PhD program in Environmental Engineering

Life Cycle Assessment of the cabin waste management in the aviation sector

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Gonzalo Blanca Alcubilla

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TABLE OF CONTENTS

I. LIST OF TABLES

II. LIST OF FIGURES

III. PREFACE

The work collected throughout this thesis is part of the LIFE Zero Cabin Waste project and has been funded thanks to the European Commission's LIFE Programme. All this research work has been carried out at the UNESCO Chair in Life Cycle and Climate Change ESCI-UPF (Pompeu Fabra University), within the PhD Program in Environmental Engineering of the Department of Civil and Environmental Engineering at the Polytechnic University of Catalonia (UPC).

Thesis supervision was carried out by the Director of the UNESCO Chair in Life Cycle and Climate Change ESCI-UPF, Prof. Pere Fullana i Palmer, and by Dra. Alba Bala Gala, responsible for the Waste Management area of the same UNESCO Chair.

The purpose of this research within the LIFE project was to test the applicability of LCA methodology in the aviation sector with the aim to environmentally improve the aviation catering waste management system from a cradle to grave perspective.

Most of the data used in this work was provided by the LIFE project consortium (Iberia[1], Ecoembes[2], Gate Gourmet[3] and Ferrovial[4]).

This PhD thesis is based on four first authored scientific papers, having the first one been published in a newly born journal on waste management, two in Q1 journals and the last one currently under review also in a Q1 journal:

Paper 1. G. Blanca-Alcubilla, A. Bala, J.I. Hermira, N. De-Castro, R. Chavarri, R. Perales, I. Barredo, P. Fullana-i-Palmer, 2018. Tackling international airline catering waste management: LIFE Zero Cabin Waste project. State of the art and first steps. Detritus, 3, 159-166.

DOI: https://doi.org/10.31025/2611-4135/2018.13698

Paper 2. G. Blanca-Alcubilla, M. Roca, A. Bala, N. Sanz, N. De-Castro, P. Fullana-i-Palmer, 2019. Airplane cabin waste characterization: knowing the waste for sustainable management and future recommendations. Waste Management, 96, 57-64.

DOI: https://doi.org/10.1016/j.wasman.2019.07.002

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[1] Iberia is the Spanish flagship airline, founded in 1927. It is currently one of the oldest airlines in the world.

[2] Ecoembes is a non-profit organization, whose corporate purpose is to devise and run systems created specifically for selective collection and recovery of packaging waste, and for its ulterior treatment and upgrading. It is the Green Dot holder in Spain

[3] Gate Gourmet is the world's largest independent airline catering and logistics company providing meals approximately at 120 airports around the world.

[4] Ferrovial is a Spanish multinational company that has several business lines, such as financing, operation and maintenance of transport infrastructure, construction and urban services.

Paper 3. G. Blanca-Alcubilla, A. Bala, N. De-Castro, R. Colomé, P. Fullana-i-Palmer, 2020. Is the reusable tableware the best option? Analysis for the aviation catering sector with a Life Cycle Approach. Science of the Total Environment, 708, 135121.

DOI: https://doi.org/10.1016/j.scitotenv.2019.135121

Paper 4. G. Blanca-Alcubilla, A. Bala, J. Ribas-Tur, P. Fullana-i-Palmer, 2021. Improving the aviation catering waste management through Life Cycle Analysis and Life Cycle Costing. Journal of Environmental Management, under review.

Furthermore, during the PhD period, another contribution to waste management research in another scientific paper as co-author has been published:

R. Abejón, J. Laso, M. Margallo, R. Aldaco, **G. Blanca-Alcubilla**, A. Bala, P. Fullana i Palmer, 2020. Environmental impact assessment of the implementation of a deposit-refund system for packaging waste in Spain: a solution or an additional problem? Science of the Total Environment, 721, 137744.
DOI: https://doi.org/10.1016/j.scitotenv.2020.137744

Lastly, some contributions to international congresses, and based on the research developed, were performed as main author:

1. ***G. Blanca-Alcubilla**, R. Chavarri, N. De Castro, M. Roca, P. Fullana-i-Palmer,* 2017. The Life+ Zero Cabin Waste Project. Waste characterizations. 16th International Waste Management and Landfill Symposium, Sardinia (Italy).

Type of presentation: Oral.

2. ***G. Blanca-Alcubilla**, A. Bala, P. Fullana-i-Palmer,* 2018. Potential energy recovery from aviation catering organic waste in Spain. The Zero Cabin Waste Project. 9th International Chemistry Congress of ANQUE. Workshop "Water-Energy-Food Nexus: A Life Cycle Thinking Approach", Murcia (Spain).

Type of presentation: Oral.

3. ***G. Blanca-Alcubilla**, A. Bala, P. Fullana-i-Palmer,* 2018. LIFE Zero Cabin Waste Project: Management of aircraft waste in aviation. The Zero Cabin Waste Project. RECUWASTE 2018, Catalonia (Spain).

Type of presentation: Oral.

4. ***G. Blanca-Alcubilla****, A. Bala, P. Fullana-i-Palmer,* 2018. Improving the Airplane Catering Service. Food and Packaging Analysis. The Zero Cabin Waste Project. 11th International Conference of Life Cycle Assessment of Food, Bangkok (Thailand).

Type of presentation: Oral.

5. ***G. Blanca-Alcubilla****, A. Bala, N. de Castro, J. Ribas, M. Delgado-Aguilar, P. Fullana-i-Palmer,* 2018. Is the reusable tableware the best option? Analysis for the aviation catering sector with a life cycle approach. CONAMA 2018, Madrid (Spain).

Type of presentation: Text.

6. ***G. Blanca-Alcubilla****, M. Delgado-Aguilar, A. Bala, N. de Castro, R. Puig, P. Fullana-i-Palmer***,** 2019. Is the single-use plastic ban by EU universally good? The case of airplane catering. SETAC Europe 29th Annual Meeting, Helsinki (Finland).

Type of presentation: Poster.

Finally, it is worth mentioning that the Alfonso Maíllo award to the best innovative study on waste management was obtained at the 2018 RECUWASTE international congress, for the contribution: "LIFE Zero Cabin Waste project: Aviation catering waste management. Environmental impacts through LCA perspective."

IV. LIST OF ACRONYMS

ACARE - Aviation Research and Innovation in Europe

ACI - Airports Council International

ADP - Abiotic Depletion Potential

AP - Acidification Potential

ATAG - Air Transport Action Group

CFRP - Carbon fiber reinforced polymer

CORSIA - Carbon Offsetting and Reduction Scheme for International Aviation

CWEP - Confederation of European Waste-to-Energy Plants

EP - Eutrophication Potential

EU - European Union

GEI - Gases de Efecto Invernadero

GHG - Green House Gas

GG - Gate Gourmet S.A.

GWP - Global Warming Potential

HDPE - High Density Polyethylene

IATA - International Air Transport Association

ICAO - International Civil Aviation Organization

ICW - International Catering Waste

IEA - International Energy Agency

ILCD - International Reference Life Cycle Data System

IPCC - Intergovernmental Panel on Climate Change

LCA - Life Cycle Assessment

LCC - Life Cycle Costing

LCI - Life Cycle Inventory

LDPE - Low Density Polyethylene

MSW - Municipal Solid Waste

PET - Polyethylene terephthalate

POCP - Photochemical Ozone Creation Potential

PP - Polypropylene

PS - Polystyrene

PVC - Polyvinyl Chloride

US - United States

VAT - Value Added Tax

V. ABSTRACT

Air transport, in 2018, was the means of transport chosen by 8.8 billion people around the world. This is a sector that expected continued passenger growth in the following years, but due to the current effects of the Covid-19 pandemic has reduced its projections. However, the sector is expected to return to normal after the passage of the pandemic. Aviation was responsible, for combustion alone, for 2% of CO_2 emissions and 12% of total greenhouse gas (GHG) emissions within the transport sector worldwide. Nevertheless, there were other GHG emissions derived from this activity, such as, among others, the emissions generated by the catering service and its waste management. In 2018, it was estimated that 5.7 million tons of waste were generated, which had to be managed. The management of this waste in the European Union is conditioned by the European regulation CE 1069/2009. This regulation limits the management of organic waste of animal origin generated on flights from countries outside the European Union (the so called "Category 1") to landfilling or incineration.

Both the introduction to this thesis and the first scientific paper describe this situation in depth, as well as the LIFE Zero Cabin Waste project, in which they have been developed. Characterizing waste streams is essential to find the complex solutions that their classification and treatment require. It is especially relevant in the aviation sector, in which the different types of waste are collected together and most of them end up in landfills, generating GHG emissions, and contributing to the current climate crisis. It is expected that, from 2021, Directive 2019/904 will enter into force and will prohibit certain single-use plastics that are currently very present in aviation menus. The most comprehensive study to date of characterizations of the waste generated during 145 flights of different origins and characteristics has been carried out during this thesis, allowing the major fractions to be found and detecting possible improvements to reduce them. It has been verified that the organic fraction is the biggest one (33%), and that another very important fraction includes the different elements and packaging that we find in the menus. To identify the origin of the most relevant impacts and to find solutions to the different problems encountered, Life Cycle Assessment (LCA) methodology is recommended, allowing to evaluate from cradle to grave, where, and because of what, the most relevant environmental impacts occur. The application of LCA evaluating the 19 elements and packaging that includes an average tourist menu, many of them made of single-use plastic, and reusable ones made of heavier materials, has led to identify those that contribute the most to GHG emissions (plastic tray 41.4% and steel cutlery set 14.4%) and has demonstrated that, contrary to expectations, GHG emissions will increase with the introduction of this new Directive.

Once collected separately and classified by fractions, the waste can be treated in different ways, this sequence of processes being the waste management system. Problematic points of the current management system have been identified, and it has been demonstrated that some management changes - which will require a regulatory change in the EU that includes separate collection at source, the recovery of organic matter, and the increase in recycled materials - would notably improve the overall environmental performance of the system. For instance, GHG emissions would be reduced by 85%.

This thesis addresses the problem of waste generation in international aviation. It presents quantitative and qualitative analysis detecting conflict points in this activity. In addition, useful alternatives for this sector are presented regarding not only waste management but also the design of catering menus that will reduce the net impacts along the life cycle.

Keywords: Waste, catering, single-use plastics, packaging, LCA, aviation, GHG.

VI. RESUMEN

El transporte aéreo, en 2018, fue el medio de transporte elegido por 8.800 millones de personas en todo el mundo. Este es un sector que esperaba un crecimiento continuo de pasajeros en los años siguientes, pero que debido a los efectos actuales de la pandemia Covid-19 ha reducido sus proyecciones para 2020. Sin embargo, se espera que el sector vuelva a la normalidad tras el paso de la pandemia. La aviación fue responsable, teniendo en cuenta solo la combustión, del 2% de las emisiones de CO_2 y del 12% de las emisiones totales de gases de efecto invernadero (GEI) del sector transportes en todo el mundo. Sin embargo, hubo más emisiones de GEI derivadas de esta actividad, entre otras, las emisiones generadas por el servicio de cáterin y su gestión de residuos. En 2018 se estimó que se generaron 5,7 millones de toneladas de residuos, que debían ser gestionados. La gestión de estos residuos en la Unión Europea está condicionada por la normativa europea CE 1069/2009. Este reglamento limita la gestión de los residuos orgánicos de origen animal generados en vuelos desde países fuera de la Unión Europea (la denominada “Categoría 1”) al vertido o incineración.

Tanto la introducción a esta tesis como el primer artículo científico describen en profundidad esta situación, así como el proyecto LIFE Zero Cabin Waste, en el que se han desarrollado. Caracterizar los flujos de residuos es fundamental para encontrar las complejas soluciones que requiere su clasificación y tratamiento. Sobre todo, en el sector de la aviación, en el que los diferentes tipos de residuos se recogen juntos y la mayoría acaba en vertederos, generando emisiones de GEI y contribuyendo a la actual crisis climática. Se espera que, a partir de 2021, entre en vigor la Directiva 2019/904 y prohíba determinados plásticos de un solo uso que actualmente están muy presentes en los menús de aviación. Se ha realizado el estudio más completo hasta la fecha de caracterizaciones de los residuos generados durante 145 vuelos de diferente origen y características, permitiendo encontrar las fracciones mayoritarias y detectando posibles mejoras para reducirlas. Se ha comprobado que la fracción orgánica es mayoritaria (33%), y que otra fracción muy importante incluye los diferentes elementos y envases que encontramos en los menús. Para identificar el origen de los impactos más relevantes y encontrar soluciones a los diferentes problemas encontrados, se recomienda la metodología de Análisis de Ciclo de Vida (ACV), que permite evaluar desde la cuna hasta la tumba, dónde y por qué ocurren los impactos ambientales más relevantes. La aplicación de LCA evaluando 19 elementos y envases que incluye un menú turístico medio, muchos de plástico de un solo uso, otros reutilizables y de materiales más pesados, ha logrado identificar aquellos que más aportan a las emisiones de gases de efecto invernadero. Demostró que, contrariamente a lo esperado, las emisiones de GEI aumentarán con la introducción de esta nueva Directiva.

Una vez recogidos por separado y clasificados por fracciones, los residuos pueden ser tratados de diferentes formas, siendo esta secuencia de procesos el sistema de gestión de residuos. Se han identificado puntos problemáticos del actual sistema de gestión, y se ha demostrado que algunos cambios en la gestión -que requerirían un cambio regulatorio en la UE que incluya la recogida selectiva en origen, la recuperación de materia orgánica y el aumento de materiales reciclados- mejoraría notablemente el comportamiento medioambiental global del sistema. Por ejemplo, las emisiones de GEI se reducirían en un 85%.

Esta tesis aborda el problema de la generación de residuos en la aviación internacional. Presenta análisis cuantitativos y cualitativos detectando puntos conflictivos de esta actividad. Además, se presentan alternativas útiles para el sector, no solo de la gestión de los residuos sino también del diseño de los menús de catering, que reducirán los impactos netos en el ciclo de vida.

Palabras clave: Residuos, cáterin, plásticos de un solo uso, envases, ACV, aviación, efecto invernadero.

1. INTRODUCTION

1.1. BACKGROUND

1.1.1. AVIATION AND THE ENVIRONMENT

Aviation is a worldwide activity that, in 2018, transported 8.800 million passengers. This means an increase, compared to 2017, of 6.4% (ACI, 2019). In 2019, in Spain, one of the world's most touristic countries, 275 million people went into its airports (AENA, 2019).

The Covid-19 virus, in 2020, has strongly affected the activity of the aviation sector: up to a -90% of traffic difference compared to 2019 numbers (Eurocontrol, 2020). Although the air traffic growth predictions before this health crisis have changed, there is no doubt that the situation will reverse as soon as the pandemic is over (Oneair, 2020).

Aviation is an activity that generates huge economic benefits around the world. In fact, it directly creates 10 million jobs and provides 2,700 million dollars to the world economy. To get an idea, it would be the 20th largest economy in the world if aviation were a country (ATAG, 2018).
Despite the economic benefit, aviation has always been in the spotlight due to its effects on the environment. Although fuel consumption and associated CO_2 emissions per passenger-kilometer in aviation have been significantly reduced compared to the 1960s (IEA, 2009), only aviation is responsible for 2% of CO_2 world emissions. Within the transport sector, it represents 12% of total GHG anthropogenic emissions (ATAG, 2020).

In civil aviation, a growing awareness of the importance of environmental protection can be noted (IATA, 2017). Airlines are determined to manage and reduce their impact on the environment in partnership with airports, service providers, air navigation and aircraft manufacturers. Fighting CO_2 emissions is at the top of the agenda, and the industry has a well-established strategy and globally agreed targets to that end. The International Air Transport Association recognizes the importance of reducing CO_2 emissions to tackle the problem of climate change and has adopted in the past years a series of measures and targets to mitigate them (IATA, 2018). These measures include:

- Improving fuel efficiency by 1.5% per year from 2009 to 2020.
- Achieving a carbon neutral growth by setting the maximum limit for net CO_2 emissions from aviation in 2020. The effect of Covid-19 on emissions from the aviation sector led to the establishment of 2019 as the base year, instead of 2020 (IATA, 2020).
- A reduction of CO_2 emissions from aviation of 50% by 2050, relative to 2005 levels.

In 2005, the aviation industry approximately emitted 650 Mt of CO_2 eq. (Adam, 2019). The aviation activity was 55% lower in 2020 than in 2019 (*Aviation – Analysis - IEA*, 2020). In 2019, 915 Mt of CO_2 eq. were emitted (ATAG, 2020). Therefore, the 50% reduction by 2050 would be similar to the one achieved due to the pandemic effects.

The 39th International Civil Aviation Organization (ICAO) assembly in 2016, agreed to adopt measures to tackle CO_2 emissions from international aviation. This global scheme of reductions established by ICAO resulted in the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Since 2019, airlines are required to report their CO_2 emissions annually to set an average of 2019 and 2020 emissions. From 2021, international flights will have to offset their emissions as required. The Covid-19 effect on aviation has drastically decreased emissions in 2020, not reflecting the target agreed. Therefore, the 2019 pre-crisis emission levels will be used for the baseline objective (IATA, 2020). Furthermore, since 2012, aviation has contributed to the emissions reduction within the EU through the EU emissions trading system (The European Parliament and the Council of the European Union, 2008).

From the scientific perspective, much research is being done to make aviation a more sustainable activity. For instance, the Strategic Research and Innovation Agenda (SRIA) sets the strategic roadmap for aviation research, development and innovation, developed by the Advisory Council for Aviation Research and Innovation in Europe (ACARE), giving account of both evolutionary and revolutionary technology (ACARE, 2020).

However, CO_2 eq. emissions from the burning of fuel in aviation is not the only source of environmental impact. During flights, passengers consume food and beverages, all packaged. This food and drink packaging along with uneaten food becomes catering waste that has to be managed.

1.1.2. CATERING WASTE CONTRIBUTION

Approximately, each person generates 1.43kg of waste per flight (including toilet waste) (Godson, 2014). According to IATA, this led to 5.7 million tonnes of waste generated in 2017 around the world (IATA, 2018b).

The concern for cabin waste dates back two decades, when the first characterizations were carried out while identifying hot spots and developing recycling strategies. (Li, Poon, Lee, Chung, & Luk, 2003). Even with this early concern, most aviation and airline catering companies have been recycling very little and the materials obtained were not of high quality due to the mixing of various waste fractions. Several factors such as low landfill disposal rates (especially for inorganic fractions), lack of suitable facilities, and limiting regulations that inhibit reusing and recycling waste coming from airplanes, clearly lead to burning or landfilling them. The sum of these above mentioned barriers has traditionally daunted airlines and other partakers to proactively look for solutions.

However, in the past years, there has been a change of trend. Several airlines and stakeholders (notably catering companies) have increased their efforts to tackle this issue. This is the case of Ryanair, for instance, that has promised to eliminate non-recyclable plastics from its operations by 2023. In addition to switching to biodegradable cups, wooden cutlery and paper packaging on-board, Ryanair said it would make its head offices, bases and operations plastic free (Topham, 2018). British Airways are committed to reduce its single use plastic waste and to use packaging with recycled material content (ATAG, 2018). Other companies such as Alaska Airways are committed to reducing the waste from all paper, cups, bottles and cans on every domestic flight they operate (Alaska Airways, 2015).

Such is the concern about this problem that even artificial intelligence is being used to detect food leftovers, therefore preventing food waste and money loss due to waste management. This will avoid loading unpopular food on the plane (Future, 2020).

It is worth to state that these initiatives made by diverse aircraft companies are usually single initiatives, missing a comprehensive and holistic point of view.

1.2. LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) methodology is the central axis of the research presented in this thesis, carrying out different studies (Chapters 5 and 6) that present different characteristics.

The first appearance of the LCA concept dates back to the 60s, specifically in the US when a series of experts began to worry about the limitations of energy sources and materials, and their associated effects on the natural environment. Already in the 70s, with the predictions of population increase and with the demand for material and energy resources, numerous increasingly detailed studies were carried out (including material balances of the processes with consumption of raw materials and generation of waste) aimed at, above all, to a correct management of energy resources (Bjørn et al., 2017).

LCA is a methodology that consists of the compilation and evaluation of the inputs, outputs and potential environmental impacts of a system or a product throughout its life cycle, also known as from cradle to grave (Life Cycle Initiative, 2020). This methodology has as its main characteristic the holistic approach, taking into account all the properties of a system, since it cannot be determined or explained by isolating its components (IHOBE, 2009).

In many cases, it is difficult to cover all activities from cradle to grave. The amount of inputs and outputs of a system or object throughout its life cycle is quite important. That is why the methodology to carry out these studies is framed in ISO 14040:2006 (Environmental management - Life cycle assessment - Principles and framework) and ISO 14044:2006 (Environmental management - Life cycle assessment - Requirements and guidelines), and further developed in guides such as the ILCD Handbook (European Commission, 2010).

Within these standards, the phases to be followed in the performance of a complete LCA study are defined. Figure 1-1 depicts the previously named phases.

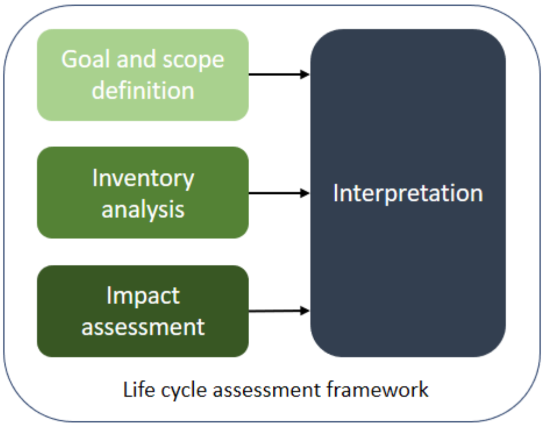

Figure 1-1 LCA phases (ISO, 2006b)

Firstly, the goal and the scope and the detail of the study are defined. At this stage, crucial aspects such as functional unit, system boundaries, evaluation and the interpretation methodology are detailed. Secondly, in the inventory analysis the inputs and outputs of the system under study are quantified, including the use of resources (raw material and energy), emissions to the atmosphere, discharges to soil and water and waste generation. The ISO standard (ISO, 2006) recommends using data directly obtained from the studied processes through measurements "in situ", requesting first-hand data. Once all the inputs and outputs have been collected (referenced to the selected functional unit) and having adjusted the system limits after a sensitivity analysis, the life cycle impact assessment can be performed.

In the life cycle impact assessment phase, the results of the inventory analysis are related to the environmental effects they give rise to, in order to assess the importance of the potential impacts that would be generated.

This evaluation phase has three mandatory successive elements and three optional ones (Baumann & Tillman, 2006), described in Figure 1-2.

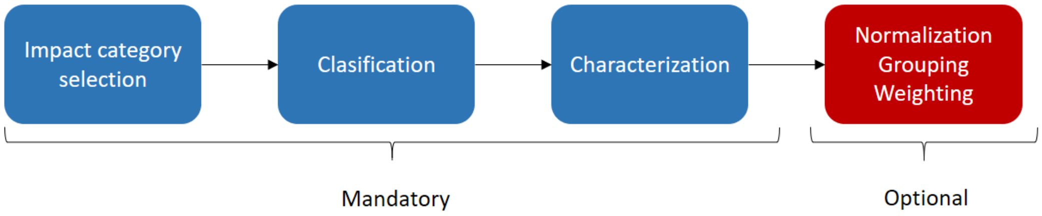

Figure 1-2 Steps in the impact assessment stage (after ISO, 2006a)

Depending on the objective of the LCA study, a number of impact categories will be chosen. Among the most common are: climate change, acidification, eutrophication, toxicity and resource depletion. During classification, environmental loads due to resources consumption, generation of emissions and waste, are grouped depending on the potential environmental effects produced by each of them. Certain components are assigned to only one impact category, while others contribute to more than one category. The characterization element consists of the calculation of the potential contribution of each component detected in the inventory analysis to an impact category. Normalization, grouping and weighting are not advisable according to (ISO, 2006). Weighting has not a scientific basis and different interpretations of the results could take place.

1.2.1. LCA IN AVIATION CATERING WASTE: A STATE OF THE ART

An extensive review of the literature on LCA studies resulted in no previous LCA studies including the management of catering waste from airplanes. However, when isolating different aspects of the catering activity such as transport, packaging, kind of food…numerous studies were found. The review is focused on:

- The use of LCA in aviation in general and in catering in particular. In the aviation sector, most studies using LCA compare different manufacturing materials.
- Catering, where the impact of the food supply chain is relevant, including several LCAs in food groups, types of packaging and cutlery.
- The different waste management alternatives have been reviewed as well.

1.2.1.1. LCA IN AVIATION

When evaluating the impact on aviation, it is important to bear in mind that there are stages that occur for a longer time and others that represent less time in the life cycle. "Processes occurring once in the life-cycle of an entire aircraft fleet have a minor influence on the environmental impacts (EI), as their impact is distributed over all passenger-kilometers traveled by the whole fleet. Processes occurring each

flight have the highest contribution to the environmental impacts of an aircraft as their impact is only distributed over the passenger-kilometers of a single flight" (Johanning, Scholz, & Tor, 2013).
Three main stages in the life cycle of aviation are: manufacturing, operation and decommissioning. The operation phase is the most impactful on the environment and in which the most energy consumption is generated (Lopes, 2010, Howe, et al., 2013). The operation stage represents more than 82% in energy consumption and more than 79% in GHG emissions (Horvath & Chester, 2008). Investments in improving technology, such as reducing weight, improving engine efficiency, and using alternative fuels (Beck et al., 2011) are being constantly developed.

Emissions from the aviation sector are largely directly related to the transported weight (Godson, 2014, IATA, 2018a). Therefore, LCA studies have also been carried out where the use of traditional materials such as aluminum is compared with composite materials such as carbon fiber when manufacturing an airplane. Carbon fiber reinforced polymer (CFRP) is a composite material that has been used as a structural component in “next generation” aircrafts due to its reduced weight compared to aluminum. Taking into account the manufacturing stage and final disposal, CFRP contributes more to the GHG emissions than aluminum due to the consumption of fossil fuels during these processes. On the other hand, if the airplane life time (30 years) is included, the contributing impact of the CFRP is inferior since, being a lighter material, it allows flights with fewer emissions due to lower fuel consumption, and contributes to a 25-30% reduction in GHG over the life of the aircraft (A. J. Timmis et al., 2015). The application of lightweight materials to aircraft structures will result in lower emissions even if production and / or disposal stages are not favorable (Beck et al., 2011), and the results are favorable shortly after the first flights (Horvath & Chester, 2008).

1.2.1.2. LCA IN CATERING

The most important impact by far in aviation is due to fuel consumption in the operation of the airplane. Thus, the catering will probably influence more or less in terms of the weight that the chosen option implies. Anyway, if looked at it in absolute terms, the amount of catering moved by the aviation sector is enormous, so their study makes perfect sense. The catering process is one more stage in the food production chain. This chain begins with agriculture, a stage that, according to the IPCC, is estimated to contribute 10-12% of global CO_2 emissions (5,100-6,100 MT CO_2 eq) (IPCC, 2007b). This figure increases to the range between 16.8 and 32.2% when emissions from fuel use, fertilizer production, and land use change are taken into account (Bellarby et al., 2008).

There are three dominant GHG in the stages named above:

- CO_2 emissions in agriculture are mainly due to the stages where fuel is consumed, that is, where machinery is used. The manufacture of synthetic fertilizers and the burning of biomass also contribute, although to a lesser extent. After the agriculture stage, CO_2 emissions are notable in the transport and distribution stages and in the refrigeration processes. The country of origin largely determines the total impact of the LCA of a food product, and, when it is transported by plane, GHG emissions shoot up (Sim, Barry, Clift, & Cowell, 2007).
- Regarding CH_4 emissions, most of them are attributable to the digestion of ruminants. Per kg of gas, methane contributes 25 times more than CO_2 to global warming (IPCC, 2007b).
- Lastly, N_2O emissions are associated with the application of nitrogen fertilizers, manure and urine production. N_2O has a greenhouse effect potential 298 times higher than CO_2 (IPCC, 2007a).

By the time food reaches the caterer, the majority of GHGs have already been emitted into the atmosphere, but additional energy will continue to be used to cook food, refrigerate, wash, and other kitchen processes. The following figure (Figure 1-3) shows the source of GHG emissions in the United Kingdom within the food chain, with agriculture being the most impactful stage followed by transport and food processing (Caputo et al., 2014) (Garnett et al., 2017).

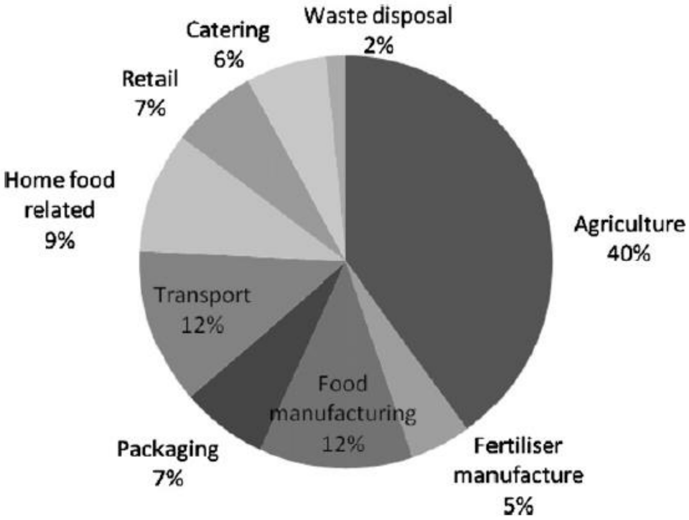

Figure 1-3 GHG emissions in the food supply chain (Garnett et al., 2017)

1.2.1.3. LCA FOR PACKAGING AND CUTLERY

The function of the containers is to protect and preserve the product, so that it arrives in good hygienic conditions for consumption or that it is resistant to external environmental factors such as light, gases or humidity (Ecoembes, 2017).

Packaging is a fundamental element of almost all food products and a source of environmental burden and waste, since, after consuming the packaged product, it becomes waste, requiring subsequent management. It is also true that the packaging that correctly protects and preserves the product can be an important tool to reduce the total environmental impact, even if there is an increase in the impact of the packaging itself. This is especially true for food items where the environmental impact of food is high relative to the packaging, for example cheese (Williams & Wikström, 2011).

In the catering process, we find elements that can be both reusable and not reusable, such as glasses or cups for drinks, and cutlery.

The study carried out by Pro.mo (a business group in the sector of the production of disposable plastic cutlery made up of 6 Italian companies that covers around 80% of the sector's turnover) compares plates and glasses made of different materials using LCA (Pro.mo/Unionplast, 2009). The study takes into account the complete life cycle of the different items, from the extraction of raw materials, through production, transformation, distribution, use and end of life (with 3 different scenarios). As a final result, reusable tableware has significantly lower impact categories values than disposable tableware (up to 75% impact reduction for the global warming potential). For single use items, most of the impacts came in the production stage. Meanwhile for the reusable items, the washing process stage is where most of the impacts take place. Nevertheless, using an optimized washing process in a country with a low energy mix will reflect more favourable results than in a country with a fossil energy based energy mix and less efficient processes (Woods & Bakshi, 2014).

Another LCA study where single use and reusable cups are compared through LCA determined that most of the impacts for the single-use cup is due to the production of PP and the manufacture of the cup. In the case that the reusable cup is used 10 times, the contribution to the different impact categories of the waste generated after the cup is used is negligible compared to the manufacturing and washing processes contributions (Garrido & Alvarez del Castillo, 2007).

1.2.1.4. LCA IN FOOD

As already seen in the catering section, the agricultural stage is the one with the highest energy consumption and GHG emissions of the entire food chain. Food processing and logistics are the next most important stages in terms of environmental impact, due to their energy intensity and related emissions to the atmosphere that occur through the production of heat, steam and electricity, and during transportation (Tassielli et al., 2017).

There are numerous LCA studies on different foodstuff. In all of them, animal origin (Foster et al., 2007; Tilman & Clark, 2014), highly processed (Roy et al., 2009), and intensively produced (Haas et al., 2001) food products appear as those with the greatest impact (Cederberg & Mattsson, 2000). Therefore, a change of diet can lower the GHG emissions (Batlle-Bayer et al., 2019; Tassielli et al., 2017). In addition, those food items coming from far away countries by truck, ship or even by plane affect notably the food carbon footprint (Sim et al., 2007; Wallgren, 2006).

Finally, waste management of food waste is usually the second most contributing stage in the food life cycle to global warming, after the production stage (Eide, 2002); therefore, a reduction in food losses could reduce the food system related emissions as well (Garcia-Herrero et al., 2018a).

1.2.1.5. LCA IN WASTE MANAGEMENT

LCA methodology has been widely used in the waste management studies due to its capability to identify valuable solutions to decrease environmental impacts (Barton et al., 1996; Ekvall et al., 2007a).

In most of the studies, the landfill stage is found to be the waste management process that contributes the most to the different environmental impact categories (Cherubini et al., 2009). For the other kind of waste management treatments, the impact results may differ depending on the material being treated. For instance, for plastics and paper, most of the studies recommend recycling instead of landfilling and/or thermal processes (Tyskeng & Finnveden, 2010; Jean-Charles et al., 2010).

However, with the exception of the landfilling of organics and paper, there are no firm conclusions that one waste treatment technology is better than another. The diversity of waste composition, local energy mix, efficiencies of treatments, etc., increases the need to make LCA studies on waste management for each case (Laurent et al., 2014).

Regarding pre-treatments such as source separation, they will increase the recycling efficiency and therefore its environmental benefits (G. Liu et al., 2017), although, to a certain extent, determined by the source separation model and the national peculiarities (Abejón et al., 2020).

2. OBJECTIVES

The main objective of the doctoral thesis is to develop a methodology to propose sustainability improvements in all the life cycle stages related to catering waste in the aviation sector, an economic sector where Life Cycle perspective has not been used for this application.

To achieve this overall goal, a series of specific objectives are proposed:

1. To understand the cabin waste generation problem, identifying sources, amounts, types and treatments of waste produced, by performing high scale in-situ waste characterizations.
2. To identify, by performing LCA studies, airplane cabin menus key factors that contribute the most to the environmental impact of catering in aviation, and to propose more sustainable solutions, focused on food, packaging, tableware and the application of DIRECTIVE (EU) 2019/904.
3. To first ever check LCA methodology to assess the environmental impact of the different kinds of airplane catering waste management options, considering the current regulations, while detecting the stages and characteristics that mostly contribute not only to the emission of GHG but to other environmental impact categories as well.
4. To analyse the eco-efficiency of different waste management options, by putting in common environmental impacts and economic performance, revealing the most sustainable approach to airplane catering waste management.

3. WORK HYPOTHESIS

The following picture represents the logical consequential process of the research work presented.

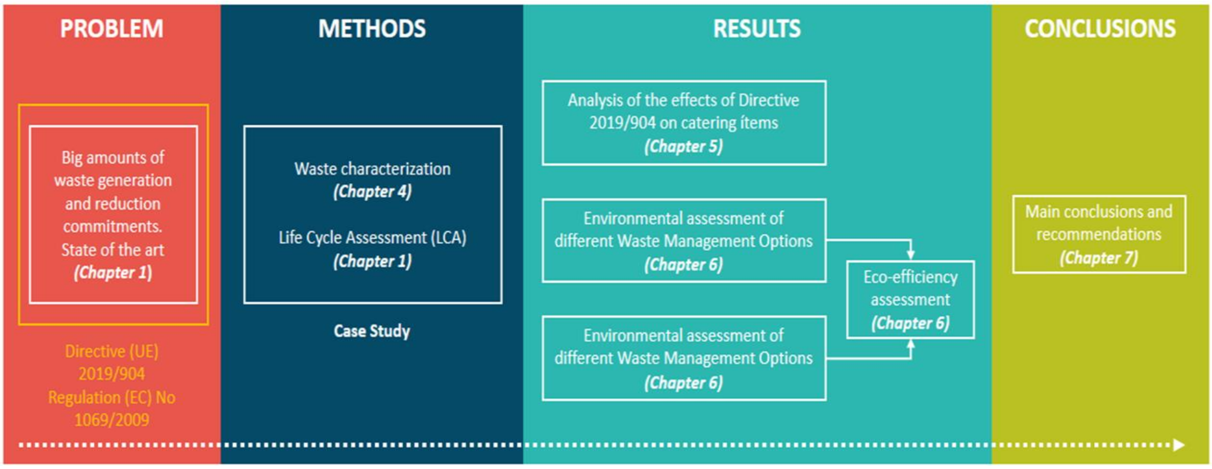

Figure 3-1 Research logic

The research carried out arises in response to the growing problem of aviation catering waste and the environmental cost of its management. A first step is to carry out a state of the art of the existing LCAs regarding waste management to know where and how the environmental impacts take place (chapter 1). Waste management that consists of landfilling and that above all contains a large amount of organic waste turned out to be the greatest source of environmental impact. From this research, it is revealed the crucial importance of the composition and the amount of waste generated per person in the different flights. Therefore, the second natural step is to analyze and characterize the waste generated during the flights (chapter 4 result). This information would be used as an input for the subsequent specific LCAs studies. Iberia flights landing in Madrid-Barajas Adolfo Suárez airport (from now on Barajas airport) were chosen as the case study. We had first hand and high quality data to develop the case study.

The legislation that regulates the management of the aviation catering waste (Regulation (EC) No 1069/2009) is very restrictive for the European legislative scenario. The management of waste generated on flights from countries outside the European Union is limited to incineration or controlled landfilling. This prevents enormous amounts of waste from being recycled to obtain secondary raw materials and contributes to the GHG emissions in landfill due to organic matter decomposition. To analyze the effects of this regulation and possible alternatives, LCA was tested as a methodology to compare the current waste management system with different management alternatives, in order to identify the environmental promising solutions. This could be the case where the recycling of materials and the valorization of organic matter after a previous sterilization takes place, as less waste would end up in a landfill, with the corresponding emissions, and more secondary materials would be obtained (results presented in chapter 6). However, technology changes are not only performed taking into account the environmental behavior, but also its economic impact. Thus, an analysis of the eco-efficiency of the different options (that means balancing economic and environmental results) needs to be carried out (results presented in chapter 6).

Other legislation affecting the aviation sector is the Directive (UE) 2019/904. In this regard, an LCA analyzing different alternatives is performed (chapter 5). The results of the LCA of the catering menu highlights that the upcoming legislation banning certain single-use plastic items will have an upward impact on the generation of GHG emissions in the aviation sector. The replacement of single-use plastics with other materials (surely heavier and with associated environmental impacts not so commonly known throughout their life cycle) could increase GHG emissions in the aviation sector. As could be seen in the state of the art of LCAs already carried out in the food sector, transport can be a significant part of the impact due to the weight transported and the type of vehicle, with airplanes being the way of transport that generates the most GHG emissions per km travelled. That is why the realization of an LCA study to know the current impacts of each catering item and the potential effect, on the environment, of the prohibition of single-use plastics in the aviation sector should be developed.

Using the LCA methodology could initiate a review of the previously mentioned regulations by the competent authorities.

4. KNOWING THE AIRPLANE CATERING WASTE

Already published as:

Blanca-Alcubilla, G., Roca, M., Bala, A., Sanz, N., De Castro, N., & Fullana-i-Palmer, P. (2019). *Airplane cabin waste characterization: Knowing the waste for sustainable management and future recommendations*. Waste Management, 96, 57–64.

https://doi.org/10.1016/j.wasman.2019.07.002

4.1. ABSTRACT

The aviation industry generates a significant amount of waste. Nowadays, companies are making efforts to enhance waste management and reduce waste generation. In order to improve present practices and implement a proper waste management system, the quantities, materials, and typology of waste generated need to be studied.

A total of 145 airplanes were analysed. We differentiated 5 strips of duration and identified 4 different generation sources within the cabin associated with the business and tourist passenger classes. We classified and characterized the waste into 20 different materials. Results provide a detailed, representative and adapted study of the catering waste generated in the aviation industry. The characterization, which allows distinguishing between manipulated and unmanipulated materials, aims at providing useful information to reduce the generation of waste.

The analysis performed in the present study shows that the flying distance increases the waste generation, as more food is served. It also shows that organic matter, paper/cardboard and packaging are the dominant materials in the waste generated in flights. The results of the characterizations obtained allow making some recommendations. The use of bi-compartmentalized waste trolleys to separate on-board recyclable materials from the rest is desirable to obtain a clean recoverable waste stream. Supressing unpopular food from menus, identified analysing the leftovers, could also reduce the amount of waste generated.

Changes in the CE 1069/2009 regulation would allow more waste to be recycled instead of landfilled. Ultimately, the information obtained from this study will be used to design a more sustainable waste management system.

4.2. THE CATERING CABIN WASTE

The main source of waste generated in many planes is the food that is served to passengers. Food serving is in fact a factor that passengers take into account in their process of choosing which airline to fly with (Fairuz I Romli, 2016). Therefore, there are incentives for companies to provide increased amounts of food to satisfy their passengers, even when this implies generating a larger amount of uneaten food (Kate Springer, 2017). The packaging of servings and the uneaten food generates significant amounts of waste.

The enormous amounts of waste generated in airplane cabins are not being properly managed by most airlines and catering companies from a sustainability point of view (Pitt & Smith, 2003). The collected waste is typically of low quality because multiple waste fractions are mixed (Olivia Boyd, 2017, Kate Springer, 2017).

In order to have a solid basis to design future protocols and measures to improve cabin waste management, it is crucial to know the specific composition of the waste produced in different flights (Hristovski et al., 2006, Shinee et al., 2007, Kumar & Goel, 2009). The composition of the waste generated in flights could be assumed to be similar to that produced in restaurants (Tatàno et al., 2017). However, there are factors that determine differential characteristics of this waste (Heikkilä et al., 2016). Indeed, the food served in the aviation sector is subject to strict catering guidelines and the legislation that is applicable is different than that for restaurants (IFSA, 2016, ISO, 2005, European Union, 2004). In addition, food waste of animal origin generated in aircraft coming from outside the European Union, and the one that has been in contact with it, is classified as category 1 (Cat.1), and considered dangerous because of the possibility of spreading animal diseases. Therefore, it must be disposed of in an authorized landfill. On the other hand, food waste produced on flights of European origin does not present this hazard and is classified as category 3 (Cat. 3) waste, and can be disposed of in a landfill for municipal solid waste (European Parliament, 2009).

To our knowledge, there only exists four preliminary studies that conducted airplane or airport waste characterizations. (Tofalli et al., 2018, Li et al., 2003), analyzed a rather small number of flights (27 and 8) with little diversity in terms of waste material characterization and generation stream. Thus, the number of waste streams assessed and the information obtained in these studies were rather limited. The study by Mehta (2015) does not contain information about the percentage that cabin waste represents relative to the total waste managed in an airport and its composition, and the information about how the study has been done regarding the amount and characteristics of the airplanes analyzed and the stream form where waste comes (Mehta, 2015). Finally, (Pitt & Smith, 2003) published a study in the early 2000s about the low disposal fees for waste in the United Kingdom. It stressed the importance of increasing recycling in the British airports but no information about airplane waste generation is included.

The present study aims to collect a fairly larger set of data to generate a more representative characterization of the waste generated in planes by studying a sample of 145 flights operating in the Barajas airport gathering information regarding a larger set of key influencing parameters.

This characterization study aims to provide evidence required to dimension and design a more sustainable management system that will reduce the amount of waste that ends up in landfill, increase the recycling rate, prevent the generation of waste and set the basis for future replication by other airlines.

4.3. METHODOLOGY

This paper characterizes the waste collected in Iberia flights landing in Barajas airport. The data collection of cabin waste was led by Ecoembes S.A in close collaboration with Gate Gourmet S.A. (GG). The characterization performed includes catering waste (organic and inorganic), newspapers and magazines. As a result of the characterization, the analysis obtains an inventory of the flights, the type of planes, and the kind of waste found in each type of flight. The analysis differentiates between business and tourist classes, given that there are significant variations in the type of menu, the display and the number of servings, which also depends on the flight duration. The analysis produces an inventory of the type and quantity of waste arriving daily to GG's facilities.

The following sections describe the sample of planes and waste streams characterized, the classification categories used and the process that was followed to conduct the waste characterization.

4.3.1. SAMPLE

The data gathering was made between November and December 2016 (Table 4-1).

Table 4-1 Waste characterization – date registry

Stream	National	European	Short International	Medium International	Long International	
Business	10/11/2016	11/11/2016	15/12/2016	23/11/2016	08/11/2016	02/12/2016
	15/11/2016	15/11/2016		24/11/2016	22/12/2016	08/11/2016
	16/11/2016	16/11/2016		12/12/2016	30/11/2016	22/11/2016
	18/11/2016	17/11/2016		13/12/2016	15/12/2016	01/12/2016
	24/11/2016	15/11/2016			10/11/2016	14/12/2016
		23/11/2016			05/12/2016	02/12/2016
		25/11/2016			14/11/2016	20/12/2016
		15/12/2016			12/12/2016	17/11/2016
		20/12/2016			23/12/2016	16/12/2016
					29/11/2016	29/11/2016
					11/11/2016	13/12/2016

Stream	National	European	Short International	Medium International	Long International	
Galley	10/11/2016	11/11/2016		25/11/2016	08/11/2016	05/12/2016
	15/11/2016	15/11/2016			22/12/2016	09/11/2016
	16/11/2016	16/11/2016			30/11/2016	22/11/2016
	18/11/2016	17/11/2016			15/12/2016	01/12/2016
		15/11/2016			10/11/2016	14/12/2016
					05/12/2016	02/12/2016
					10/11/2016	21/12/2016
					12/12/2016	17/11/2016
					22/12/2016	16/12/2016
					29/11/2016	29/11/2016
					11/11/2016	13/12/2016
Waste	10/11/2016	10/11/2016	15/12/2016	18/11/2016	08/11/2016	05/12/2016
	15/11/2016	15/11/2016		22/11/2016	22/12/2016	09/11/2016
	16/11/2016	16/11/2016		25/11/2016	30/11/2016	22/11/2016
	18/11/2016	17/11/2016		12/12/2016	15/12/2016	01/12/2016
	24/11/2016	15/11/2016		14/12/2016	10/11/2016	14/12/2016
	20/12/2016	23/11/2016			05/12/2016	02/12/2016
	23/12/2016	23/12/2016			14/11/2016	21/12/2016
		25/11/2016			12/12/2016	17/11/2016
		14/12/2016			23/12/2016	16/12/2016
		20/12/2016			29/11/2016	30/11/2016
					11/11/2016	13/12/2016
Tourist				18/11/2016	08/11/2016	02/12/2016
				23/11/2016	22/12/2016	09/11/2016
				24/11/2016	30/11/2016	22/11/2016
				12/12/2016	15/12/2016	30/11/2016
				13/12/2016	10/11/2016	14/12/2016
					05/12/2016	01/12/2016
					14/11/2016	21/12/2016
					12/12/2016	17/11/2016
					22/12/2016	16/12/2016
					29/11/2016	30/11/2016
					11/11/2016	13/12/2016

In total, the waste produced in 145 flights was analyzed with the objective to obtain its characterization for national, European and international flights (those coming from outside the European Union borders). Flights were selected under the criteria of diversifying their origins in order to have a good representation of the different types of flights landing in Barajas airport.

The waste streams corresponding to four types of trolleys were identified and analyzed separately. The four types of streams include the waste collected with the two trolleys that carry the menus for the passengers: the tourist menu trolley and the business menu trolley. In these trolleys, the trays are re-deposited with meals and packaging waste after its consumption. A third stream corresponds to the waste trolley, which is used so that passengers deposit the additional waste generated during the flight. Finally, the galley trolley is the one that contains drinks and snacks, which constitute the sale on board and is used to collect back drinking packaging served apart from the menus (Figure 4-1).

Figure 4-1 Sample of cabin waste

The types of menus and number of servings offered depend on the flight type and its duration. Menu trolleys are classified according to the type of menu they contain; they may be either of the business or the tourist type. For flights of less than 3 hours, where European and national flights are included, menus are only served in the business category. Tourist menus are thus only served in medium and long flights. In long flights, there are up to 2-3 menu servings for tourist and business class passengers.

Table 4-2 shows which types of trolleys (and corresponding waste streams) are to be considered, depending on the type of flight. It also shows the number of servings per type of menu in each type of flight, depending on its duration. Also, the number of planes and the total number of passengers of each type for which waste coming from the different streams was analysed. It is to be noted that the analysis excluded those streams where the amount of waste generated weighed less than 3 kg, which mostly corresponded to the galley stream of short flights. Finally, it also shows the number of groups and flights per bulk that were studied for each type of flight.

Table 4-2 Flight information

	National	European	Short international	Medium international	Long international			
Time of flight	<3h			3-7h	9-10.30h	7-9h	>10.30h	
Menus served	1			2	2	3	3	**Business**
	0			1	2	2	3	**Tourist**
Waste flows	Galley Waste Business			Galley Waste Business Tourist	Galley Waste Business Tourist			
Nº groups	5	7	3	1	3	2	-	
Flights per group	10	8	2	4	1	2	22	
Nº of planes analyzed*	25	31	2	7	22			
Total flights	50	62	4	7	22			
Business passengers	14.4	11.9	13.4	15.1	37.8			
Tourist passengers	103.8	129.5	128.1	87.3	208.3			
Total passengers	118.2	140.9	141.4	102.4	246.1			

*National, European and Short International flights are round trips. On each flight, trolleys are loaded in Madrid and taken out once they land in Madrid again.

Pictures of typical examples of the business menu and the first serving of the tourist menu are correspondingly presented in Figures 4-2 and 4-3.

Figure 4-2 Example of a business menu

Figure 4-3 Example of a tourist menu

Figure 4-4 presents an image of a typical second serving of the tourist menu. What is distinctive of this second serving is the fact that it is generally delivered in a cardboard box instead of on a reusable tray. This obviously makes a difference in the composition of waste.

Figure 4-4 Example of a 2nd tourist menu

For flights with a duration shorter than 3 hours, waste from several flights of the same type was grouped in bulks before the characterization took place to have enough waste amounts.

4.3.2. CHARACTERIZATION PROCESS

There is not a unique way to make characterizations of waste (Dahlén & Lagerkvist, 2008). One needs to determine which variables characterize the units under analysis and in which categories streams and waste materials are categorized in order to produce a usable and relevant characterization. Therefore, the characterization methodology generally used by Ecoembes was applied after adapting the characterization template with the fractions that we were interested in knowing.

The flights analysed in the present study were classified depending on their duration, which determines the number of menus that are served (as shown in Table 1-1). The chosen categories of flights are:

- National flights: journey time not exceeding 3 hours, inside Spain.
- European flights: journey time not exceeding 3 hours, inside the EU.
- Short international flights: journey time not exceeding 3 hours, coming from outside the EU.
- Medium international flights: journey time between 3 and 7 hours, coming from outside the EU.
- Long international flights: journey time exceeding 7 hours, coming from outside the EU.

National and European flights were analysed separately in order to capture possible differences due to the distinctive passenger profiles travelling in such flights and the relative shorter length of national flights. International flights were classified distinguishing between short, medium and long flights, since flight duration determines the types of food services that are provided to passengers, in turn affecting the amount and kind of waste generated.

We also considered the number of passengers in each flight as well as the waste streams that each type of passenger could generate. Information on the number of passengers of each type (tourist, business, and crew) per group of flights was obtained from Iberia. In order to estimate the generation of waste per passenger for each type of waste stream the following was assumed:

- For the business stream, the number of crew members was added to the number of passengers traveling in this class. Crew menus are very similar to those of business which justifies that they are treated together.
- The number of passengers traveling in the tourist class was used to compute the waste per passenger of the tourist stream.
- For the waste stream, the total number of passengers (crew, business, and tourist) was used, assuming that they equally contribute to this type of waste.
- For the galley stream, the generation per passenger was only calculated taking into account passengers and crew on flights of more than 3 hours of duration. For shorter flights, since samples weighted less than 3 kg, the generation per passenger was not accounted for.

The waste to be characterized was identified according to two levels of classification. The first level of classification distinguishes waste in three groups according to the manipulating condition: manipulated, unmanipulated, and other materials. Food and its packaging is considered to be manipulated once the packaging has been opened by the passenger, whether it has been consumed or not. Food and its packaging is considered unmanipulated only when its packaging has not been opened. The reason to distinguish these materials is that the catering operator is interested in knowing the usage ratio of the packaged food that has been opened. This allows the operator to plan the amount of food to be loaded on the plane. The second level of classification identifies the specific materials considered: packaging (aluminium, film, color HDPE, natural HDPE, other plastics, PET, PP, PS, PVC, Steel, tetra pack, wood), liquid in packaging, organic matter, cutlery, glass, napkins, paper and cardboard, solid in packaging and others (see Table 4-3).

Table 4-3 Categories for the classification of materials in characterizations

Manipulated	Unmanipulated	Others
Packaging - Aluminum - Film - Color HDPE - Natural HDPE - Other Plastics - PET - PP - PS - PVC - Steel - Tetra pack - Wood Liquid in packaging Organic matter Cutlery Glass Napkins Paper and cardboard Solid in packaging	Packaging - Aluminum - Film - Color HDPE - Natural HDPE - Other Plastics - PET - PP - PS - PVC - Steel - Tetra pack - Wood Liquid in packaging Organic matter	Others

4.3.3. CHARACTERIZATION FIELDWORK PROCEDURE

As soon as the trolleys under study arrived at GG facilities, they were labelled and separated from the rest. This was done to avoid mixing waste of different flights and to minimize interferences of the work dynamics in the facilities. GG staff informed Ecoembes staff about the truck numbers carrying the waste under study. Ecoembes staff received the waste from the trucks at the GG loading dock and transported it to an area of the facility provided by GG for the development of the project. Next, trolleys were classified according to the stream from which they came (waste, galley, business and tourist menu). Differentiation could be done by sight, as every trolley used for each stream was different and the tableware was also distinguishable for each stream (Figure 4-5).

Waste trolley

Galley trolley

Business trolley

Tourist trolley

2nd tourist trolley

Figure 4-5 Visual distinction between trolleys

The trolleys were strapped and tagged to avoid mixing with those of different streams, and the trays with the menus and cutlery were taken to the washing process. Finally, the waste contained in the trolley was emptied directly into containers, to be transferred to the characterization zone. Here, it was stored until it was characterized. Depending on the work to be done, it could be characterized the same day or after 1 or 2 days. Figure 1-6 illustrates the process for each stream.

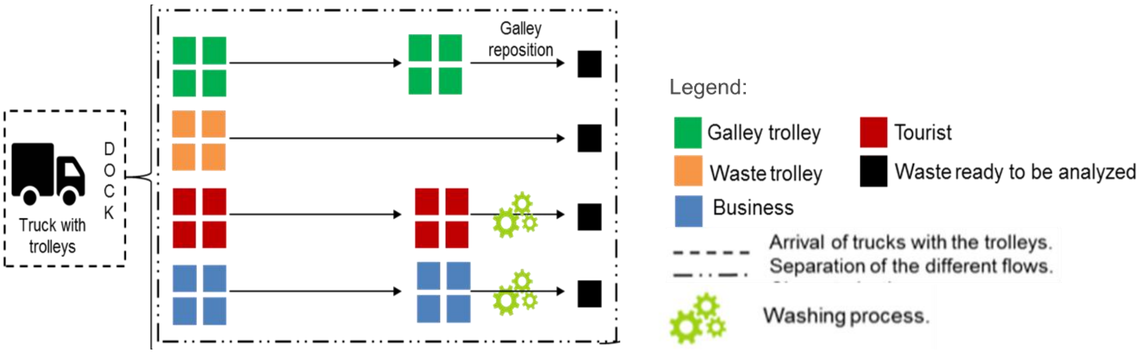

Figure 4-6 Processes for each waste stream

Ecoembes´ staff gathered the waste of the same types of flights, differentiating the 4 possible streams until a sufficiently big amount of waste (>3 kg) was obtained to carry out the characterization. For this reason, in short flights, where the generation of waste is low, the analysis accumulated waste from several flights. Waste was then classified by degree of manipulation and type of material. Finally, all the classified waste was weighted.

4.4. RESULTS AND DISCUSSION

4.4.1. WASTE GENERATION

In order to characterize the waste under analysis, the average weight per passenger and flight was computed. Table 4-5 shows the main results of this characterization out of Table 4-4 for each stream and type of flight.

Table 4-4 Complete database results

	Bulks	Number of flights	Total passengers	Galley trolley	Waste trolley	Business trolley	Tourist trolley	Total waste per bulk
National	1	10	527.5	2.56	40.58	12.11	-	55.25
	2	10	780.5	2.08	27.83	22.03	-	51.94
	3	10	652.5	6.31	24.47	11.66	-	42.44
	4	10	627.0	3.69	10.23	18.91	-	32.83
	5	10	602.5	-	37.7	7.9	-	45.6
European	1	8	551.0	2.48	27.72	25	-	55.2
	2	8	587.0	2.35	60.65	27.74	-	90.74
	3	8	621.5	1.76	19.32	19.1	-	40.18
	4	8	591.0	-	74.14	25.58	-	99.72
	5	8	519.0	5.46	15.07	25.83	-	46.36
	6	2	127.5	-	29.34	9.44	-	38.78
	7	2	136.5	-	15.13	-	-	15.13
	8	2	132.5	3.76	25.7	14.56	-	44.02
	9	8	555.0	-	81.73	17.91	-	99.64
	10	8	454.5	-	46.21	13.35	-	59.56
Short inter	1	4	229.0	-	22.63	9.62	-	32.25
Medium inter	1	1	87.5	-	13.01	8.39	6.55	27.95
	2	1	80.0	-	18.35	8.36	21.08	47.79
	3	2	94.5	5.51	22.85	20.32	35.22	83.9
	4	2	76.5	-	29.04	18.7	33.48	81.22
	5	1	64.5	-	19.18	-	21.68	40.86
Long inter	1	1	155.5	31.19	17.49	36.69	65.1	150.47
	2	1	171.5	5.34	21.54	31.96	62.01	120.85
	3	1	100.0	10.9	26.98	25.78	43.94	107.6
	4	1	136.0	14.97	26.32	37.18	38.74	117.21
	5	1	98.0	9.07	26.98	27.84	22.38	86.27
	6	1	98.0	26.45	42.44	30.48	32.94	132.31
	7	1	126.0	8.61	21.64	22.88	45.67	98.8
	8	1	125.0	10.38	19.79	22.49	46.84	99.5
	9	1	112.5	10.41	21.78	36.75	32.4	101.34
	10	1	146.0	17.87	37.06	45.17	47.14	147.24
	11	1	132.0	21.84	25.31	30.67	43.97	121.79
	12	1	170.5	36.34	38.39	29.87	50.06	154.66
	13	1	117.5	15.57	34.92	43.79	36.48	130.76
	14	1	145.0	47.27	45.11	53.47	57.17	203.02
	15	1	53.0	11.63	19.9	18.5	21.2	71.23
	16	1	65.0	10.61	21.94	26.5	26.11	85.16
	17	1	143.0	31.16	36.51	37.1	45.19	149.96
	18	1	175.0	10.18	49.31	37.21	38.65	135.35
	19	1	134.5	17.83	45.73	33.55	23.44	120.55
	20	1	134.5	13.5	21.66	17.33	23.38	75.87
	21	1	103.0	26.56	19.26	24.79	26.8	97.41
	22	1	99.0	31.57	8.91	15.15	34.38	90.01

Table 4-5 Waste generation per type of flight

		Waste streams				
		Galley trolley	Waste trolley	Business trolley	Tourist trolley	Total
National	Number of planes in the sample	20	25	25	0	25
	Number of flights in the sample	40	50	50	0	50
	Number of bulks analyzed	4	5	5	0	14
	Total kg	14.64	140.81	72.61	0.00	228
	Total passengers	5,175	6,38	724	5,656	6,38
	Average kg/flight	0.37	2.82	1.45	0.00	5
	Average kg/passenger	0.003	0.022	0.100	0.000	0.125
	Standard deviation of bulk weights	1.89	12.47	5.12	0.00	9
European	Number of planes in the sample	18	31	30	0	31
	Number of flights in the sample	36	62	60	0	62
	Number of bulks analyzed	5	10	9	0	24
	Total kg	15.81	395.01	178.51	0.00	589
	Total passengers	5,081	8,551	981	7,541	8,551
	Average kg/flight	0.44	6.37	2.98	0.00	10
	Average kg/passenger	0.003	0.046	0.182	0.000	0.231
	Standard deviation of bulk weights	1.48	24.73	6.52	0.00	29
Short international	Number of planes in the sample	0	2	2	0	2
	Number of flights in the sample	0	4	4	0	4
	Number of bulks analyzed	0	1	1	0	2
	Total kg	0.00	22.63	9.62	0.00	32
	Total passengers	458	458	57	401	458
	Average kg/flight	0.00	5.66	2.41	0.00	8
	Average kg/passenger	0.000	0.049	0.169	0.000	0.218
	Standard deviation of bulk weights	0.00	0.00	0.00	0.00	-
Medium international	Number of planes in the sample	1	5	4	5	5
	Number of flights in the sample	1	5	4	5	5
	Number of bulks analyzed	1	5	4	5	5
	Total kg	5.51	102.43	55.77	118.01	282
	Total passengers	95	403	54	350	403
	Average kg/flight	5.51	20.49	13.94	23.60	64
	Average kg/passenger	0.058	0.254	1.042	0.338	1.693
	Standard deviation of bulk weights	0.00	5.94	6.46	11.55	25
Long international	Number of planes in the sample	22	22	22	22	22
	Number of flights in the sample	22	22	22	22	22
	Number of bulks analyzed	22	22	22	22	66
	Total kg	419.25	628.97	685.15	863.99	2,597
	Total passengers	2,741	2,741	416	2,325	2,741
	Average kg/flight	19.06	28.59	31.14	39.27	118
	Average kg/passenger	0.153	0.230	1.647	0.372	2.401
	Standard deviation of bulk weights	11.01	10.84	9.48	12.77	31

Results show that the generation of waste per passenger and flight is larger for longer flights. Medium and long flights generate a much larger amount of waste than the rest of the flights. This is due to the fact that, on flights that exceed 3 hours, food is also served to the tourist class. Since the majority of the passengers are of the tourist class, the total residues increase in great amount.

Figure 4-7 depicts the relation between waste production per passenger (measured in kg of waste per passenger) and flight duration (in hours) for the four streams considered, as well as for the total quantity of waste.

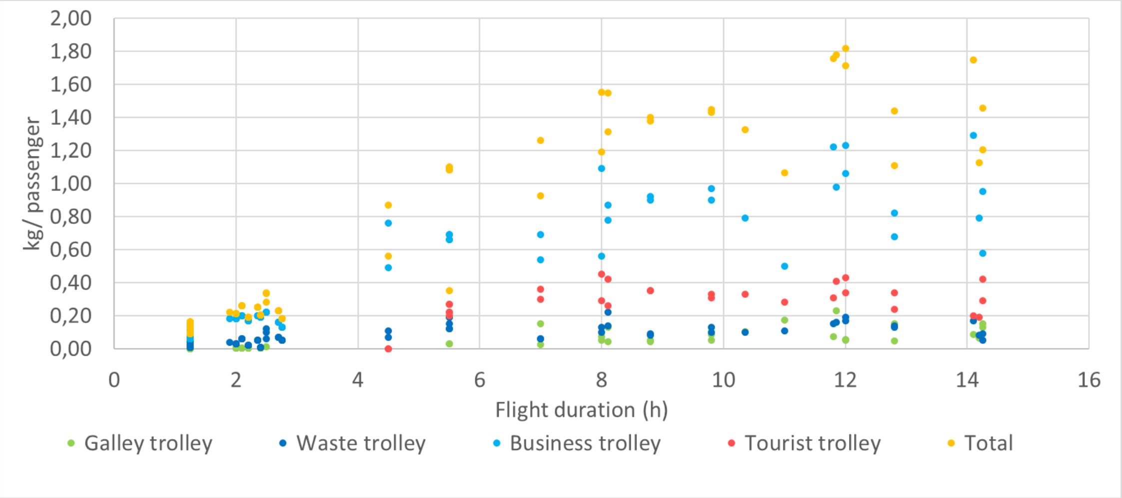

Figure 4-7 Waste generation per stream, passenger and flight duration

The interdependence between waste generation and flight distance is due to two main factors. The first factor is the length of the flight. The longer the flight is the more likely a passenger will order food or drinks from the on-board selling. This will generate waste from the galley and waste trolley streams. The other influencing factor is the increasing number of menus served when the flight lasts longer, both for the business and tourist classes. There is a positive correlation between waste generated per passenger and flight duration.

We also analysed whether for a particular menu the waste generated was larger the longer the flight. The first menu in the tourist class was analyzed for this purpose. The analysis shows that, for this particular menu, waste per passenger is smaller the longer the flight. This relation is shown in Figure 4-8.

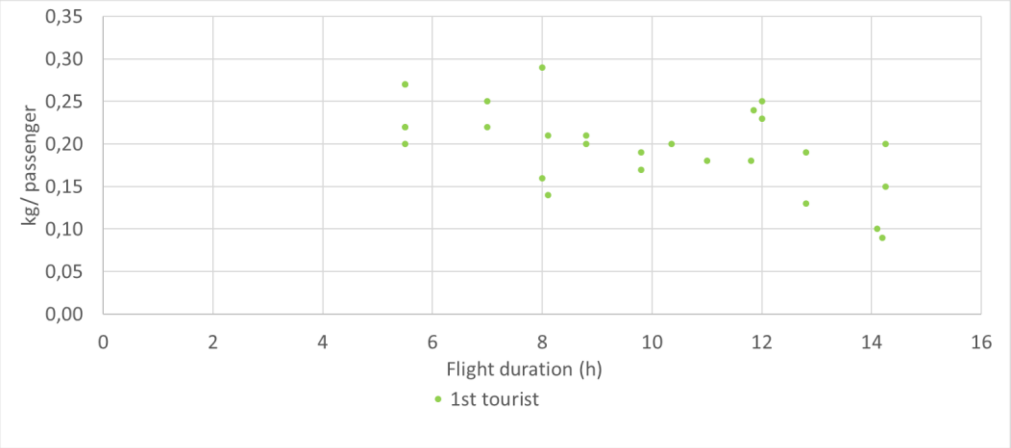

Figure 4-8 Waste generation for the 1st tourist menu per passenger and flight duration

There are two possible explanations why there is a smaller waste production per passenger in the long-distance flights for this certain menu than in shorter flights. First, it is likely that passengers eat more food during the servings in longer flights, producing less leftovers. Second, when flights are longer, passengers are more likely to keep some packed food from the menus in order to consume them at a later time during the flight. Waste composition and distribution

Waste coming from different streams was weighted. Table 4-6 presents the distribution of waste generation per stream, types of flight and material whether it has been manipulated or not.

Table 4-6 Distribution (%) of the waste generation per type of flight and stream

			Manipulated Material (%)								Unmanipulated material (%)			
	Streams	**%**	**Packaging**	**Liquid in packaging**	**Organic matter**	**Cutlery**	**Glass**	**Napkins**	**Paper and cardboard**	**Solid in packaging**	**Packaging**	**Organic matter**	**Liquid in packaging**	**Others (%)**
National	**Galley**	8	6.9	9.0	19.9	0.9	1.2	4.9	39.8	0.8	0.6	11.0	0.0	4.9
	Waste	60												
	Business	32												
	Total	100												
European	**Galley**	5	11.4	11.1	20.9	1.1	7.1	4.4	27.5	0.7	1.1	8.9	0.3	5.0
	Waste	63												
	Business	31												
	Total	100												

			Manipulated Material (%)								Unmanipulated material (%)			
	Streams	%	Packaging	Liquid in packaging	Organic matter	Cutlery	Glass	Napkins	Paper and cardboard	Solid in packaging	Packaging	Organic matter	Liquid in packaging	Others (%)
Short international	Galley	-	16.7	6.0	20.0	2.9	10.9	6.2	24.7	0.8	0.5	1.8	0.4	4.9
	Waste	67												
	Business	29												
	Total	96*												
Medium international	Galley	7	11.3	15.8	37.7	0.9	1.5	4.4	7.8	0.9	2.0	10.5	2.7	4.9
	Waste	33												
	Business	21												
	Tourist	39												
	Total	100												
Long international	Galley	14	13.3	8.0	31.0	1.0	7.0	2.6	13.3	1.0	2.1	12.4	3.8	4.9
	Waste	19												
	Business	22												
	Tourist	47												
	Total	100												

*Results show that national, European, and short international flights have a very similar waste distribution.

The waste collected via the general waste stream represents the largest proportion in national (60%), European (63%) and short international (67%) flights. In medium international flights, waste is mostly coming from the tourist and waste streams, respectively representing 39% and 33% of the total waste collected. In long international flights most of the waste corresponds to the tourist (47%) and business trolleys (22%).

For all waste streams, paper and cardboard and organic matter (both manipulated and unmanipulated) are the waste fractions with a higher contribution in weight. Paper and cardboard is the largest fraction collected in national flights (40%) and short international flights (25%), whereas organic matter dominates in European flights (30%). The high percentage of paper in the waste trolley fraction in national flights is mainly due to the newspapers that are offered in these short flights and the limited amount of other waste materials.

Organic matter represents 48% of the weight collected in the medium flights and 43% of the weight collected in longer flights. In long international flights, paper and cardboard represent a remarkably larger proportion (13.3%) than in the medium international flights (7.83%). This difference is particularly salient in the tourist stream where paper and cardboard represents 10.28% in international flights, whereas it represents 1.68% in the medium international flights. This is due to the cardboard packaging in which the tourist menu is offered in international flights (see Table 4-2).

In order to know from which stream the leftovers from the menus came from, the composition of unmanipulated waste that was analysed. Table 4-7 presents the distribution of unmanipulated waste per type of flight and waste stream.

Table 4-7 Percentage of unmanipulated waste over the total waste generation per type of flight and stream

Unmanipulated organic matter (%)		
National	Galley	1.3%
	Waste	0.4%
	Business	9.2%
	Total	**11.0%**
European	Galley	2.3%
	Waste	0.3%
	Business	6.3%
	Total	**8.9%**
Short international	Waste	0.0%
	Business	1.8%
	Total	**1.8%**
Medium international	Galley	0.0%
	Waste	1.6%
	Business	3.0%
	Tourist	5.9%
	Total	**10.5%**
Long international	Galley	0.8%
	Waste	0.5%
	Business	2.9%
	Tourist	8.2%
	Total	**12.4%**

For national, European and short international flights, the unmanipulated waste per passenger is mostly produced in the business class. This changes when food is served in the tourist class, which causes the tourist stream to become the highest contributor to unmanipulated organic matter waste in medium (5.9%) and long (8.9%) flights. This happens because some food is not consumed nor opened and because there are more tourist passengers by far. Figure 4-9 shows a representative picture exemplifying unmanipulated and manipulated packaged food waste.

Figure 4-9 A sample of unmanipulated packaging on the left and manipulated on the right

The packaging materials used differ depending on the type of flight. Table 4-8 presents the distribution of packaging waste material obtained from the characterization for every type of flight and stream.

Table 4-8 Percentage of different packaging materials related to the total packaging for each type of flight within each type of trolley

		Aluminum	Film	Color HDPE	Natural HDPE	Other Plastics	PET	PP	PS	PVC	Steel	Tetra pack	Wood
National	Galley	0.1%	2.6%	0.0%	0.0%	0.1%	1.4%	2.5%	0.5%	0.0%	0.0%	1.5%	0.0%
	Waste	11.9%	7.2%	0.1%	0.0%	2.2%	25.0%	12.7%	1.7%	0.0%	2.1%	5.7%	0.0%
	Business	4.0%	6.2%	0.0%	0.0%	2.1%	1.7%	1.0%	7.4%	0.0%	0.0%	0.0%	0.0%
	Total	**16%**	**16%**	**0%**	**0%**	**4%**	**28%**	**16%**	**10%**	**0%**	**2%**	**7%**	**0%**
European	Galley	0.0%	0.6%	0.0%	0.0%	0.0%	0.5%	0.2%	0.3%	0.0%	0.0%	0.3%	0.0%
	Waste	16.8%	9.9%	0.1%	0.0%	1.5%	26.7%	12.2%	1.5%	0.0%	3.8%	3.8%	0.0%
	Business	3.3%	7.0%	0.0%	1.5%	0.9%	3.9%	4.1%	0.7%	0.0%	0.4%	0.0%	0.0%
	Total	**20%**	**18%**	**0%**	**2%**	**2%**	**31%**	**17%**	**2%**	**0%**	**4%**	**4%**	**0%**
Short international	Waste	20.5%	11.0%	0.0%	0.2%	0.7%	29.1%	12.8%	0.9%	0.0%	2.5%	1.3%	0.0%
	Business	1.0%	5.4%	0.0%	1.0%	1.0%	5.9%	5.4%	0.6%	0.0%	0.6%	0.0%	0.0%
	Total	**22%**	**16%**	**0%**	**1%**	**2%**	**35%**	**18%**	**2%**	**0%**	**3%**	**1%**	**0%**
Medium international	Galley	0.0%	1.1%	0.0%	0.0%	0.1%	0.2%	0.0%	0.1%	0.0%	0.0%	0.2%	0.2%
	Waste	7.8%	3.2%	0.2%	0.0%	0.4%	8.8%	12.1%	0.6%	0.0%	0.1%	9.4%	0.0%
	Business	2.7%	3.6%	0.2%	0.0%	0.2%	1.1%	1.5%	1.3%	0.0%	0.3%	0.1%	0.0%
	Tourist	25.0%	5.4%	0.0%	0.0%	0.7%	1.6%	0.1%	11.5%	0.0%	0.0%	0.1%	0.0%
	Total	**36%**	**13%**	**0%**	**0%**	**1%**	**12%**	**14%**	**13%**	**0%**	**0%**	**10%**	**0%**
Long international	Galley	0.2%	1.3%	0.0%	0.0%	0.0%	0.7%	5.9%	0.1%	0.0%	0.0%	2.0%	0.1%
	Waste	4.4%	4.4%	0.0%	0.1%	0.2%	4.3%	5.1%	0.4%	0.0%	0.7%	3.5%	0.1%
	Business	2.4%	2.3%	0.1%	0.0%	0.0%	2.1%	2.4%	0.8%	0.0%	0.1%	0.1%	0.0%
	Tourist	22.4%	8.8%	0.0%	0.0%	0.8%	6.1%	7.4%	10.5%	0.0%	0.0%	0.1%	0.0%
	Total	**29%**	**17%**	**0%**	**0%**	**1%**	**13%**	**21%**	**12%**	**0%**	**1%**	**6%**	**0%**

For national flights, the most common packaging materials are PET (2.1%), PP (1.2%), Aluminum (1.2%) and Film (1.2%). For European flights, the contribution of these materials increase; PET (3.9%), Aluminum (2.5%), film (2.2%), and PP (2.1%). This is possibly due to the fact that passengers tend to order more drinks and food in longer flights.

For international flights, since in medium and long international flights menus are served in the tourist class, there are differences in the packaging material composition of waste: the main contributors are almost the same but the contributions differ in percentage. In short international flights, the dominant materials are PET (10.5%), PP (6.3%), film (5.8%) and aluminum (5.6%). In medium international flights the most common materials are aluminum (13.3%), film (7.7%), PP (5.7%), PET (5.2%) and PS (5.1%). Finally, waste in long international flights mainly contains aluminum (19.3%), PP (18%), film (12.3%), PET (9.7%) and PS (7.4%).

The menus served in the tourist class in medium and long international flights increase the presence of certain materials such as aluminum packaging waste, including lids, food dishes, and some drinks. There is also an increase in PP due to the single use cups. The film waste, used in bags that wrap the cutlery or to cover certain foods, also increases. PET, present in packaging such as water bottles, and PS, mainly used in yogurt packaging and plastic dish lids, also increase.

An estimation of the overall distribution of the cabin waste generated by Iberia planes landing in Barajas airport in 2016 was computed taking into account the actual distribution of planes per type of flight, provided by Iberia. The distribution of flights depending on their origin is national (27%), European (49%), short international (3%) medium international (2%) and long international (19%). Table 4-9 presents the estimated distribution of waste materials.

Table 4-9 Estimated overall distribution of waste materials of planes landing in Barajas airport (2016)

Materials (%)		
Manipulated	Packaging	11%
	Organic matter	23%
	Napkins	4%
	Cutlery	1%
	Paper and cardboard	28%
	Solid in packaging	1%
	Liquid in packaging	10%
	Total	**83%**
Unmanipulated	Packaging	1%
	Organic matter	10%
	Liquid in packaging	1%
	Total	**12%**
Others	Others	5%
	Total	**5%**

Results show that the predominant material in planes landing in Barajas airport is organic matter (33%), followed by paper and cardboard (28%) and packaging (12%). As expected, the overall percentage in weight of manipulated material is higher than that of unmanipulated material. It is estimated that 83% of the waste of all flights is manipulated. However, there is still 12% of unmanipulated food which becomes waste, indicating that there is still room to reduce food waste by increasing the catering service efficiency.

4.5. CONCLUSIONS AND RECOMMENDATIONS

Waste characterizations are necessary to analyse the current management system situation and to introduce improvements in the waste management process allowing an increase of efficiency and a reduction of environmental impact of the system.

Our study shows that the generation of waste in airplanes increases with flight duration (h). There is a quantitative leap in waste generation in medium and long International flights. This is because, in these flights, food is served for the tourist class passengers, who are the majority. Due to this increase in menu service, organic matter is the main waste fraction in medium and long flights (respectively representing 48% and 44%). The study also finds that unmanipulated waste increases with flight duration. However, less waste per passenger is generated in the first tourist menu served when the flights are longer.

Food waste is estimated to account for 33% of the total waste generated in flights. Several measures could be undertaken to reduce food waste. First, companies could study the kinds of food that are found in the leftovers. This would give them information about what changes are necessary on the menus that are offered. A possible alternative would be to allow passengers to choose the desired menus, including an adapted menu for children, during the online check-in. Some airlines like Qantas have already implemented this function (“Menu Select | Qantas ES,” 2018). Avoiding to serve snacks and drinks with short expiration dates would minimize the generation of waste in the galley trolley. Finally, it is to be noted that organic matter is nowadays taken to landfills. Taking this waste to energy recovery plants to produce biogas should be studied, since it could potentially improve the carbon footprint of the system. For this, a change in the CE 1069/2009 Regulation is required.

In national, European and short International flights, the main waste fraction is paper and cardboard, mostly magazines and newspapers (correspondingly representing 40%, 27% and 25%). An alternative to reduce this kind of waste would be to replace the newspapers and magazines with digital media on the seat screens, whenever possible. This could reduce waste generation on flights under 3 hours long around 30%.

Our analysis estimates that packaging represents 12% of the cabin waste. There are numerous plastic packages that can be separated on board from the rest of waste to follow a recycling process. On the other hand, given that most packaging waste comes from individual drinks, in order to decrease it, airlines could opt to replace individual packaging with larger formats pouring the drinks directly in glasses. This would allow reducing the packaging weight per product weight ratio.

The results of the present study indicate that waste management in airplanes can be improved. Nowadays, the waste collection method in place does not separate the different types of materials. Therefore, recycling requires an important effort to classify materials at the sorting plants. In order to facilitate this process, we recommend separating recyclable from non-recyclable waste during the flight. This would be possible by replacing the current waste trolley, which has a single compartment, by trolleys which allowed separation.

The separation of waste in the cabin would optimize the system and increase the process efficiency.

5. ECODESIGN IN THE AVIATION CATERING TABLEWARE

Aalready published as:

Blanca-Alcubilla, G., Bala, A., de Castro, N., Colomé, R., & Fullana-i-Palmer, P. (2020). *Is the reusable tableware the best option? Analysis of the aviation catering sector with a life cycle approach.* Science of the Total Environment, 708, 135121.

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5.1. ABSTRACT

The menus served during the flight are quite similar between different airlines and are composed of the food itself, packaging (paper envelopes, film, etc.) and tableware (mainly trays, plates, glasses, cups and cutlery). In 2016, 1,522 tonnes of tourist class menus were served in Iberia aircrafts landing at Barajas airport in Spain. From this amount, 51% by weight was packaging and tableware, and the remaining 49% food.

As changes in the food have little room for improving, since the same amount would be delivered regardless how it is served, this study focuses on the possibilities of packaging and tableware to reduce GHG emissions. The assessment has been done using life cycle assessment methodology (LCA) in order to identify the hotspots along the whole life cycle of packaging and tableware items. The case study chosen was the catering service of Iberia, the national airline of Spain. The functional unit used was “the service of 1,000 tourist class menus on Iberia flights that landed in Madrid in 2016”.

The results show that the impacts of reusable and single use items take place at different stages of their life cycles. For reusable ones, 76% of the impact is produced during the flight phase, meanwhile, for single use ones, 53% of the impact comes from the production stage.

Variables such as material, weight and the number of reuses can greatly influence (GHG) emissions. From the results of the analysis some eco-design strategies have been proposed and analysed. The paper reveals that the lighter single-use packaging and tableware for airline catering are less harmful under a life cycle perspective become.

5.2. AVIATION CATERING RELATED IMPACTS ON THE ENVIRONMENT

5.2.1. AVIATION AND PLASTICS

Tonnes of plastic packaging and other items are arriving to our seas, affecting the marine ecosystem (Eriksen et al., 2014). Current plastic recycling rates are quite low at the global level, being these between 14 - 18%. The rest of plastic waste ends up incinerated (24%), or disposed of in landfill or the natural environment (58 - 62%) (OECD, 2018). Recycling rates for plastics in the EU average 30% (European Parliament, 2018) and plastic pollution is expected to double in the next 20 years (World Economic Forum, 2020). Therefore, the European Commission is currently developing measures in order to ban certain single use plastics by 2021. The ban will apply to single use plastic items such as cotton buds, cutlery, plates, straws, drink stirrers and sticks for balloons (European Commission, 2018).

As can be noted, most of the listed items are used in the catering sector. This prohibition will result in the use of other materials for the manufacture of the above mentioned items. The materials commonly used in reusable items (e.g. glass and metals) tend to be heavier than the single-use ones (Garrido & Alvarez del Castillo, 2007). As can be easily deducted, in the case that those prohibited single-use items are used in aviation catering services, not only the production or end of life stages should be considered, but also the use stage, since this stage could be a high contributor to the overall GHG emissions.

For sure, this European proposal is going to affect the environmental impact of the aviation catering sector. Single use items will probably be substituted by reusable ones, increasing the transported weight (other single use alternatives, such as bamboo and bioplastics have other environmental issues, such as eutrophication (Wu et al., 2009), land use (Piemonte & Gironi, 2012) and ecosystem destruction (J. Liu et al., 2011). Therefore, GHG emissions related to catering will increase in the aviation sector, a fact against the international goals to fight climate change (United Nations, 2015).

In 2016, 1,522 tonnes of tourist class menus (776 tonnes of packaging and tableware, and 746 tonnes of food) were transported by the Iberia aircrafts landing at Barajas airport, having a direct effect on the overall GHG emissions of flights.

In addition to the flight stage, the production of food (Mattsson, 1999), packaging (Ligthart et al., 2007, Madival et al., 2009, Poovarodom et al., 2012) and tableware (Postacchini et al., 2016), as well as their management as waste (Cherubini et al., 2009, Guo et al., 2014), also generate GHG emissions along their life cycle (Hanssen et al., 2017).

5.2.2. AVIATION AND FOOD WASTE

One way to reduce the impact of catering services is by reducing the amount of food waste (Hoehn et al., 2019, Garcia-Herrero et al., 2018b, Williams & Wikström, 2011, Bogner et al., 2008). EU-28 produces about 100 Megatonnes of food waste every year (FUSIONS, 2015). If we consider that every tonne of food waste emits 2.27t CO_2 eq., this results in 227 Mt of CO_2 eq. emitted per year, taking into account the full life cycle for the food (Timmermans, 2015), representing ~ 5% of total EU28 GHG emissions (European Environment Agency, 2018). In this sense, efforts are already being made within the Zero Cabin Waste project (Zero Cabin Waste, 2016) to analyze what type of food is most often found in the leftovers of airplane catering to replace it with another, thus reducing the organic matter waste.

Another way to reduce the food carbon footprint would be to modify the type of food offered in the menus (Stehfest et al., 2009; Batlle-Bayer et al., 2019). It is true that the food production phase has the greatest impact on the food life cycle and that a diet with less meat products has a lower carbon footprint (Scarborough et al., 2014; Clune, Crossin, & Verghese, 2017), although it is very important to compare products including their nutritional value as well (Batlle-Bayer et al., 2019). However, due to commercial reasons inherent to the airline, apart from measures such as a fully vegetarian menu, many changes in the food amount served in the menus are not possible. On the other hand, the substitution of heavy packaging materials for lighter ones, such as glass for plastic, could reduce emissions during the transport phase (Humbert et al., 2009).

Taking into account that the amount of weight transported due to the packaging and the tableware is higher than that of the food itself, it certainly makes sense using the life cycle assessment methodology (LCA hereafter) to analyze and improve the system. LCA has been applied to know the impact of each catering element through their individual life cycle stages, as well as to identify which variables (such weight or number of uses) have the main contribution to the overall impact. Improvements in design can only be properly targeted if hotspots are well known.

5.3. METHODOLOGY AND DATA

Gabi Professional software was used to model the systems. The selected characterization method employed was the one recommended by the Single Market for Green Products Initiative by the European Commission, for the so-called Product Environmental Footprint (PEF) (European Commission, 2012). Since climate change is the most relevant environmental impact category for the aviation sector, subjected to strong regulation targets, the results of this paper focus on this particular impact category. In relation to the other above mentioned issue which is most relevant to the European Commission, plastic pollution, no methodology of including marine littering into LCA has been developed yet, although some initiatives have started (Civancik-Uslu et al., 2019).

5.3.1. GOAL AND SCOPE

The objective of this study is to evaluate the GHG emissions of the existing catering service provided to Iberia by the catering operator Gate Gourmet (GG) at Barajas airport (Madrid, Spain). This has been done from a life cycle perspective to be able to identify those stages where there is a potential GHG mitigation.

5.3.2. FUNCTIONAL UNIT

The functional unit (FU) of the study is “the service of 1,000 tourist class menus on Iberia flights that landed in Madrid in 2016”. GG is the main catering service in Madrid airport, and its service to Iberia represents 76% of the total menus served by the company in that airport and year (Figure 5-1).

Figure 5-1 Tourist menu

5.3.3. SYSTEM BOUNDARIES

The stages included in the analysis are: production and manufacturing of the different materials of which the packaging and the tableware are made of, transport up to GG facilities, transport up to the airplane, flight phase, catering discharge from the aircraft to GG facilities, washing of reusable items, and end of life treatment (landfilling). For reusable items an average number of 10 uses before its end of life has been used. The transport to the landfill as well as the credits due to energy recovery (for the paper fraction) have been also taken into account (see Figure 5-2).

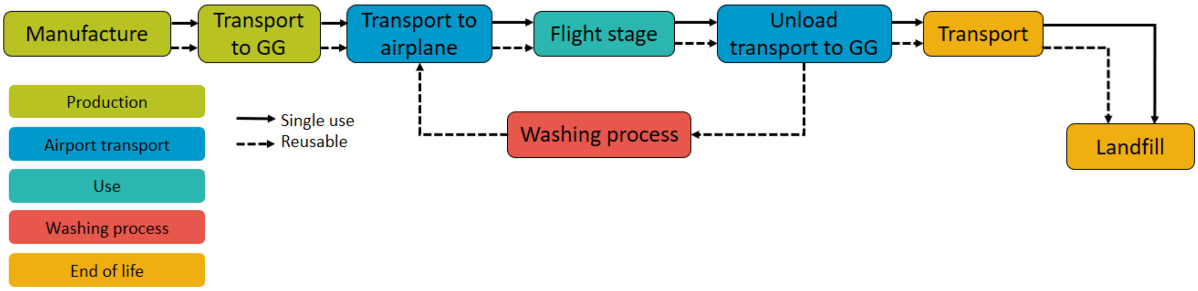

Figure 5-2 Studied system

5.3.4. INVENTORY

The life cycle inventory was built by means of the information provided by GG.

Table 5-1 summarizes the material of each tableware item present in the menu, as well as its weight, its reusability or not, and the number of uses considered, whereas Table 5-2 summarizes the parameters used for the transport stages.

Table 5-1 Tableware characteristics

Item	Material	Weight	Reusable	Number of uses	Weight per functional unit (kg)
1st course	ABS	0.0280	YES	10	2.8
1st course lid	PS	0.0042	YES	10	0.42
2nd course	Aluminum	0.0079	NO	1	7.9
2nd course lid	Aluminum	0.0043	NO	1	4.3
Butter packaging	PP	0.0007	NO	1	0.7
Coffee creamer packaging	PP	0.0007	NO	1	0.7
Coffee cup	Paper	0.0200	YES	10	2
Condiments film	LDPE	0.0005	NO	1	0.5
Condiments packaging	Paper	0.0003	NO	1	0.3
Condiments washcloth	Cellulose	0.0020	NO	1	2
Condiments packaging 2	Paper	0.0002	NO	1	0.2
Cutlery set film	LDPE	0.0008	NO	1	0.8
Cutlery set napkin	Cellulose	0.0031	NO	1	3.1
Cutlery set	Steel	0.0713	YES	10	7.13
Dessert course	ABS	0.0280	YES	10	2.8
Dessert lid	PS	0.0042	NO	1	4.2
Drink cup	ABS	0.0254	YES	10	2.54
Tablecloth	Paper	0.0050	NO	1	5
Tray	PP	0.2000	YES	10	20

Table 5-2 Truck transport inventory

Stage	Distance (km)	Utilization (%)	Payload (t)	Gross weight (t)
Manufacture-GG	607	85	22	From 28 to 34
GG-Airplane	8.3	85	3.3	7.5
Airplane-GG	8.3	85	3.3	7.5
GG -landfill	32	85	17.3	From 20 to 26

All data regarding truck types and transport distances were provided by the catering (GG) and the waste management operator (Ferrovial). The truck utilization rate used was the default one in the GaBi database except for the transport stage between GG facilities and the sorting plant, as there were foreground data available from Ferrovial. Payloads used were also the predefined ones in the GaBi database for each type of truck.

5.3.5. ASSUMPTIONS

The flight distance was set at 2,500 km (outbound EU flight average distance served for tourist menus) and the chosen utilization rate of the aircraft was 82% for an A330 with payload capacity of 65t (Iberia, 2016).

All waste materials were considered to go to landfill. It is necessary to clarify that international catering waste (ICW) is not considered hazardous waste when the planes are traveling within EU territory only, and it is classified as Cat3 waste. However, in flights from countries not included in EU territory, ICW is considered as animal by-product and, therefore, classified as high-risk Cat1 waste. It is assumed that a potential risk of the spread of animal diseases exists, being dangerous both to animal and human health, if not properly disposed of. The European Parliament regulates the way in which ICW can be disposed of, and waste classified as Cat1 must be disposed of by burial in an authorized landfill according to the EU 1069/2009 Regulation (European Parliament, 2009).

The type of landfill used includes landfill gas utilisation and leachate treatment and without collection, transport and pre-treatment.

5.4. RESULTS

The GHG emission distribution to each of the studied stages are shown in Table 5-3.

Table 5-3 GHG emission distribution

Production	Transport	Flight	Washing	End of life
29.13%	0.28%	62.81%	4.01%	3.78%

For this menu composition, the flight stage is the one where most of the GHG gases are emitted.

The results of the CO_2 eq. emissions from each analyzed item life cycle, for the chosen functional unit, are shown in Figure 5-3. Clearly, the reusable items group is the one that generates most of the impact (73.5% in total).

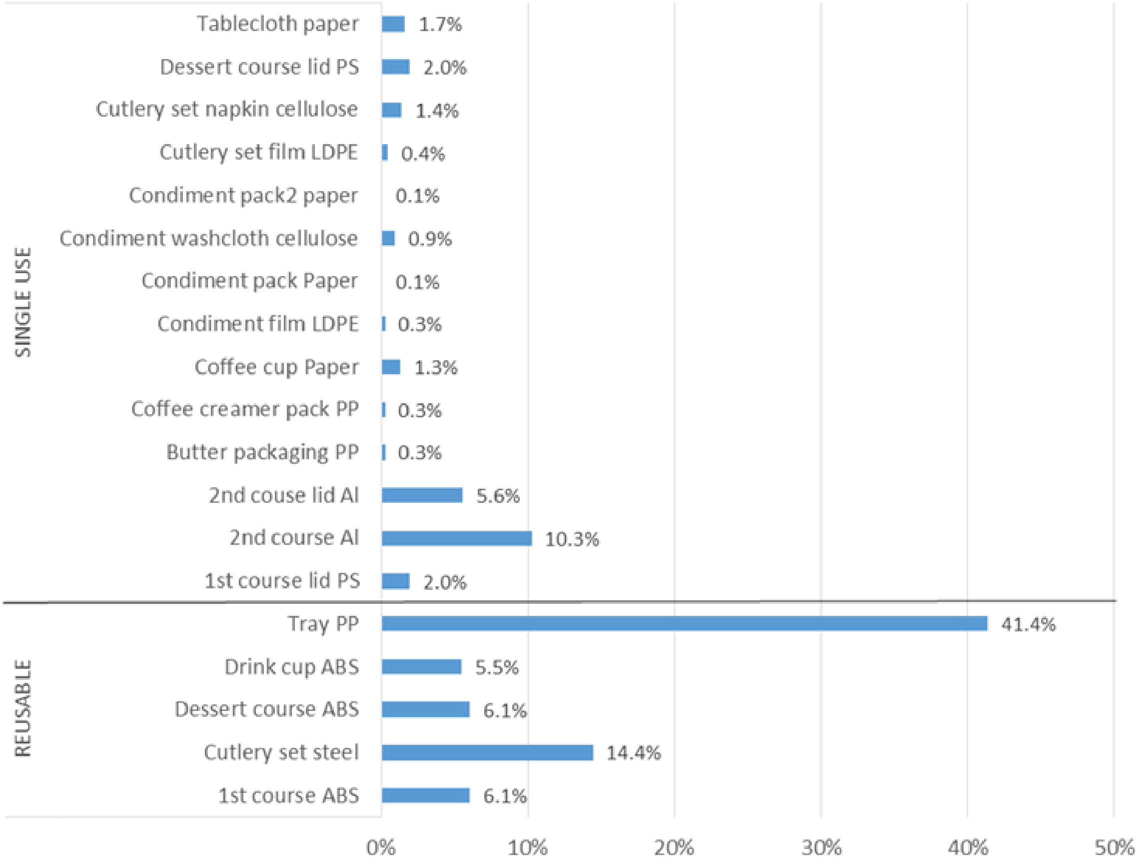

Figure 5-3 Contribution to global warming potential per item

In addition, Tables 5-4 and 5-5 show how the impact of each item is distributed along their life cycle.

Table 5-4 Distribution of CO2 eq. Emitted by the reusable items in each stage

	Production	Airport transport	Flight	Washing	End of life	Total kg CO2 eq.
1st course ABS	19.82%	0.32%	74.15%	5.24%	0.46%	50.00
Cutlery set steel	14.33%	0.35%	79.37%	5.61%	0.34%	119.46
Dessert course ABS	19.82%	0.32%	74.15%	5.24%	0.46%	49.95
Drink cup ABS	19.82%	0.32%	74.15%	5.24%	0.46%	45.31
Tray PP	11.12%	0.34%	77.77%	5.50%	5.28%	341.45

Table 5-5 Distribution of CO2 eq. Emitted by the single use items in each stage

	Production	Airport transport	Flight	End of life	Total kg CO2 eq.
1st course lid PS	63.23%	0.15%	34.49%	2.13%	14.91
2nd course Al	87.05%	0.05%	12.37%	0.53%	78.22
2nd course lid Al	87.05%	0.05%	12.37%	0.53%	42.58
Butter packaging PP	57.28%	0.18%	40.07%	2.47%	2.14
Coffee creamer pack PP	57.28%	0.18%	40.07%	2.47%	2.14
Coffee cup Paper	21.25%	0.21%	48.43%	30.11%	10.11
Condiment film LDPE	69.45%	0.13%	28.65%	1.77%	2.14
Condiment pack Paper	21.25%	0.21%	48.43%	30.11%	0.76
Condiment washcloth cellulose	50.56%	0.15%	35.24%	14.05%	6.95
Condiment pack2 paper	21.25%	0.21%	48.43%	30.11%	0.51
Cutlery set film LDPE	69.45%	0.13%	28.65%	1.77%	3.42
Cutlery set napkin cellulose	50.56%	0.15%	35.24%	14.05%	10.77
Dessert course lid PS	63.23%	0.15%	34.49%	2.13%	14.91
Tablecloth paper	21.25%	0.21%	48.43%	30.11%	12.64

For reusable items, most of the CO_2 eq emissions take place in the flight stage while, for single-use items, the majority of the impact takes place in the production stage. In order to reduce the GHG emissions in different stages of the life cycle, several eco-design strategies were tested.

5.4.1. ECODESING STRATEGIES

Steel cutlery was taken as an example, since it is the second item with the highest emissions during its life cycle and has different easily comparable design alternatives.

The effects on the results of some key variables were analysed through a sensitivity analysis: number of uses, flight distance and weight. Figure 5-4 depicts how the number of reuses influences the GHG emissions in some of the life cycle stages.

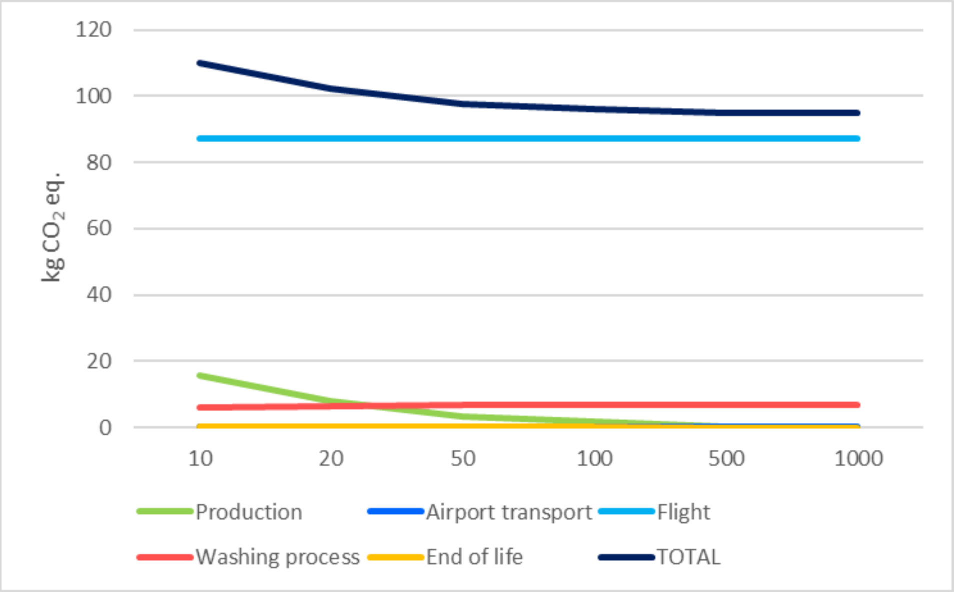

Figure 5-4 kg of CO2 eq. For steel cutlery for different number of reuses

Production stage is the one that is affected the most by an increase of reuses. GHG emissions in the production stage decrease as more reuses need less cutlery production.

For the transport stages (airport transport stage and flight), reusing the cutlery has no GHG reductions as the weight is the only factor that contributes in this case. Flight stage is the one that contributes the most to the global impact. Although the impact slightly increases in the washing phase, the overall impact decreases by 12.6%, if the reuses increase from 10 to 100 (Table 5-6).

Table 5-6 Total kg of CO2 eq. For steel cutlery for different number of reuses

Reuses	Total kg CO2 eq.
10	110.0
20	102.3
50	97.6
100	96.1

Being the flight stage the stage which contributes most to CO_2 eq. emissions, an asymptote near to 100 reuses occurs with no GHG improvements thereafter.

Another variable affecting the impact of reusable cutlery is the flight distance (Figure 5-5).

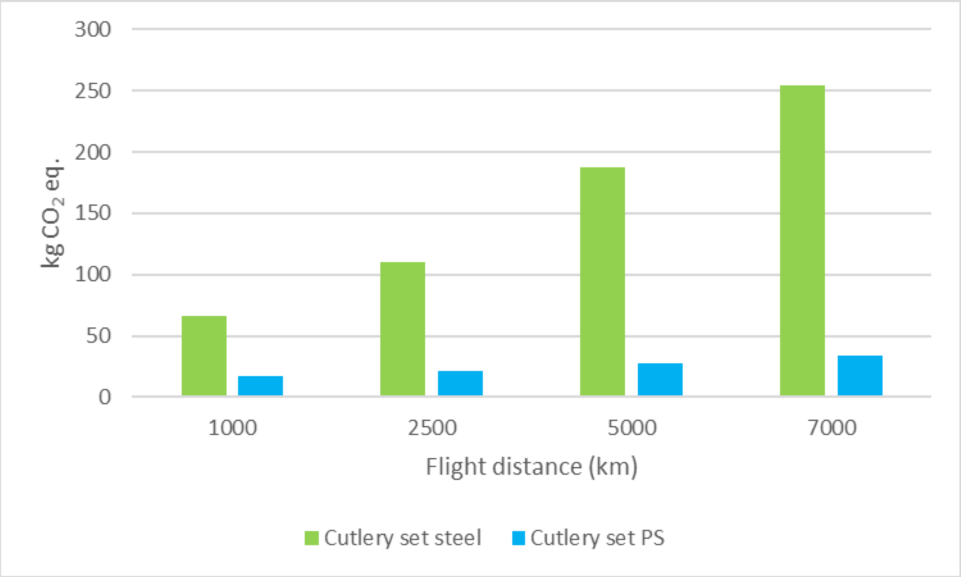

Figure 5-5 kg CO2 eq. Emitted for the steel and y PS cutlery according to different flight distances

The results have been compared with those that would be obtained if metal cutlery was replaced by single-use plastic. Plastic cutlery is made of PS, with a weight of 6 g (compared to 71 g by the metal cutlery), and its end of life scenario is landfilling.

As can be expected, the greater the flight distance, the greater the emissions. It can be observed that, if the steel cutlery were replaced by others of PS of a single use, the environmental impact for its entire life cycle would be 80% lower in a 2.500km long flight (the one assumed to be representative).

Two other eco-design measures were tested (Figure 5-6). If weight reduction measures were taken for the metal cutlery, a proportional reduction in the environmental impact would be obtained.

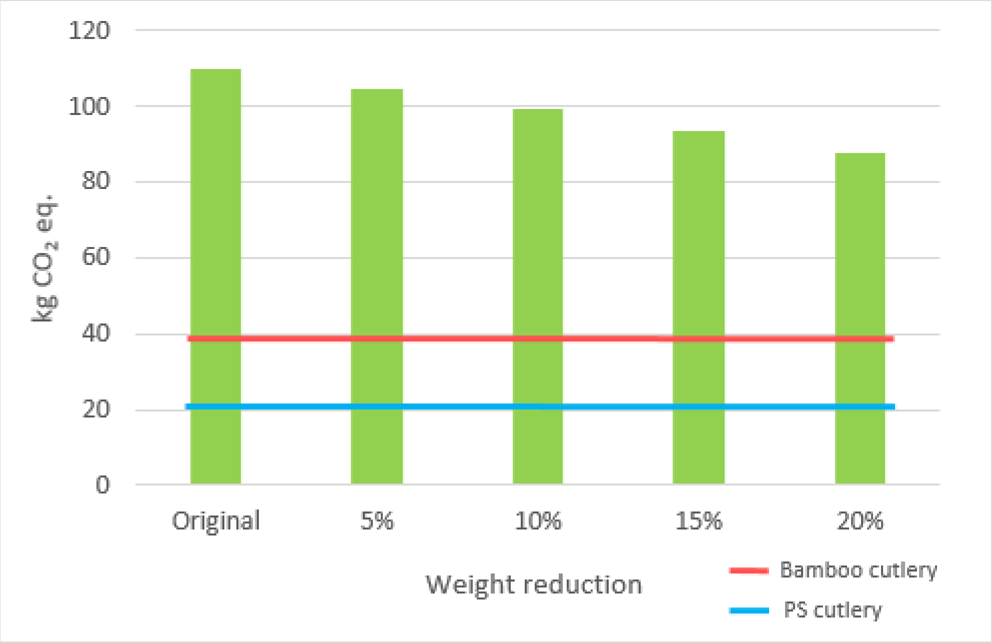

Figure 5-6 Comparison of kg CO2 eq. Emitted by the steel cutlery with respect to the PS and bamboo, if the weight of the reusable solution was reduced

In addition, an alternative solution to plastic was added to the analysis, single-use bamboo cutlery was added to the analysis too, with 26 g of weight, and considered to be landfilled at the end of life.

Even with a 20% weight reduction, PS cutlery GHG emissions would still be 76% lower. Bamboo cutlery would be 56% better than reusable metal as well, and would have about double the emissions of the PS solution. Of course, other impact categories may point in different directions.

5.5. DISCUSSION

The choice of the most environmentally sustainable catering material in the case of aviation will depend on the impact of manufacturing, weight, number of uses, and recyclability. Aluminum materials have a high manufacturing impact compared to other single-use materials. For example, the aluminum lid of the second plate has a similar weight (4.3 g) to the plastic lid PS of the first plate (4.2 g). However, the overall impact of the aluminum lid is almost three times higher than that of PS (42.59 and 14.91 respectively). Therefore, for light single use packaging, when selecting the material, the focus should be made on the manufacturing stage impacts.

In this case, almost 63% of the total emissions are produced during the flight, this is why it is really important to take into consideration the weight when reducing the overall impact. Indeed 73% of the total impact is produced by reusable items (5 out of 19) which are heavier than the single use ones.

The number of uses has only a relevant effect on the manufacturing stage. Increasing the number of reuses will reduce manufacturing impacts but not flight stage impacts. Nevertheless, reusable items are normally heavier than single use ones so they are expected to generate more GHG emissions due to the flight stage.

Finally, it is worth mentioning that the current Regulation for this cabin catering waste does not allow it to be recycled. Thus, a change of this European Regulation is needed, as this waste can be sterilized previously and be led to a recycling process reducing the overall impact.

5.6. CONCLUSIONS

For reusable items used in aviation catering services, ecodesign strategies should focus on minimizing the weight of the item while increasing the number of possible reuses up to 100. On the other hand, for single-use items, strategies should focus on the production stage (changing materials or decreasing their weight). To summarize, the best solution for the catering in the aviation sector, attending the climate change impact category, would be to use lightweight materials, allowing several uses, a controlled collection system (which would avoid littering), and an easy way to recycle. Nevertheless, further investigation, regarding PS and bamboo alternatives, is needed to add other impact categories to the analysis, such as land use, toxicity or eutrophication potential.

This analysis has been done taking into account the current ICW regulations, which only allow landfilling of catering waste coming from non-European countries. If some changes in these regulations occur, it would be interesting to consider the analysis of alternative end of life scenarios including incineration and recycling.

On the other hand, given the current intention to prohibit certain single-use plastics (including cutlery, plates, cups...) by the European Commission (European Commission, 2018), we recommend the use of the LCA methodology to know, in each case and for aviation in particular, if the use of these items is environmentally more beneficial or not. In cases where transport is the dominant stage, as in aviation, it can be observed that much lighter single-use items generate less GHG throughout their complete life cycle.

6. ECOEFFICIENCY IN THE AVIATION CATERING WASTE MANAGEMENT THROUGH LIFE CYCLE ANALYSIS AND LIFE CYCLE COSTING

Submitted as:

Gonzalo Blanca-Alcubilla, Alba Bala, Joan Ribas, Pere Fullana-i-Palmer. *Ecoefficiency in the aviation catering waste management through Life Cycle Analysis and Life Cycle Costing.* Under review.

6.1. ABSTRACT

The aviation sector has shown continued growth in the recent years before Covid-19 pandemia. With the increase in passengers, who consume food and drinks during the flight, waste generation increases. Aviation is also in constant search for solutions to reduce the environmental impact of its activity. One of the solutions may be to have a better waste management system. The study carried out, within the framework of the LIFE Zero Cabin Waste Project, suggests implementing separate waste collection on the plane, increasing the recyclable fraction and stablishing the organic matter fraction management, which generally ends up in landfills, by means of bio-digestion. Using life cycle assessment and life cycle costing methodologies, not only the environmental but also the economic performance of the existing management system in 2016 (system A) is compared with that proposed throughout the project (system B) for the treatment of 1,000 kg of catering waste. The results show that, with the management system change, the contribution to several environment impact categories, such as the fossil resources depletion, acidification or global warming, would decrease. In fact, the carbon footprint of the alternative management system is reduced by 85%. This operational change needs an initial outlay that increases operational costs by 5%. However, the ecoefficiecy of system B is greater for most of the environmental categories than for system A. For instance, Global Warming Potential ecoefficiency increases by 84%.

6.2. AVIATION CATERING WASTE MANAGEMENT

Landfilling rates in EU-28 are decreasing year after year as a result of the implementation of the Directive 31/1999 on landfills and the Directive 62/1994 on packaging and packaging waste, and their goals on reducing disposal rates. MSW landfilled in EU-28 dropped from 64 % in 1995 to 23 % in 2017 (Eurostat, 2019b). Recently, the development of the Directive (EU) 2018/850 on the landfill of waste has stated that, by 2030, waste suitable for recycling or for any other recovery option will not be permitted to be disposed of into a landfill, which will keep the landfill rates decreasing (European Parliament And The Council Of The European Union, 2018).

Notwithstanding this effort, the overall EU-28 landfill rate is still 45.7%, while in Spain it is 53.6%, being above the average (Eurostat, 2019a).

The final disposal of waste in landfills is still a cheap practice in some European countries and as a result a still economically profitable activity. The cheapest is Lithuania (3 €/t) while the most expensive is Belgium (100 €/t). In the case of Spain, prices vary between 7 € and 41 €/ton (CEWEP, 2017). However, the environmental costs are high. Organic matter, which is degraded in landfills, emits enormous quantities of GHG, being methane and carbon dioxide the dominant ones. Globally, in 2010, approximately 11% of the estimated global methane emissions, nearly 800 million tCO_2 eq. were produced in landfills, and which were the third largest anthropogenic source of methane (*The Global Methane Initiative (GMI)*, 2011). When only regarding food waste, from 0.57 to 2.97 t CO_2 eq (depending on the percentage of CH_4 captured) are emitted per tonne of food waste landfilled (Moult et al., 2018). Taking into account that 88 million tonnes of food waste are produced in EU-28 (Åsa et al., 2016), CO_2 eq. emissions coming from this source are between 50.2Mt and 261Mt per year, currently representing between 2 and 6 percent of total EU27 GHG emissions (Eurostat, 2020).

6.2.1. CASE UNDER STUDY

In the LIFE Zero Cabin Waste project case, 63% of the 4,597 tonnes produced due to the catering activity for Iberia in Barajas airport in 2016 were Cat 1. Therefore, 2,877 tonnes of Cat 1 went straight to landfill. From the Cat 3 waste fraction, 60% was not recovered and, as a result, 1,028 tonnes more ended up in landfills. This means that, in 2016, the total amount diverted to landfills was about 3,905 tonnes.

The transversal collaboration of all the agents involved in the management system (airline, catering, green dot holder, waste management companies, and research institutions) is essential in dealing with the problems previously described.

Some eco-design measures have been proposed to change the waste management system. Firstly, the waste trolleys on board have been replaced with others which have two compartments. This change allows separating the recoverable waste from the rest, obtaining cleaner and easier recyclable fractions. Furthermore, in the case of flights where Cat 1 waste is produced, the new trolleys allow to recover onboard recoverable materials that have not been in contact with waste from animal origin; thus, they can be managed as Cat 3. This leads to an increase of recoverable materials going to a recycling process instead of going to landfill.

Next, after being downloaded from the plane and taken to the caterer facilities, the waste was classified by differentiating Cat 1 from Cat 3. On the one hand, Cat 3 waste followed a recycling process after passing through a sorting plant. Inorganic materials were sent to a recycler, while the organic matter was sent to a composting process and the rejected materials ended up in a landfill. On the other hand, if the current legislation regarding Cat1 waste management allowed it after being changed, Cat 1 waste would be taken to a sterilization process after which, the organic matter would enter a bio-digestion process, significantly reducing the amount of organic matter that ends up in the landfill and, therefore, reducing also the associated GHG emissions (Lee et al., 2017). Other materials not sorted on the plane would end up in landfills.

6.3. LIFE CYCLE ASSESSMENT AND LIFE CYCLE COSTING

After learning about the situation of catering waste produced in the aviation sector, and the intention of establishing a waste management system that reduces the overall environmental impact of the catering system, the need to evaluate the environmental performance of an alternative management model vs the existing one arises. For this, the Life Cycle Assessment (LCA) methodology was used, since it allows to compare the environmental performance of both the original system (system A) and the alternative one (system B) (Bala et al., 2020). In this way, we were able to know those factors that contribute to reducing the impact and to what extent. LCA in the aviation industry is mostly related to inherent points such as construction materials (Calado et al., 2018; Timmis et al., 2014; and Beck et al., 2011) or fuels (Bicer & Dincer, 2017; de Jong et al., 2017; and Pereira et al., 2014).

There are waste management LCA in other sectors, such as the one performed by (Cherubini et al., 2009) on waste management strategies on packaging, accompanied since long ago by many others in landfilling (Rieradevall et al., 1997) or incineration (Margallo et al., 2014). Waste management is one of the more prolific LCA areas and includes, for instance: electrical devices (Solé et al., 2012), industrial waste (Puig et al., 2013) construction (Balaguera et al., 2018), food (Laso et al., 2018), etc. Still, no LCA about an aviation catering waste management system was found. The diverse waste management options (Laurent et al., 2014) and the heterogeneity of the waste produced in airplanes (Cat 1, Cat 3, different materials…) raises the need to perform an LCA for this case, to be sure the proper actions are taken.

For the private sector, such as the aviation one, a change in the waste management system, considering only its environmental performance, will not be fully considered unless it is supported by an economic analysis. The integration of Life Cycle Costing (LCC) in the study generates the necessary confidence for decision making (Norris, 2001). Some of the measures previously described, such as the use of bi-compartmented trolleys to improve the separate waste collection, had already been implemented. However, some others such as the sterilization process are expensive alternatives, and yet to be settled. Therefore, it has become necessary to carry out a cost-effectiveness evaluation between the environmental and economic benefits. The integration of a LCC analysis into the LCA for system A and B adds the necessary information so that the flying company may decide to change the original system into the alternative one, granting, in addition, a better economic result.

Given the complexity of access to data, the nonexistence of specific previous studies, the diversity of waste, and the combined application of LCA and LCC, this work may be a reference not only to Iberia but to other airlines worldwide.

6.4. METHODOLOGY AND DATA

6.4.1. LCA METHODOLOGY

Gabi Professional (database SP39) was the LCA software used to model the systems and scenarios for the study. As for the characterization factors, the ones from CML 2001 method were used (Heijungs & Guinée, 1992). Table 6-1 shows the list of impact categories that have been considered, which correspond to the most relevant for this kind of systems.

Table 6-1 Impact categories included in the study

Impact categories	Measurement unit
Abiotic Depletion (ADP elements)	[kg Sb eq.]
Abiotic Depletion (ADP fossil)	[MJ]
Acidification Potential (AP)	[kg SO_2 eq.]
Eutrophication Potential (EP)	[kg Phosphate eq.]
Global Warming Potential (GWP 100 years), excl. biogenic carbon	[kg CO_2 eq.]
Photochem Ozone Creation Potential (POCP)	[kg Ethene eq.]

6.4.1.1. GOAL

The objective of this study is to analyze the environmental and economic impact of the current cabin waste management system at Barajas airport in Madrid, Spain (system A), in comparison with an alternative system that considers all the proposed measures stated in section 3.2.1 (system B).

6.4.1.2. FUNCTIONAL UNIT

The functional unit chosen for the comparison is "the management of 1,000 kg of both the waste coming from the catering of Iberia aircrafts arriving in Madrid and the waste produced in the catering operator facilities and managed by the waste management company", according to the composition of the waste produced in 2016 for system A and in 2019 for system B. This differentiation is needed, as we are also taking into account the effect of using bi-compartmented waste trolleys on the plane in 2019, which were not used in the previous years.

6.4.1.3. SYSTEM BOUNDARIES

When dealing with a waste management LCA, the scenario under study is a gate to grave system, in which waste takes none of the upstream impacts into the waste management system (Ekvall et al., 2007). We have differentiated four main life cycle stages in the system, and two credits:

- Waste collection. This includes the collection and transport of waste from the airplanes to the GG facilities.
- Sorting plant. Both the impact associated with the selection of recoverable packaging in the packaging waste selection plants and the truck transport needed are included.
- Recycling. In addition to the truck transport to the recycler process impacts, it also includes the impacts related to the transformation of the materials recovered in the sorting plants until the moment they are ready to be reintroduced into the market (in the form of pellets for plastics, ingot for aluminum, and plate for steel). It also includes the biodigestion and composting processes in system B.
- Landfill. This includes the impact associated with the dumping process of the different materials in landfill over a 100-year time horizon.
- Energy credits. This includes the savings associated with the electricity that is recovered in the landfill by the capture and use of biogas.
- Material credits. This takes into account the savings associated with avoiding the extraction and manufacture of virgin materials due to their recovery and recycling.

Figure 6-1 and Figure 6-2 show the waste management systems A and B respectively.

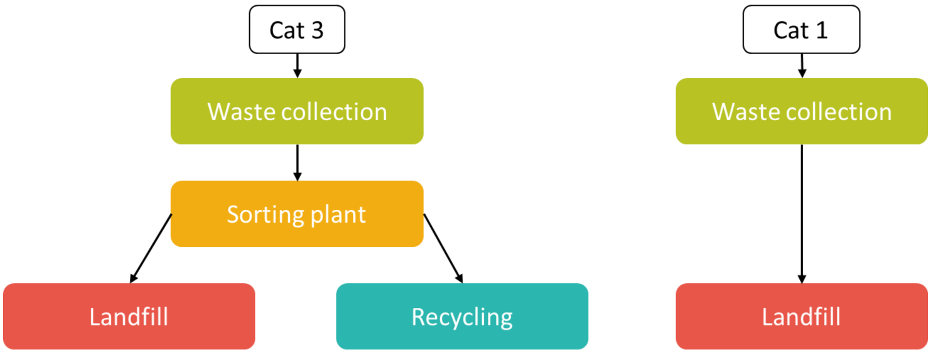

Figure 6-1 System A

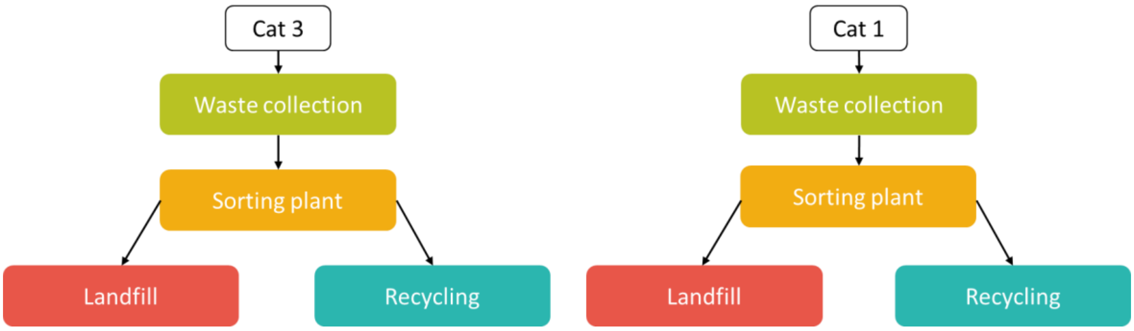

Figure 6-2 System B

6.4.2. INVENTORY

The Life Cycle Inventory (LCI) was built through the information provided by the stakeholders participating in the project. It is made of a detailed compilation of environmental inputs and outputs for each life cycle stage.

Table 6-2 summarizes the 2016 (system A) and 2019 (system B) waste compositions differentiated into Cat 1 and Cat 3 for 1,000 kg. This waste composition is the result of the characterizations made in the caterer facilities. These characterizations included catering waste coming from the airplanes and the caterer kitchen. Due to the separate waste collection onboard implemented in system B, waste composition for Cat 1 and Cat 3 changed in 2019.

Table 6-2 Waste generation and composition

	System A (2016)		System B (2019)	
	Cat 1	Cat 3	Cat 1	Cat 3
Organic matter	32.63%	7.58%	7.69%	13.47%
Glass	5.01%	0.53%	1.19%	4.67%
Paper and Cardboard	9.99%	10.73%	4.60%	12.90%
Other	3.82%	6.61%	12.29%	13.80%
PET	1.51%	0.34%	1.20%	1.07%
HDPE	0.03%	0.12%	0.01%	0.12%
PP	2.87%	1.70%	1.38%	4.45%
Other plastics	3.11%	8.41%	3.86%	12.84%
Steel	0.09%	0.14%	0.12%	0.53%
Aluminum	3.52%	1.26%	2.39%	1.42%
Total	**62.58%**	**37.42%**	**34.73%**	**65.27%**

Table 6-3 summarizes the parameters used for the transport stages. All data regarding truck types and transport distances were provided by the catering company and the waste management operator.

Table 6-3 Transport parameters

Transport	Distances (km)	Weight (kg)	Filling %	Maximum authorized weight (kg)
Airplane to catering facilities	8.5	14,000	85%	18,000
Catering facilities to sorting plant	37	6,000	85%	10,000
Catering facilities to Cat 1 landfill	36	7,000	85%	10,000
Sorting plant to Cat 3 landfill	60	16,000	90%	18,000
Sorting plant to paper recycler	2	16,000	85%	18,000
Sorting plant to HDPE recycler	38	16,000	85%	18,000
Sorting plant to PP recycler	348	16,000	85%	18,000
Sorting plant to PET recycler	640	16,000	85%	18,000
Sorting plant to aluminum recycler	38	8,000	85%	10,000

The truck utilization rate used was the average one in the GaBi database (85%) for all types of trucks. The sorting plant efficiency rate for the selection process is set as 85% according to the waste manager. Finally, the selected materials to follow the recycling process are aluminum, HDPE, PET, PP, paper, and cardboard and steel in system A. The previous materials are also recycled in system B but it also includes other plastics (PVC, PS, etc).

For the calculation of the credits obtained, the Qs/Qp ratio that reflects the quality of the secondary material (Qs) compared to the original primary material (Qp) has been used. The closer this value gets to 1, the closer to the virgin material the quality of the secondary material obtained is and the better provides its functionality. The ratio values used (Table 6-4) are those indicated by the product category rules of the European Union Product Environmental Footprint (PEF) program (European Commission, 2018).

Table 6-4 QS/QP factors

Material	Qs/Qp factor
Aluminum	1
Other plastics	0.75
Paper	0.85
PEAD	0.9
PET	0.9
PP	0.9
Steel	1

6.4.3. ASSUMPTIONS

Few assumptions were made, as most of the data used were first hand given by all the agents taking part in the waste management system:

- The separation effectiveness of the different fractions of recoverable materials has been estimated based on the separation efficiency provided by the waste manager. This has been applied to both system A and system B.

- The electrical energy obtained by the recovery and treatment of biogas in landfills has been assumed to displace the Spanish electricity production mix.

- The chosen process for paper waste in landfill (GaBi database) considers the recovery of electrical energy and also thermal energy. However, in the 11 incinerators in Spain, only electrical energy is recovered. For this reason, the energy recovered in heat form has been converted into electrical energy. Therefore, the efficiency data in the conversion to electrical energy of the BREF document of Best Available Techniques of European reference for Waste Incineration, which assumes an efficiency between 17% and 30%. In the model, the average value has been used, that is, 23.5%.

- According to real data provided by the waste manager about the operating results of one of its biodigestion plants, as an average, the energy required for operation equals that obtained, so the final energy balance is equal to 0.

- The energy consumption by the sterilizer used in system B has been estimated at 156 kWh, using the technical information available from a suitable sterilizer[5].

- The utilization transport occupancy rate, by both the caterer and the waste manager, have been established at 85%, according to the waste manager. This rate was also used in those transport stages in which the utilization rate was unknown.

6.4.4. LCC METHODOLOGY

Unlike for LCA, there is no ISO standard framing LCC, but there are extensive literature and consensus on how to conduct cost accounting. In the following sections, the methodology, scope, inventory, and results obtained from the LCC analysis are detailed.

The methodology consists on cost accounting activities throughout all stages of the studied system lifecycle. This approach corresponds to a conventional LCC, according to the LCC models defined by the SETAC working group on LCC (Swarr et al., 2011). Basically, it consists on an inventory and analysis of quantitative costs (direct and indirect, variable and fixed) allocated to the exchange of flows between the different actors of the system under study. In this case, we take into account the flying company, the

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[5] https://medicalwaste.en.made-inchina.com/product/EvFJHUGxslRZ/China-Hospital-Medical-Waste-Sterilizer-with-MicrowaveDisinfection-Equipment-Biomedical-Infectious-Waste-Treatment-10.html (search made in December 2019).

caterer, and the waste manager, since waste is collected on the plane until it is managed, either by recycling, recovering energy, or landfilling.

6.4.5. SYSTEM BOUNDARIES

Both LCA and LCC must use the same scope for the study. Only in this way both results can be integrated. Therefore, in this case, the defined scope, the functional unit, the systems, and its limits are the same as those defined for the LCA.

6.4.6. HOW THE SYSTEM AND THE ECONOMIC FLOWS WORK

The economic flows between the different agents involved are described below:
Firstly, the airline buys the menus from the caterer. Secondly, the caterer prepares and loads the menus on the airline flights. After the caterer collects the waste streams from the landed aircrafts, the waste is stored until the waste manager collects it, charging the caterer a management fee. Finally, the waste manager, after recovering different materials in the sorting plant, sells them to recyclers. This way, the waste manager gets additional income. These material and money flows are depicted in figure 6-3.

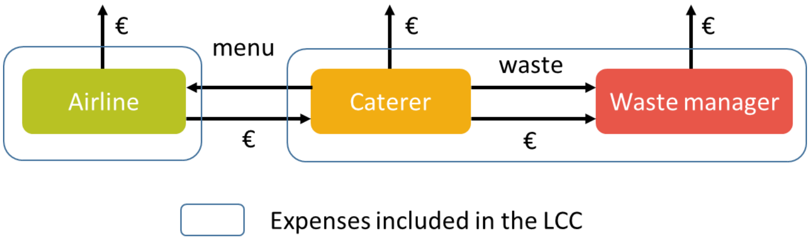


Figure 6-3 Economic flow between agents

Since the LCC has to be compatible with the LCA in terms of system boundaries, in the cost analysis, the income or expenses from the sale of the menus are not included. It only includes costs from the collection of waste in the cabin until it ends in a recycler, or landfilled.

6.4.7. INVENTORY

Incomes and costs have been included in the study for all those activities involved in system A and system B. Fixed and variable costs have been differentiated. For fixed costs, an amortization of 10 years has been applied to all cases. VAT has not been included.

There are a number of activities which imply a cost for the systems under study.

- Waste collection on the airplane. This includes, as fixed costs: modifying the inner basin of the trolley to divide the compartment in two; carrying out the separation of waste in flight; and the purchase of identification stickers to indicate to the crew how to carry out the separation of the recoverable materials from the rest. Variable costs include the waste bags for the trolleys.
- Transport and management by the caterer. A new dock for loading waste was built to get proper waste management in the caterer facilities. The accounted fixed costs associated with the new dock were taken into account, while the variable costs were associated with: the track truck fuel; washing consumption such as electricity, water, detergents and gas; waste management; and extra staff for waste management. Costs associated with the waste management by the waste manager cover transportation, treatment, and document management.
- Waste management at sorting plant. The fixed costs of this last stage include the acquisition of new machinery (turners, sterilizer, digester) required for the waste management in system B. Variable costs include the necessary personnel for the operation of the plant with the new processes present in system B.

Regarding incomes, only that from the sale of materials recovered at the sorting plant is recorded. The obtained compost is still considered as waste, due to its low quality, and it has no commercial value. Since the organic waste recovered in the airplane cabin does not correspond to a differentiated collection, no income has been applied for the sale of this product.

6.5. RESULTS

6.5.1. LCA RESULTS

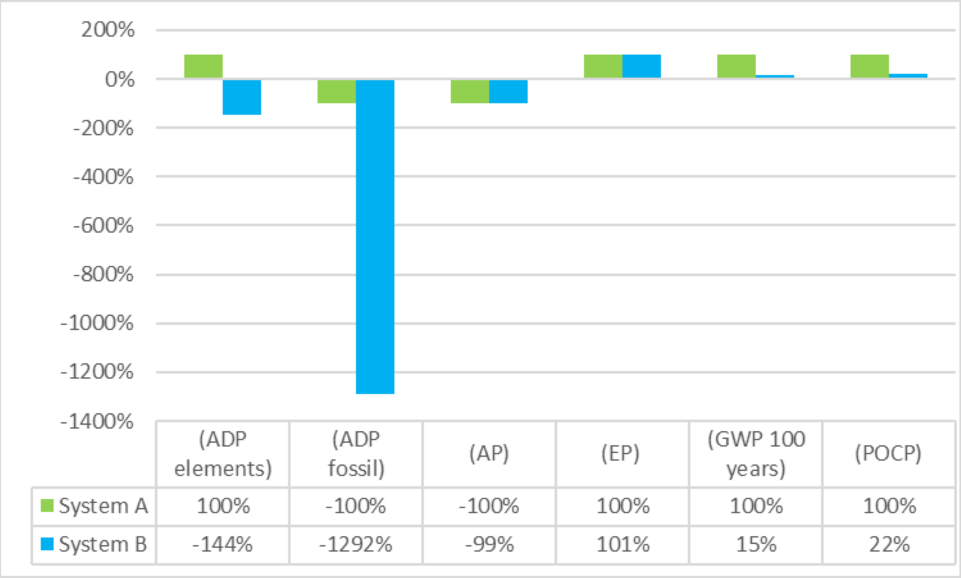
6.5.1.1. GLOBAL RESULTS

Table 6-5 shows the global results of the environmental analysis carried out for the two analyzed scenarios. A more detailed result table is in Annex A. The impacts have been differentiated from the credits (savings) to see their contribution separately. A negative overall result means that the savings due to materials recycling are greater than the impacts associated with their collection and treatment. From the results of Table 6-5, it appears that system B represent an impact saving in all the impact categories, except for the eutrophication potential (EP) and acidification potential (AP). The origin of this slightly bigger contribution will be analyzed in the subsequent sections.

Figure 6-4 shows the results relative to system A (100%).

Table 6-5 Total results for system A and B

	Impacts	
	System A	System B
ADP elements [kg Sb eq.]	1.49E-04	2.12E-04
ADP fossil [MJ]	2.00E+03	2.77E+03
AP [kg SO2 eq.]	4.34E-01	8.26E-01
EP [kg Phosphate eq.]	2.44E+00	2.50E+00
GWP 100 years [kg CO_2 eq.]	4.75E+02	3.89E+02
POCP [kg Ethene eq.]	1.48E-01	1.41E-01
	Credits	
	System A	**System B**
ADP elements [kg Sb eq.]	-1.10E-04	-2.68E-04
ADP fossil [MJ]	-2.47E+03	-8.93E+03
AP [kg SO2 eq.]	-6.23E-01	-1.01E+00
EP [kg Phosphate eq.]	-7.31E-02	-1.14E-01
GWP 100 years [kg CO_2 eq.]	-1.62E+02	-3.43E+02
POCP [kg Ethene eq.]	-5.15E-02	-1.20E-01
	Total (Impacts + credits)	
	System A	**System B**
ADP elements [kg Sb eq.]	3.87E-05	-5.57E-05
ADP fossil [MJ]	-4.76E+02	-6.16E+03
AP [kg SO2 eq.]	-1.89E-01	-1.87E-01
EP [kg Phosphate eq.]	2.37E+00	2.39E+00
GWP 100 years [kg CO_2 eq.]	3.13E+02	4.70E+01
POCP [kg Ethene eq.]	9.67E-02	2.08E-02



	(ADP elements)	(ADP fossil)	(AP)	(EP)	(GWP 100 years)	(POCP)
🟩 System A	100%	-100%	-100%	100%	100%	100%
🟦 System B	-144%	-1292%	-99%	101%	15%	22%

Figure 6-4 Relative impacts for system A and B

The environmental results obtained per impact category are not comparable with each other, as they are expressed in different units. In order to compare these results and to analyze the relative importance of the different impact categories, it is necessary to apply normalization. In this case, the results have been normalized with the average emissions of different regions of Europe (25 + 3) from the year 2000. For the calculation, the values used by the CML 2016 method have been chosen. The characterization factors from this method have also been used to obtain the environmental results. As can be seen in Figure 6-5, the impact categories with higher representation are the depletion of fossil resources and the eutrophication potential, followed by the potential of global warming and the formation of photochemical oxidants. From these results, it is clear that system B performs better than system A.

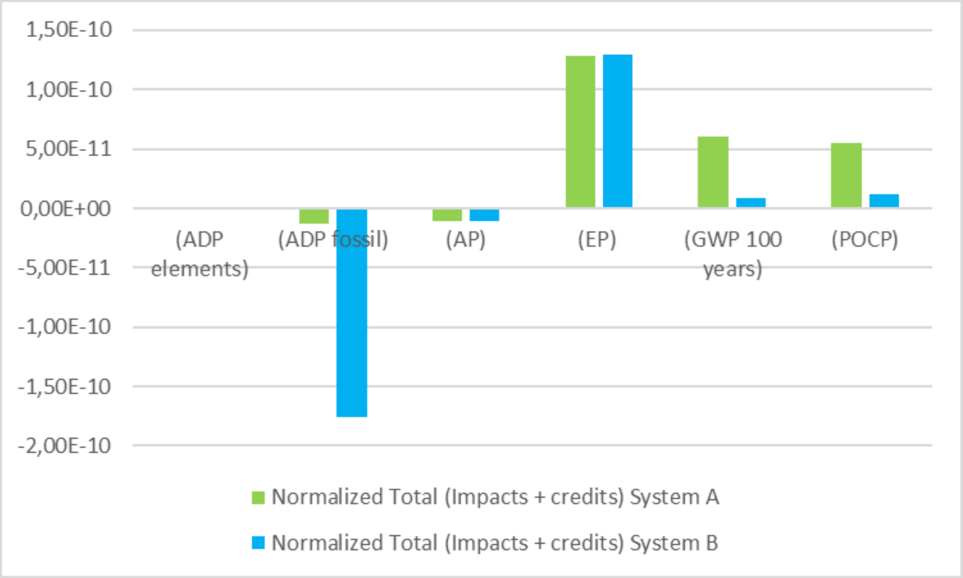


Figure 6-5 Normalized results for system A and B

6.5.1.2. CAT 1 AND CAT 3 CATEGORY ANALYSIS

This section breaks down the results for each of the scenarios analyzed by Cat 1 and Cat 3 waste management, as material composition for each category varies. In all cases, the results are shown in absolute and relative values.

- **System A**

Table 6-6 presents the results of system A disaggregated according to whether the waste is classified as Cat 1 (dangerous according to the EU 1069/2009 Regulation) or Cat 3 (compatible with urban waste). Table 6-7 shows the relative impact and credit results. As can be seen, Cat 3 waste has a greater environmental impact in the categories of material depletion (ADP elements), fossil resource depletion (ADP fossil), acidification (AP), and eutrophication (EP), which vary between 61% and 95%. However, Category 1 waste has a greater contribution to the impact on global warming (GWP 100 years) and on the potential for the formation of photochemical oxidants (POCP), greater than 62% in both cases.

Regarding credits, it should be noted that, in all cases, over 94% of credits are mainly due to the recovery of materials from Cat 3 waste. The contribution percentage of Cat 1 waste to the credit is associated with the recovery of the biogas generated in a landfill to generate electricity.

Table 6-6 Absolute results for system A per FU differentiated into Cat 1 and Cat 3 waste

	Impacts		
	Cat 1	Cat 3	TOTAL
ADP elements [kg Sb eq.]	6.70E-06	1.42E-04	1.49E-04
ADP fossil [MJ]	5.60E+02	1.44E+03	2.00E+03
AP [kg SO_2 eq.]	1.68E-01	2.66E-01	4.34E-01
EP [kg Phosphate eq.]	5.14E-01	1.93E+00	2.44E+00
GWP 100 years [kg CO_2 eq.]	2.94E+02	1.82E+02	4.75E+02
POCP [kg Ethene eq.]	9.53E-02	5.29E-02	1.48E-01
	Credits		
	Cat 1	**Cat 3**	**TOTAL**
ADP elements [kg Sb eq.]	-2.95E-06	-1.07E-04	-1.10E-04
ADP fossil [MJ]	-1.12E+02	-2.36E+03	-2.47E+03
AP [kg SO_2 eq.]	-2.64E-02	-5.97E-01	-6.23E-01
EP [kg Phosphate eq.]	-2.92E-03	-7.01E-02	-7.31E-02
GWP 100 years [kg CO_2 eq.]	-9.86E+00	-1.52E+02	-1.62E+02
POCP [kg Ethene eq.]	-1.87E-03	-4.97E-02	-5.15E-02
	Total (Impacts + credits)		
	Cat 1	**Cat 3**	**TOTAL**
ADP elements [kg Sb eq.]	3.75E-06	3.50E-05	3.87E-05
ADP fossil [MJ]	4.47E+02	-9.24E+02	-4.76E+02
AP [kg SO_2 eq.]	1.41E-01	-3.31E-01	-1.89E-01
EP [kg Phosphate eq.]	5.11E-01	1.86E+00	2.37E+00
GWP 100 years [kg CO_2 eq.]	2.84E+02	2.94E+01	3.13E+02
POCP [kg Ethene eq.]	9.34E-02	3.26E-03	9.67E-02

Table 6-7 Relative results for system A differentiated into Cat 1 and Cat 3 waste

	Impacts		
	Cat 1	**Cat 3**	**TOTAL**
ADP elements [kg Sb eq.]	5%	95%	100%
ADP fossil [MJ]	28%	72%	100%
AP [kg SO_2 eq.]	39%	61%	100%
EP [kg Phosphate eq.]	21%	79%	100%
GWP 100 years [kg CO_2 eq.]	62%	38%	100%
POCP [kg Ethene eq.]	64%	36%	100%
	Credits		
	Cat 1	**Cat 3**	**TOTAL**
ADP elements [kg Sb eq.]	3%	97%	100%
ADP fossil [MJ]	5%	95%	100%
AP [kg SO_2 eq.]	4%	96%	100%
EP [kg Phosphate eq.]	4%	96%	100%
GWP 100 years [kg CO_2 eq.]	6%	94%	100%
POCP [kg Ethene eq.]	4%	96%	100%

- **System B**

Table 6-8 shows the results for system B disaggregated by waste category, Cat 1 and Cat 3, while Table 6-9 shows the relative results. The environmental impact in all the impact categories is higher in the case of Cat 3 waste. This ranges from 63% of the potential for photochemical oxidant formation (POCP) to 96 % in the case of exhaustion of materials (ADP elements).

Regarding credits, also for system B, the treatment of Cat 3 waste is responsible for practically all the savings (greater than 99% in all cases).

Table 6-8 Relative impacts per FU for system B differentiated into Cat 1 and Cat 3 waste

	Impacts		
	Cat 1	**Cat 3**	**TOTAL**
ADP elements [kg Sb eq.]	7.75E-06	2.04E-04	2.12E-04
ADP fossil [MJ]	4.18E+02	2.35E+03	2.77E+03
AP [kg SO_2 eq.]	2.13E-01	6.12E-01	8.26E-01
EP [kg Phosphate eq.]	1.91E-01	2.31E+00	2.50E+00
GWP 100 years [kg CO_2 eq.]	1.30E+02	2.60E+02	3.89E+02
POCP [kg Ethene eq.]	5.20E-02	8.85E-02	1.41E-01
	Credits		
	Cat 1	**Cat 3**	**TOTAL**
ADP elements [kg Sb eq.]	-1.24E-06	-2.67E-04	-2.68E-04
ADP fossil [MJ]	-4.72E+01	-8.88E+03	-8.93E+03
AP [kg SO_2 eq.]	-1.11E-02	-1.00E+00	-1.01E+00
EP [kg Phosphate eq.]	-1.23E-03	-1.13E-01	-1.14E-01
GWP 100 years [kg CO_2 eq.]	-4.14E+00	-3.38E+02	-3.43E+02
POCP [kg Ethene eq.]	-7.84E-04	-1.19E-01	-1.20E-01
	Total (Impacts + credits)		
	Cat 1	**Cat 3**	**TOTAL**
ADP elements [kg Sb eq.]	6.52E-06	-6.23E-05	-5.57E-05
ADP fossil [MJ]	3.71E+02	-6.53E+03	-6.16E+03
AP [kg SO_2 eq.]	2.02E-01	-3.89E-01	-1.87E-01
EP [kg Phosphate eq.]	1.90E-01	2.20E+00	2.39E+00
GWP 100 years [kg CO_2 eq.]	1.26E+02	-7.86E+01	4.70E+01
POCP [kg Ethene eq.]	5.12E-02	-3.04E-02	2.08E-02

Table 6-9 Relative results per FU for system B differentiated into Cat 1 and Cat 3 waste

	Impacts		
	Cat 1	**Cat 3**	**TOTAL**
ADP elements [kg Sb eq.]	4%	96%	100%
ADP fossil [MJ]	15%	85%	100%
AP [kg SO_2 eq.]	26%	74%	100%
EP [kg Phosphate eq.]	8%	92%	100%
GWP 100 years [kg CO_2 eq.]	33%	67%	100%
POCP [kg Ethene eq.]	37%	63%	100%

	Credits		
	Cat 1	**Cat 3**	**TOTAL**
ADP elements [kg Sb eq.]	0%	100%	100%
ADP fossil [MJ]	1%	99%	100%
AP [kg SO_2 eq.]	1%	99%	100%
EP [kg Phosphate eq.]	1%	99%	100%
GWP 100 years [kg CO_2 eq.]	1%	99%	100%
POCP [kg Ethene eq.]	1%	99%	100%

This dominance of Cat 3 impacts (not taking credits obtained into account) in system B compared to the ones in system A is due to several reasons:

- Waste that was Cat 1 in system A, now it is Cat 3 in system B, increasing Cat 3 waste amount.

- Cat 3 waste has a bigger transport stage than Cat 1. Cat 3 waste, compared to Cat 1 waste, is taken to different material recyclers after being taken to the sorting plant (Figures 6-1 and 6-2 and Table 6-3). Transport between stages and electricity use in the sorting plants contribute to the increase of GWP impact category for Cat 3 in system B compared to system A. Nevertheless, the credits obtained make system B more environmentally sustainable (Table 6-5).

Table 6-10 compares the Total (Impacts+Credits) results of system B regarding system A.

Table 6-10 Relative difference between system A and B per FU differentiated into Cat 1 and Cat 3 waste

	Total (Impacts + credits)		
	Cat 1	**Cat 3**	**TOTAL**
ADP elements [kg Sb eq.]	174%	-178%	-144%
ADP fossil [MJ]	83%	-707%	-1,292%
AP [kg SO_2 eq.]	143%	-118%	-99%
EP [kg Phosphate eq.]	37%	119%	101%
GWP 100 years [kg CO_2 eq.]	44%	-267%	15%
POCP [kg Ethene eq.]	55%	-933%	22%

6.5.1.3. ANALYSIS THROUGH STAGES.

In this section, a contribution analysis is carried out by stages of the life cycle for each of the scenarios and also differentiating between Cat 1 and Cat 3 waste. In all cases, the results have been disaggregated into the stages described in 6.4.7.

The results are shown in relative values, differentiating their contribution to impact and credit separately.

- **System A.**

Table 6-11 and Table 6-12 show the contribution results by stages for Cat 1 and Cat 3 waste for system A. As can be seen, for Cat 1 waste, all the environmental impacts are practically concentrated in the landfill stage (more than 97% in all cases), as well as 100% of the credits, which are associated with the production of electricity from the biogas recovered from the landfill by the decomposition under anaerobic conditions of the organic waste.

Regarding Cat 3 waste, the recycling process is the one that has the greatest contribution to resource depletion (ADP elements), with 95.5% of the total impact, followed by the potential for eutrophication (EP), with 88.9%, and fossil resource depletion (ADP fossil), with 75.5%. It should be said that, for the acidification potential (AP), the recycling and landfill stages have a very similar contribution (45.4% and 43.3%, respectively). Regarding global warming (GWP 100 years), the landfill stage concentrates 55.9% of the impacts, followed by the recycling stage with 38.1%. Finally, as to the formation of photochemical oxidants (POCP), 81.1% is due to the landfill stage.

About credits, more than 96% in all cases are due to the recovery of packaging materials, and paper and cardboard.

Table 6-11 Stage results for Cat 1 waste in system A

	Category 1					
	Waste collection	**Sorting plant**	**Recycling**	**Landfill**	**Material Credits**	**Energy Credits**
ADP elements [kg Sb eq.]	0.5%	0.0%	0.0%	99.5%	0.0%	100.0%
ADP fossil [MJ]	0.9%	0.0%	0.0%	99.1%	0.0%	100.0%
AP [kg SO_2 eq.]	0.9%	0.0%	0.0%	99.1%	0.0%	100.0%
EP [kg Phosphate eq.]	0.1%	0.0%	0.0%	99.9%	0.0%	100.0%
GWP 100 years [kg CO_2 eq.]	0.1%	0.0%	0.0%	99.9%	0.0%	100.0%
POCP [kg Ethene eq.]	-0.6%	0.0%	0.0%	100.6%	0.0%	100.0%

Table 6-12 Stage results for Cat 3 waste in system A

	Category 3					
	Waste collection	Sorting plant	Recycling	Landfill	Material Credits	Energy Credits
ADP elements [kg Sb eq.]	0.0%	2.0%	95.5%	2.5%	98.7%	1.3%
ADP fossil [MJ]	0.2%	8.2%	75.9%	15.7%	97.7%	2.3%
AP [kg SO_2 eq.]	0.4%	10.1%	45.8%	43.7%	97.9%	2.1%
EP [kg Phosphate eq.]	0.0%	0.2%	89.0%	10.8%	98.0%	2.0%
GWP 100 years [kg CO_2 eq.]	0.1%	5.6%	38.2%	56.1%	96.9%	3.1%
POCP [kg Ethene eq.]	-0.7%	1.7%	19.2%	79.8%	98.2%	1.8%

Table 6-13 breaks down the impact of savings differentiated by recovered materials. As can be seen, the materials that represent the highest percentage of savings are aluminum and paper. This saving varies in the case of paper from 18.1% contribution to the depletion of fossil resources (ADP fossil) to 58.3% of the potential for eutrophication (EP). In the case of aluminum, it varies from the 27% contribution to resource depletion (ADP elements) to 66.3% in the case of acidification potential (AP). In addition, worthy of note is the contribution of steel recycling to 41.2% of the impact on resource depletion (ADP elements).

Table 6-13 Saving contribution per material recycled in system A

	Aluminum	Steel	Paper	HDPE	PET	PP
ADP elements [kg Sb eq.]	27.0%	41.2%	25.3%	0.3%	1.6%	4.6%
ADP fossil [MJ]	39.9%	1.0%	18.3%	2.3%	9.2%	29.4%
AP [kg SO_2 eq.]	66.3%	0.9%	23.7%	0.3%	2.5%	6.4%
EP [kg Phosphate eq.]	32.5%	0.7%	58.1%	0.3%	2.4%	6.0%
GWP 100 years [kg CO_2 eq.]	54.6%	1.6%	24.0%	0.8%	6.1%	12.9%
POCP [kg Ethene eq.]	44.0%	1.4%	35.2%	0.7%	5.5%	13.2%

- **System B.**

Table 6-14 and Table 6-15 show the contribution results by stages for the Cat 1 waste and Cat 3 for system B. As can be seen, for Cat 1 waste, and unlike the previous cases, the impact of landfilling remains significant, varying between 56.4% for depletion of fossil resources (ADP fossil) and 97.6% in the case of potential eutrophication (EP), but here the selection and recycling stages also have a significant contribution. In the case of the selection process, the impact is due to the electrical consumption associated with the triage in the selection plant to separate the organic matter from the rest of the flows. Its contribution varies between 1.4% for the eutrophication potential (EP) and 33.8% for resource depletion (ADP elements). Regarding the recycling process, this contemplates the impact associated with the sterilization, bio-digestion, and composting processes. Their contribution varies between 0.8% to the eutrophication potential (EP) and 17.5% to the global warming potential (GWP 100 years).

Regarding Cat 3 waste, the recycling process has the highest contribution to resource depletion (ADP elements), with 95.8% of the total impact, followed by the potential for eutrophication (EP) with 91.3%, from the depletion of fossil resources (ADP fossil), with 84%, the potential of acidification (AP) with 64.6% and global warming (GWP 100 years) with 58.4%. Lastly, regarding the formation of photochemical oxidants (POCP), 58.7% is concentrated in the landfill stage.

In reference to credits, more than 98% are due to the recovery of packaging materials, and paper and cardboard (Table 6-16).

Table 6-16 breaks down the impact savings differentiated by recovered materials. As can be seen, and unlike system A, the savings contribution of different materials is more evenly distributed. This is due in part to the recovery of the "other plastics" fraction that was not recovered in system A. Among all the savings, we can outline: 62.2% of the contribution of steel recycling to resource depletion (ADP elements), 52.3% of recycling of other plastics to fossil resource depletion (ADP fossil), and 43.4% of aluminum recycling to acidification potential (AP).

Table 6-14 Stage results for Cat 1 waste in system B

	Category 1					
	Waste collection	Sorting plant	Recycling	Landfill	Material Credits	Energy Credits
ADP elements [kg Sb eq.]	0.2%	33.8%	9.6%	56.4%	0.0%	100.0%
ADP fossil [MJ]	0.7%	26.3%	13.1%	60.0%	0.0%	100.0%
AP [kg SO_2 eq.]	0.4%	11.1%	8.6%	79.9%	0.0%	100.0%
EP [kg Phosphate eq.]	0.1%	1.4%	0.8%	97.6%	0.0%	100.0%
GWP 100 years [kg CO_2 eq.]	0.2%	7.3%	17.5%	75.0%	0.0%	100.0%
POCP [kg Ethene eq.]	-0.6%	3.1%	2.1%	95.4%	0.0%	100.0%

Table 6-15 Stage results for Cat 3 waste in system B

	Category 3					
	Waste collection	Sorting plant	Recycling	Landfill	Material Credits	Energy Credits
ADP elements [kg Sb eq.]	0.0%	2.4%	95.8%	1.7%	99.6%	0.4%
ADP fossil [MJ]	0.2%	8.8%	84.4%	6.6%	99.5%	0.5%
AP [kg SO_2 eq.]	0.3%	7.2%	64.6%	27.9%	98.9%	1.1%
EP [kg Phosphate eq.]	0.0%	0.2%	91.3%	8.5%	99.0%	1.0%
GWP 100 years [kg CO_2 eq.]	0.2%	6.8%	58.4%	34.6%	98.8%	1.2%
POCP [kg Ethene eq.]	-0.7%	3.4%	38.5%	58.7%	99.4%	0.6%

Table 6-16 Saving contribution per material recycled in system B

	Aluminum	Steel	Paper	HDPE	PET	PP	Other plastics
ADP elements [kg Sb eq.]	12.0%	62.2%	10.1%	0.1%	2.0%	6.1%	7.5%
ADP fossil [MJ]	10.9%	0.9%	4.5%	0.5%	7.0%	23.9%	52.3%
AP [kg SO_2 eq.]	43.4%	2.0%	14.0%	0.1%	4.5%	12.6%	23.4%
EP [kg phosphate eq.]	22.3%	1.7%	35.9%	0.2%	4.6%	12.3%	23.0%
GWP 100 years [kg CO_2 eq.]	26.3%	2.6%	10.4%	0.3%	8.2%	18.5%	33.6%
POCP [kg Ethene eq.]	19.8%	2.1%	14.3%	0.3%	7.0%	17.7%	38.8%

6.5.1.4. LCC RESULTS

The LCC results in Table 6-17 reflect the total cost-income balance for system A and system B.

Table 6-17 LCC results per FU (€/t)

	System A	System B	% increase ((B-A)/A*100)
Waste collection on the airplane	28.89	52.44	82%
Transport and management by the caterer	255.57	229.40	-11%
Waste management at sorting plant	-	18.47	-
Material selling	21.63	23.42	8%
Total (expenses minus material selling)	262.82	276.89	5.1%

If we analyze the balance by stages of the life cycle, we can see that, for the airline, system B involves an extra cost of 82% (almost twice the initial cost), associated with the separate waste collection on the airplane. For the caterer, the implementation of the new measures in system B leads to an 11% decrease in the total cost of its activity. The investment of building the new docks is partially offset by the reduction in the costs of managing the generated waste, due to lower waste management costs, if they are collected separately, as well as improvements in the washing process. Finally, regarding the waste manager, the implementation of the new measures in system B leads to an 8% higher income, due to the greater amount of recyclable materials (paper and cardboard, PET, HDPE, PP, Other plastics, steel and aluminum) that can be sold to the recycler. For the whole chain, the introduction of system B would mean a 5.1% increase of costs.

6.5.2. COST-EFFICIENCY RESULTS

Environmental indicators, like the GWP, offer environmental impact information of a system and they are defined in a way that the higher the value the lower the environmental performance. According to WBCSD (2000): “Eco-efficiency is a management strategy that links financial and environmental performance to create more value with less ecological impact”. Eco-efficiency may be defined as the ratio between an environmental cost indicator and an economic output indicator (Masakazu et al., 2009). Therefore, as the environmental indicators, the eco-efficiency indicators are also defined to aim at low values, e.g., the lower the numerator or the higher the denominator, the lower the eco-efficiency indicator but the higher the eco-efficiency performance.

The numerator may be chosen among the environmental indicators given by a LCA while the financial indicator in the denominator may be: sales, value added, or any kind of economic benefit (Müller & Sturm, 2001). However, as a waste management system will have more costs than outputs per se, it is difficult to find a positive financial indicator. Less cost would mean more economic output and, therefore, more efficiency, and a lower value of the indicator. To make this possible, in the denominator we should place the reciprocal of the cost value.

Eco-efficiency indicator = (LCA indicator) / (1/cost indicator)

Therefore, the higher the environmental impact or the higher the cost, the higher the eco-efficiency indicator and the lower the eco-efficiency.

The results of the environmental analysis (Table 5) are now combined with those of the economic analysis (Table 6-17), with the intention of determining which system is more eco-efficient or cost-effective (lower impact at a lower cost). If the impact/cost ratio were higher in system B than in system A, it would mean that for every euro spent on the new management system, greater environmental impacts would be generated. In the case of comparing negative values between both systems (we are referring to credits), a higher value (or closer to zero) would equally mean that for each euro spent more impacts would be generated, since fewer credits would be obtained per euro spent. Table 6-18 and Table 6-19 shows the cost-effectiveness results of the 2 systems analyzed, expressed by tonne in absolute and relative values respectively. System B presents better cost-effective values than system A for all the impact categories except, very slightly, for the EP.

Table 6-18 Cost-efectiveness per tonne managed in absolute values

Impact category	Unit	System A	System B
ADP elements	[kg Sb eq./€]	1.02E-02	-1.54E-02
ADP fossil	[MJ/€]	-1.25E+05	-1,70E+06
AP	[kg SO2 eq./€]	-4.97E+01	-5.18E+01
EP	[kg Phosphate eq./€]	6.22E+02	6.62E+02
GWP 100 years	[kg CO2 eq./€]	8.23E+04	1.30E+04
POCP	[kg Ethene eq./€]	2.54E+01	5.76E+00

Table 6-19 Cost-efectiveness per tonne managed in relative values

Impact category	Unit	System A	System B
ADP elements	[kg Sb eq./€]	100%	-152%
ADP fossil	[MJ/€]	100%	-1,361%
AP	[kg SO2 eq./€]	100%	-104%
EP	[kg Phosphate eq./€]	100%	106%
GWP 100 years	[kg CO2 eq./€]	100%	16%
POCP	[kg Ethene eq./€]	100%	23%

6.6. DISCUSSION ABOUT LCA RESULTS

From the environmental analysis, it appears that system B represents a saving of environmental impacts in all the categories analyzed with respect to system A, with the exception of the case of eutrophication potential (EP). For this indicator, however, the results should be taken with caution.

The greatest impact on this category is associated with the 2.17% increase of paper that is recovered in system B as Cat 3. Life cycle inventories from two different data sources have been used to model the impact of both the recycling process and the savings associated with the paper fraction. In the case of the recycling process, data from the FENIX project database have been used (FENIX, 2013), with Spanish average data, and, in the case of paper saved, from the GaBi database with data from FEFCO (FEFCO, 2012). The level of detail of these inventories is not the same and, in particular, the levels of Chemical Oxygen Demand (COD) of the FENIX process are very high compared to those of GaBi, exactly 4 times bigger. This means that the recycling of a greater amount of paper supposes levels of COD much higher than those saved in the recycling process. Given the inconsistency of databases and the impossibility of finding data from the two processes in the same database, the results on this impact category should be taken into account carefully.

Regarding the GWP 100 years, the savings are associated with the stabilization processes of organic matter waste (through bio-digestion and composting), prior to the discharge process. In this way, methane emissions associated with the decomposition of organic waste in the landfill, which have a 25.25 times higher contribution than carbon dioxide emissions, are largely avoided. As for ADP fossil, this great gain is associated with the recovery of plastics and, mostly, with the fraction of mixed plastic waste that was not separated in system A. The composition of the mixed plastic is mostly LDPE, with an energy density of 47.3 MJ/kg (to which a substitution factor has been applied with respect to the virgin of 0.75), which means great associated savings in ADP fossil category.

As for the analyzed waste fractions, it should be said that for both systems the greatest contribution to the impact of Cat 1 waste corresponds to the landfill stage. Since all organic matter and the paper and cardboard contained in this fraction decompose under anaerobic conditions in the landfill, releasing methane which, as previously discussed, has a much higher global warming potential than that of carbon dioxide. The incorporation of the processes of sterilization and bio-digestion of organic Cat 1 waste in system B represent an environmental saving of fossil depletion (ADP fossil) of 25%, eutrophication potential (EP) of 63%, global warming (GWP 100 years) of 56%, and formation of photochemical oxidants (POCP) of 45%. However, it represents an increase in the impact on the use of element resources (ADP elements) and in the acidification potential (AP) of 16% and 27% respectively. Regarding credits, the fact of recovering a lesser amount of methane in landfill and the associated electricity production represents a reduction in the credit of Cat 1 waste in system B compared to system A of 58%.

Regarding Cat 3 waste, the incorporation of the selection measures at source (cabin) increased the waste considered as Cat 3 that follows a valorization process. This has led to an increase of environmental impacts associated with the selection and recycling of recoverable waste fractions, but also to greater savings due to the credits associated with not having to extract and produce new virgin raw materials. In absolute terms, the treatment of Cat 3 waste represents net environmental savings, except for the EP, the results of which must be taken with great caution, as previously mentioned. To mention the most significant impact reduction cases, the fossil resource depletion category varies 707%, and for global warming (GWP 100 years) 267%, compared to system A. In the case of the GWP 100 years for Cat 3 waste, it is worth mentioning the savings in methane emissions by stabilizing organic waste in a composting process prior to the landfilling process in system B.

6.7. CONCLUSIONS

A selective collection of waste on airplanes cabins and the correct management of recoverable waste would considerably reduce the environmental impacts of the aviation catering waste management systems. Although the proposed management system increases the impact in certain stages due to energy and fuel consumption by mechanical and transport processes, it allows obtaining credits that clearly offset the small impact increases. Indeed, the carbon footprint would be reduced by up to 85%. The increase in recycling plastic materials that previously ended up in landfill when mixed with the organic fraction of Cat 1 would reduce the impact category of fossil resource depletion by 1194%. Regarding the sterilization and bio-digestion of the organic matter fraction that previously ended in landfill, those processes would help to reduce the landfill stage relative contribution to the impact on GWP by 24.9% compared to system A (from 99,9% to 75% contribution). Nevertheless, as explained before, this waste treatment for Cat 1 is not allowed yet in Europe and, hopefully, this study can be useful to make a legislation change proposal.

Although the environmental impacts after changing system A into system B are certainly reduced, this will fall into cost increases by about 5%. This increase, in principle, comes from the initial investments in order to achieve the cabin separate waste collection. Once the 10 years of amortization have passed, the system B operation costs will decrease. Nevertheless, as landfill use will certainly increase its cost in the next years, system B may be more cost effective as well.

When both environmental impact and cost evaluation are taken into account and combined into an eco-efficiency indicator, the result is clear: the system proposed, representing a better approach to circular economy, delivers a clearly more eco-efficient solution. If GWP is taken as environmental indicator and overall cost as financial indicator, the eco-efficiency increases by 84%.

7. GENERAL CONCLUSIONS OF THE THESIS

The conclusions of this thesis are classified into three main blocks. The first one is about the methodology applied, the second one takes into account everything related to the catering service process and the third one is related to the management of waste derived from catering.

7.1. CONCLUSIONS ON THE METHODOLOGY USED

1. The developed methodology (a combination of waste characterization + LCA + LCC) has been proven useful, identifying the origin of environmental impacts and suggesting solutions to reduce the impacts in an eco-efficient way. However, each country has peculiarities when it comes to managing waste, such as changes in the catering menu composition or different local waste management regulation, which may cause the results to differ among airlines and countries.

2. There are legal decisions which may reduce the risk on one parameter, such as human health, while increase the impact on the environment, for instance, through increasing climate change. Using life cycle analysis for legal decision-making may help identifying this kind of problems and point out possible solutions that are not aprioristically visible.

7.2. CONCLUSIONS ON THE CATERING STAGE

3. Although the vast majority of reviewed LCA studies on packaging agrees that the greatest environmental impact occurs in the manufacturing stage, it is not the case for aviation catering, into which the main impact occurs in the use stage due to the weight of the packaging, which generates 62.8% of the total GHG emissions.

4. The above mentioned weight specially affects reusable items (compared to single-use ones), as they must be more robust to undergo different additional processes such as cleaning and transport. Even being 5 of the 19 studied in number, they are responsible for 73.5% of the total impact.

5. For reusable items, several ecodesign options have been found able to lessen their impact at different stages of their life cycle:
    - An increase in the number of reuses would reduce the relative impact in the end-of-life and production stages (this last one being the second stage that contributes the most)

but not the impact of the use stage, since this measure does not affect the weight transported.

- Reducing the weight of the reusable items will reduce the impact in every life cycle stage as it affects directly the functional unit. However, the single-use solution (always lighter) would still have less impact than the reusable ones. Even considering a 20% weight reduction, reusable items has 76% more impact than single-use.

- When comparing single use PS or bamboo cutlery with reusable steel cutlery (no matter how many reuses, as it follows an asymptotic curve); reusable steel one is still the worst solution for climate change, due to the extra weight on the flight stage.

6. For aviation catering, single-use plastic items turn out to be the solution that contributes the least to GHG emissions. That is why the application of the DIRECTIVE (EU) 2019/904 on the single-use plastics ban will negatively affect in terms of the generation of GHG in the aviation sector. It should also be noted that the problem of plastic littering in this sector is practically non-existent since they enter a closed management system once they are collected from the airplane as waste.

7. Bamboo single use items have almost twice the weight of that of PS; therefore, almost double climate change impact as well. In addition, if a close loop is implemented, recycling of PS seems more efficient than that of wood.

8. The hotspots and the characteristics that influence the impact throughout the life cycle have been identified, but concrete alternatives should be explored in the form of lighter, reusable and 100% recyclable materials that would avoid the increase in GHG emissions after the single-use plastics ban.

7.3. CONCLUSIONS ON THE WASTE GENERATION AND MANAGEMENT

Before being able to identify hotspots and improvements to the studied waste management system, it was necessary to understand it from inside. This was achieved by carrying out a characterization study of the waste generated in 145 flights, classifying according to flight length, passenger class, origin, material and whether the packaging containing the food had been manipulated or not. This research solved objective 1 of the thesis, concluding that:

9. Generation of waste is directly related to the flight duration, as the number of services increases along with the distance travelled. For the shortest flights, 0.125 kg of waste per passenger are generated while, in the longest flights, the waste generated per passenger increases to 2.4 kg. When the flight is 3h long, food is served to tourist class passengers as well, increasing waste generation.

10. Organic matter is the dominant waste fraction (on average, 33% of the total waste generated), followed by paper and cardboard (28%, mostly coming from written press), and packaging (12%).

11. The generation of organic waste and packaging have a margin of reduction, since, on average, 12% of that waste has not been manipulated during the flight. This implies that either the food served is not attractive to passengers or that too much food is served. This adjustment of quantities and type of food could be carried out by studying the content of the leftovers to avoid serving that type of product and reducing the amount of food served. Another solution that may help to reduce waste generation would be the pre-selection of food by the passengers before the food is loaded to the plane. This way, passengers will certainly get the food desired and no extra food would be stocked and transported in the plane and thrown away upon arrival.

12. Considering that packaging represents 12% of the total waste, the individual drink packaging could be replaced with larger packaging (even a galley based dispensing system) from where drinks could be served, reducing this way the amount of packaging per product.

13. As for the paper and cardboard waste generation, which is the majority of the waste generated on national flights (40% on average), it is recommended to substitute written press with digital press, thus reducing about 30% of the waste in flights up to 3h. In addition, redesigning the second tourist menu, which is served in a cardboard box, would reduce waste generation in long distance flights.

14. In the waste trolley, flows are mixed without differentiating recyclable from non-recyclable ones. A separate collection in origin would increase the efficiencies in the sorting plants. In addition, on flights where Category 1 waste (with animal origin components from outside the EU) is generated, by previously separating the packaging that does not contain organic waste from animal origin, all these fractions going directly to landfill according to current legislation could be recycled and, therefore, the associated impacts would decrease.

Regarding objectives 3 and 4 of the Thesis, an LCA of the current waste management system (system A) was carried out, comparing it with the proposed one (system B, which contains a bio-digestion step and on-board separate waste collection). After analysing the results obtained, these are the general conclusions and recommendations:

15. System B results in savings for all the environmental impact categories, compared to system A, except for the EP potential. It would specifically reduce 85% the GWP compared to the original system.

16. Although the new system increases the impacts related to transport stages and more waste follows industrial treatment processes that consume electricity, as more waste also follows recycling processes, the environmental credits generated widely compensate those impacts.

17. Landfill stage is the greatest contributor to Category 1 waste impacts, both in system A and B.

18. For Category 3 (waste coming from within the EU and recoverable materials not mixed with Cat 1), the recycling process produces most of the impacts but it also contributes to big savings (376% increased savings on the ADP fossil impact category) due to credits related to not having to extract and process virgin raw materials.

19. The proposed bio-digestion of Cat 1 organic matter in system B represented relevant impact reduction in the landfill phase, (66.8%) regarding the GWP. especially in the landfill phase.

20. The separate collection on board increased the amount of recoverables following a recycling process. This leads to credits higher than the impacts, reducing the fossil fuel depletion impact category by 707% and the global warming potential by 267%.

21. The separate collection on board requires an initial investment that increases the operational costs by 5%. Nevertheless, after 10 years of amortization, the costs will decrease as an 8% of incomes is expected after selling the recyclable materials recovered.

22. Taking into account both Life Cycle Assessment and Life Cycle Costing, system B is more cost-effective for all impact categories (except for acidification potential), especially fossil depletion, abiotic depletion and global warming.

23. The implementation of the proposed waste management system, where the Category 1 waste is valorized, is not yet totally possible due to current legislation restrictions. A change would derive notable environmental benefits in the aviation catering sector. However, just by implementing the proposed separate waste collection on board, certain environmental benefits are obtained.

7.4. NEXT STEPS

- Increasing the case studies in different countries using this methodology will allow more accurate results for each country waste management situation.

- The growing appearance of new materials used for packaging with different qualities calls for studying each case and material with the LCA methodology.

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9. ANNEX A.

Table Annex A-1. LCA results per FU

	System A						
	Cat 1						
	Waste collection	Sorting Plant	Recycling	Landfill	Material credits	Energy credits	**Total**
ADP elements [kg Sb eq.]	3,03E-08	0	0	6,66E-06	0	-2,95E-06	3,75E-06
ADP fossil [MJ]	5,27E+00	0	0	5,55E+02	0	-1,12E+02	4,47E+02
AP [kg SO2 eq.]	1,57E-03	0	0	1,66E-01	0	-2,64E-02	1,41E-01
EP [kg Phosphate eq.]	3,98E-04	0	0	5,14E-01	0	-2,92E-03	5,11E-01
GWP 100 years [kg CO2 eq.]	3,89E-01	0	0	2,93E+02	0	-9,86E+00	2,84E+02
POCP [kg Ethene eq.]	-5,79E-04	0	0	9,58E-02	0	-1,87E-03	9,34E-02
	Cat 3						
	Waste collection	Sorting Plant	Recycling	Landfill	Material credits	Energy credits	**Total**
ADP elements [kg Sb eq.]	1,81E-08	2,82E-06	1,36E-04	3,56E-06	-1,06E-04	-1,40E-06	3,50E-05
ADP fossil [MJ]	3,15E+00	1,18E+02	1,09E+03	2,26E+02	-2,31E+03	-5,35E+01	-9,24E+02
AP [kg SO2 eq.]	9,41E-04	2,70E-02	1,22E-01	1,16E-01	-5,84E-01	-1,26E-02	-3,31E-01
EP [kg Phosphate eq.]	2,38E-04	3,31E-03	1,71E+00	2,09E-01	-6,88E-02	-1,39E-03	1,86E+00
GWP 100 years [kg CO2 eq.]	2,33E-01	1,02E+01	6,94E+01	1,02E+02	-1,48E+02	-4,69E+00	2,94E+01
POCP [kg Ethene eq.]	-3,46E-04	9,24E-04	1,01E-02	4,22E-02	-4,88E-02	-8,88E-04	3,26E-03

	System B						
	Cat 1						
	Waste collection	Sorting Plant	Recycling	Landfill	Material credits	Energy credits	Total
ADP elements [kg Sb eq.]	1,68E-08	2,62E-06	7,43E-07	4,37E-06	0	-1,24E-06	6,52E-06
ADP fossil [MJ]	2,93E+00	1,10E+02	5,47E+01	2,51E+02	0	-4,72E+01	3,71E+02
AP [kg SO2 eq.]	8,73E-04	2,36E-02	1,84E-02	1,70E-01	0	-1,11E-02	2,02E-01
EP [kg Phosphate eq.]	2,21E-04	2,71E-03	1,57E-03	1,86E-01	0	-1,23E-03	1,90E-01
GWP 100 years [kg CO2 eq.]	2,16E-01	9,47E+00	2,27E+01	9,73E+01	0	-4,14E+00	1,26E+02
POCP [kg Ethene eq.]	-3,21E-04	1,62E-03	1,12E-03	4,96E-02	0	-7,84E-04	5,12E-02
	Cat 3						
	Waste collection	Sorting Plant	Recycling	Landfill	Material credits	Energy credits	Total
ADP elements [kg Sb eq.]	3,16E-08	4,92E-06	1,96E-04	3,58E-06	-2,66E-04	-1,18E-06	-6,23E-05
ADP fossil [MJ]	5,50E+00	2,06E+02	1,98E+03	1,56E+02	-8,83E+03	-4,51E+01	-6,53E+03
AP [kg SO2 eq.]	1,64E-03	4,44E-02	3,96E-01	1,71E-01	-9,91E-01	-1,06E-02	-3,89E-01
EP [kg Phosphate eq.]	4,15E-04	5,07E-03	2,11E+00	1,96E-01	-1,12E-01	-1,17E-03	2,20E+00
GWP 100 years [kg CO2 eq.]	4,06E-01	1,78E+01	1,52E+02	8,99E+01	-3,34E+02	-3,96E+00	-7,86E+01
POCP [kg Ethene eq.]	-6,04E-04	3,03E-03	3,41E-02	5,20E-02	-1,18E-01	-7,49E-04	-3,04E-02