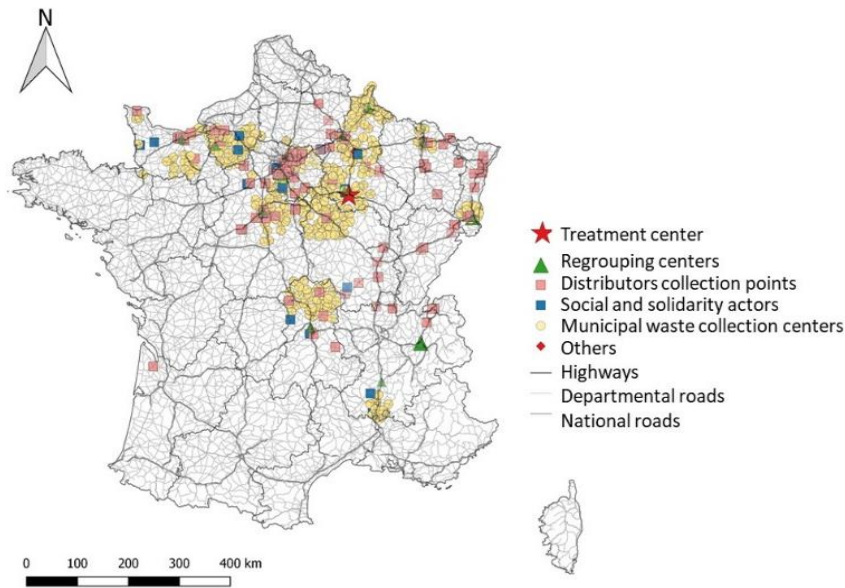


Figure 2 – Case study: location of WEEE chain actors

Table 2 – Transport activities considered in the case study

Type of lorry	Euro III	Euro IV	Euro V	Euro VI
Lorry 7.5-16 t	64.45 tkm	38.32 tkm	60.67 tkm	10.45 tkm
Lorry 16-32 t	70.06 tkm	41.65 tkm	66.27 tkm	11.36 tkm

Menikpura et al. (2014) and Baxter et al. (2016) focused in global warming impact category for assessing e-waste recycling environmental impacts. In Japan, the transport accounted for 7 to 27% of the GHG emissions depending on the type of e-waste recycled (washing machine, refrigerator, air conditioning or TV) (MENIKPURA et al., 2014). In Norway, transport accounted from 6 to 16% of total impact of e-waste treatment also depending on the type of e-waste (refrigerator, TV or mobile phone). In our case study, transport accounted for 14% of global warming potential. Regarding the total global warming potential of treating 1t on tablet in France (405 kg CO<sub>2</sub> equivalent), the result is in the range of the results for treating 1t of similar type of e-waste in Japan and Norway (from 350 to 600 kg CO<sub>2</sub> equivalent per ton of e-waste).

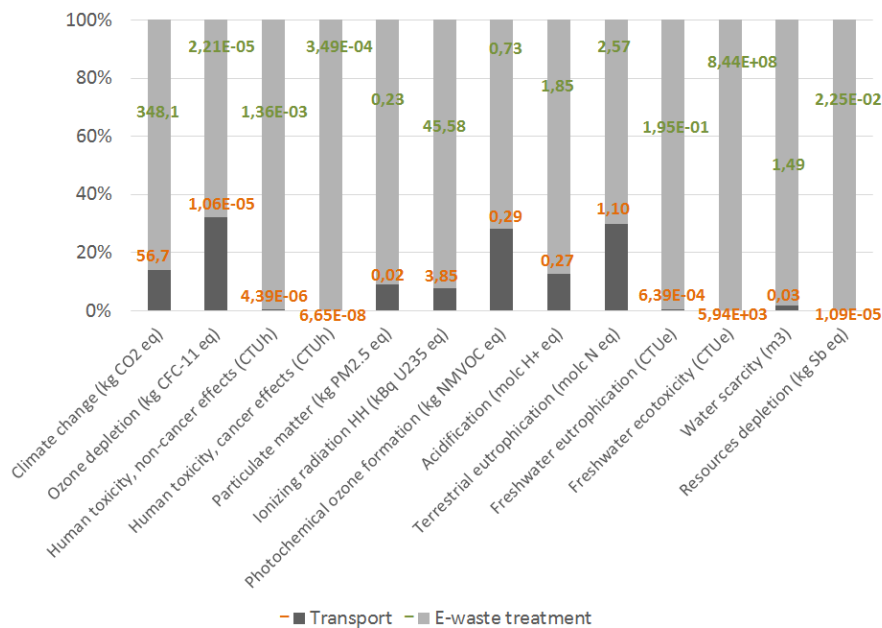


Figure 3 – Potential environmental impacts of treating 1t of tablet in France



Choi et al. (2006) assessed the impacts of computers recycling in Korea. According to the study, the increase of light oil consumption during the collection of waste-PCs, and the transportation of these PCs to recycling plants caused significant environmental burdens. Nonetheless, the contribution of the transport in terms of percentage of impacts per impact category was not presented. Biganzoli et al. (2015) assessed the environmental impacts of e-waste treatment in Italy with primary data from 2011. Diverse distances of e-waste collection were considered between different actors as well as types of transport (van or lorries). According to the authors, for all WEEE categories, the burdens of the waste collection and transport to the treatment plants resulted in negligible impacts compared to the burdens of the overall treatment process. It was not possible to verify the transport contribution because the results of the treatment processes are aggregated with the benefits associated with the avoided impacts.

Grimaud et al. (2016) assessed the environmental impacts of producing 1t of aluminum from cables shredding. The transport distance for cables collection considered in the study is significantly higher (540 km) than the average distance for e-waste collection considered in the tablet case study. The results of the study showed a very strong contribution of the transport for the collection of waste in the total impacts (from 15 to 70% depending on the impact category). Once the study is focused in cables recycling, it is difficult to correlate the results with the recycling of e-waste.

Impact of load factor was also studied based on diesel consumption and emissions related to the increase in gross vehicle weight. For most impact categories there was not a significant increase with the change in load factor (from 3.29t to 4.5t, and from 5.79t to 7.5t). For ozone depletion, it resulted in EOL total impact 3% higher. For all the other impact categories the differences were lower.

## Conclusions

Collection transport entails in low impacts in comparison to the other e-waste treatment activities as dismantling, shredding, sorting, materials recycling and disposal of non-recyclable fractions. Among others, treatment impacts (excluding transport) are related to energy consumption during e-waste treatment and emissions during smelting processes and landfill of non-recyclable fractions. Transport impacts are more relevant to certain impact categories (accounting up to 30% of the total impact) mainly due to diesel production and emissions during transport. The impact categories most relevant for transport are linked to air pollution, acidification and terrestrial eutrophication. The load factor does not change significantly the results since lorries' load factors are limited to the e-waste volume, and empty trips inherent to the process.

GIS is a tool to capture, manipulate, analyze, manage, and present spatial or geographic data from numerous sources. LCA and SIG coupling is a recent field of study, and presents potential improvements for both inventory and impact assessment phases. In the case study SIG was used to calculate the distances reducing the time for obtaining it individually considering that more than 600 distances were assessed.

Studies in the literature present a significant difference of transport contribution to EOL impact based on the type of e-waste treated. Considering that e-waste in Europe are treated per waste streams and not per type or category of product, in future studies the authors intend to assess the EOL of different e-waste streams.

The case study represents less than 5% of the total e-waste collected in France. In this context, to validate the results, the authors intend to perform the same assessment for other treatment centers in France with different types of e-waste stream.

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