POLITECNICO DI MILANO
Master of Science in Environmental and Land Planning Engineering

Environmental And Cost Analysis Of An Innovative Automatic System For Sorting Municipal Solid Waste: A Case Study At Milano Malpensa Airport

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Abstract

With the recent advancement in artificial intelligence methods, there are new opportunities to make a difference by adopting smart technologies to segregate the recyclable materials at the beginning of the waste value chain by increasing their quantity. The WiSort bin, an automatic prototype capable of sorting the waste into four different factions (paper, plastic, glass/aluminium and residual waste) has been installed in a public area of the airport of Milano Malpensa and the economic and environmental cost and benefits of such system, in a context where separate collection is more challenging for people, have been studied. Three scenarios have been identified and evaluated based on a field waste composition analysis of the content of the airport's bins (experiment 1): scenario 0, where it is assumed that all waste from public areas, despite being separately collected in different bins, is then sent to incineration with energy recovery; scenario 0 "with recycling", where it is assumed that the sorted waste streams are actually sent for recovery, according to the actual level of impurities in the bags; and scenario 1, where it is assumed that the different fractions, automatically sorted by WiSort bin with a 90% classification accuracy by weight, are sent for recycling. The cost analysis results show economic savings (55.8 €/ton) with respect to the actual situation only for scenario 1, while the environmental analysis performed through the LCA methodology shows that scenario 0 is mostly burdensome, while scenario 0 with recycling and scenario 1 are characterized by environmental benefits, especially enhanced when WiSort bin is used, for most of the impact categories. Furthermore, initial feedbacks from passengers using the bin have been collected on the field and some experiments have been designed for future further research. Some improvements have to be made in order to make the WiSort prototype more recognisable as a waste bin but, despite that, it was able to catch the curiosity and interest of the people who used it.

Sintesi

Con gli ultimi progressi nel campo dell'intelligenza artificiale, ci sono nuove opportunità di fare la differenza tramite l'adozione di tecnologie innovative per separare i rifiuti riciclabili all'inizio della catena del valore del rifiuto permettendo di aumentare la qualità della raccolta differenziata. Il cestino WiSort, un prototipo automatico in grado di separare il rifiuto in quattro diverse frazioni (carta, plastica, vetro/alluminio e indifferenziato) è stato installato in un'area pubblica dell'aeroporto di Milano Malpensa ed un'analisi economica ed ambientale dei costi e dei benefici di un sistema di questo tipo sono stati studiati in un contesto dove la raccolta differenziata è più impegnativa per le persone. Tre scenari sono stati identificati e valutati sulla base di un'analisi, svolta sul campo, della composizione del rifiuto dei cestini dell'aeroporto: lo scenario 0, dove è stato assunto che tutti i rifiuti generati nelle aree pubbliche, nonostante vengano raccolti in maniera differenziata, sono mandati ad incenerimento con recupero di energia; lo scenario 0 "con riciclo", dove è stato assunto che le varie frazioni della raccolta differenziata sono mandate a recupero secondo il livello attuale di purezza del materiale nei vari cestini; e lo scenario 1, dove è stato assunto che le varie frazioni della raccolta differenziata, separate in modo automatico dal cestino WiSort con un'accuratezza di classificazione del 90% in peso, sono mandate a riciclo. I risultati dell'analisi dei costi mostrano risparmi economici (55.8 €/ton) rispetto alla situazione attuale solo nello scenario 1 mentre l'analisi ambientale, effettuata tramite la metodologia LCA, mostra che lo scenario 0 è caratterizzato principalmente da impatti sull'ambiente mentre lo scenario 0 con riciclo e lo scenario 1 sono caratterizzati da benefici ambientali, molto più marcati quando il cestino WiSort con il livello di accuratezza assunto viene utilizzato, per la maggior parte delle categorie d'impatto. Inoltre, sono stati raccolti sul campo i primi feedback da parte dei passeggeri che hanno utilizzato il cestino ed alcuni esperimenti di usabilità sono stati progettati per futuri approfondimenti. Alcuni miglioramenti devono essere fatti per rendere il prototipo WiSort più riconoscibile come cestino di rifiuti ma nonostante ciò esso ha destato la curiosità e l'interesse delle persone che lo hanno utilizzato.

Acronyms

CBA Cost Benefit Analysis

EPR Extended Producer Responsibility

GHGs Greenhouse Gases

LCA Life Cycle Assessment

LCI Life Cycle Inventory

LCIA Life Cycle Impact Assessment

LCC Life Cycle Costing

MBT Mechanical Biological Treatment

MRF Material Recovery Facility

MSW Municipal Solid Waste

PAYT Pay As You Throw

RW Residual Waste

SRF Solid Recovered Fuel

SWM Solid Waste Management

WEEE Waste Electrical and Electronic Equipment

WSA Waste Separation Area

WTE Waste To Energy

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1 INTRODUCTION

1.1 *Objective of the study*

The WiSort bin is a prototype realized by the WiSort startup which is capable of autonomously sorting the waste into many fractions through image recognition and a machine learning algorithm. It has thus the potential of improving the quantity of the recyclable materials that can be collected, with the possibility of increasing the level of source separation and recycling scores in places where these goals are more difficult to achieve for different reasons (people's willingness, different behaviours, contexts and rules). However, it is still unknown whether a sorting system like WiSort bin could represent a better alternative to a centralized sorting system, considering the implications on the whole waste management value chain (e.g. waste collection, transport and recycling).

The main goal of this study is therefore to explore the effects of the implementation of this automatic system for sorting the municipal solid waste in a public place. The Milano Malpensa airport was chosen as a case study thanks to the availability of the airport operator (SEA) and because it was considered a good testing field due to the heterogeneity of passengers (different behaviours, different nationalities…) and for being a context where people are in a rush with a subsequent reduced attention to other things, among which waste sorting.

This study attempts to quantify the economic and environmental cost and benefits of this waste collection alternative in order to determine whether it can bring value to the municipal waste management of the airport and set guidelines for future research. In addition, field experiments are carried out to determine the waste composition of the public areas and to collect feedbacks from users of the bin.

1.2 *Thesis structure*

The study is organised in the following way: chapter 2 provides the scientific literature relevant to the topic with a focus on waste management in airports, sorting step in waste management and the frameworks used in literature to assess the municipal solid waste management from an environmental and economical point of view. Chapter 3 describes the case study, i.e. the airport of Milano Malpensa, adding details on the type of waste generated, the overall waste management chain adopted there and information regarding WiSort bin. Chapter 4 gives a detailed description of the two experiments that were carried out at the airport reporting the methodology used, the assumptions made and the results obtained. Chapter 5 and 6 describe the two main analyses of the study, i.e. the life cycle assessment (LCA) and cost analysis respectively, that were based on the information collected with the experiments on the field (detailed in chapter 4). Chapter 7 sums up the findings and shows which might be the next steps. Chapter 8 provides a description of some experiments that could be done in a future experimental campaign while chapter 9 and 10 contain the references and the appendix, respectively.

2 LITERATURE REVIEW

2.1 Municipal solid waste and regulations

With rising population and growth of economies worldwide, waste generation and related impacts have continued to increase. In 2016 the total estimated amount of municipal solid waste (MSW) was 2.01 billion tons, with 40% of it ending up in landfills, and this number is supposed to reach 3.4 billion tons in 2050 (Kaza et al., 2018).

MSW consists of any “mixed waste and separately collected waste from households, including paper and cardboard, glass, metals, plastics, bio-waste, wood, textiles, packaging, waste electrical and electronic equipment, waste batteries and accumulators, and bulky waste, including mattresses and furniture” or any waste “similar in nature and composition to waste from household” but coming from other sources such as offices, activities, institutions and public places within a municipality (Waste Framework Directive, 2008).

In the last decades, Europe has published many regulations and frameworks concerning waste management and selected waste streams in order to move from a linear economy towards a circular one by promoting waste reduction, recycling and proper final treatments with the aim of assessing the issues connected to their consequences on the environment. Among the regulations there are:

a) The waste framework directive of 2008
b) The new circular economy package directive of 2018.

These directives are shortly described in the following paragraphs.

Waste framework directive

It provides the definition of waste, it includes the different types and properties of waste (the European list of waste) and it delineates the Waste Hierarchy, where the waste management options are ranked according to their relative environmental impacts (fig. 2.1).

Figure 2.1 Waste Hierarchy (European Commission, 2008).

It also introduces the concept of "Extended producer responsibility" (EPR) and "End of waste status". The first refers to the fact that every producer of a product is responsible and in charge of the financial aspects of the treatment and disposal of the product when it becomes a waste. The second defines the conditions for a waste to acquire the status of "new product" allowing it to enter the market again.

a) The circular economy package directive

It aims at improving recycling and reducing landfilling of MSW to no more than 10% by 2030 and introducing the ban of landfilling separately collected waste. In addition to promoting reuse, providing economical incentives and pushing towards the introduction of waste as raw material for other industrial process, it also sets targets for recycling: 65% for MSW and 75% for packaging waste[1] by 2030 (with specific target percentage for each packaging type).

Despite the European framework, there are still many differences in the actual waste management of European countries. Recycling percentages in Europe go from less than 10% (Malta) up to almost 70% (Germany) with Italy achieving 51.4% in 2019. Fig 2.2 shows how the percentages of the main waste treatments vary from country to country. Some of them are more focused on incineration, especially in the north, while some other still mainly rely on landfill. Italy is currently in an average situation, where landfilling is still well above the 10% target (around 23%), despite having decreased significantly in recent years (ISPRA, 2021).

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[1] Packaging waste is a relevant waste stream in the MSW. 55% is the average percentage of packaging waste out of the total collection of the single fractions (paper packaging accounts for 29% of paper waste; glass for 91%, plastic for 95%, metal for 45% and wood for 16%) (ISPRA, 2021).

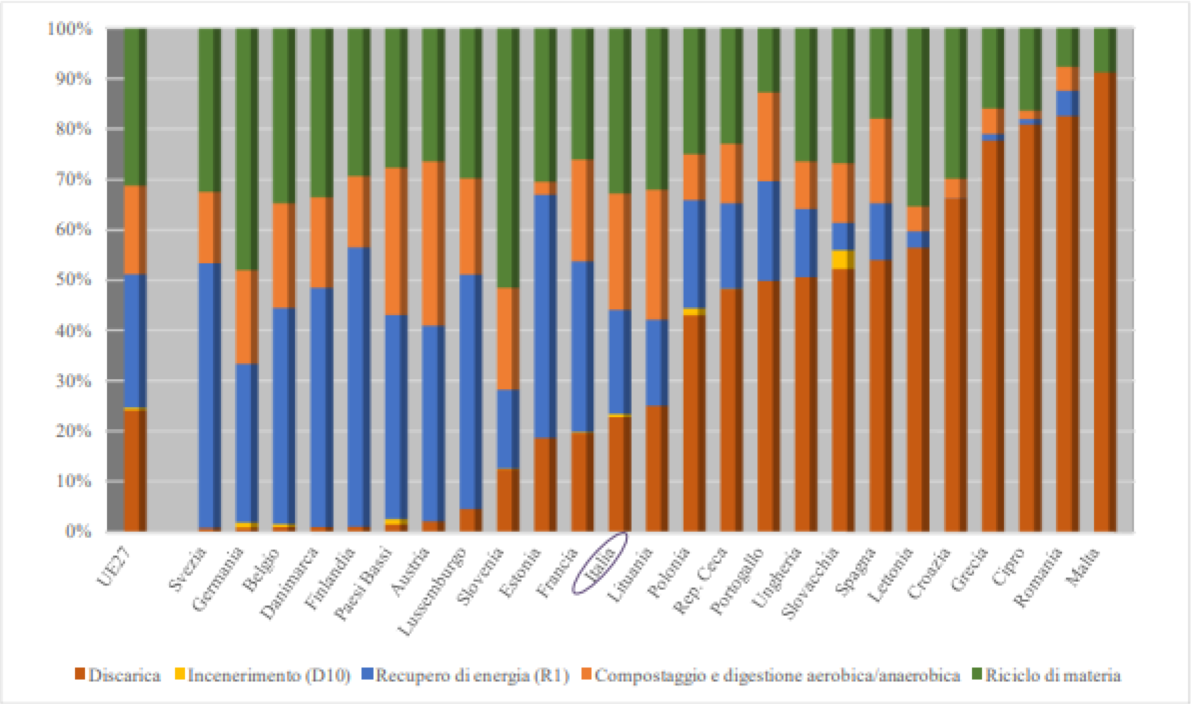

Figure 2.2 Percentages of the different treatments of MSW in European countries ordered according to increasing percentages of landfilling for year 2019. Brick red represents landfilling, yellow incineration without energy recovery, blue incineration with energy recovery, orange composting and anaerobic digestion and green represents recycling (ISPRA, 2021).

2.2 *Waste in public places*

Even though the major MSW stream in a municipality comes from households and commercial activities, waste is also generated all around the city in public places such as train stations, malls, airports, parks and streets. These latter streams are usually those with the highest contamination and where many recyclable items get lost and exit the system of the circular economy. The reasons why this happens are various, for example the absence of separated bins but also the fact that people have to make themselves familiar with a new context every time or simply that they are on a hurry: bins in public areas are in fact located in different spots and configurations and they are often made of different colour from one place to the other, making recycling more challenging (Cooley, 2013). Moreover, the lack of a true control means that it is common that the contents of the different waste bins or bags get mixed together during collection and end up in the residual waste.

This thesis will explore in details waste management in public places, taking airports as reference case.

2.3 *Waste and airports*

In the last decades the aviation sector has seen a rapid increase in the number of passengers and freight transported all over the world, only stopped and temporarily reversed by the COVID-19 pandemic (World Bank, 2020).

This has subsequently lead to an overall increase in the environmental impacts connected to this sector, among which the growth in the generation of waste.

Aviation accounts for more than 2% of the global CO_2 emissions (Lee et al., 2021), which are expected to increase in the future since this sector is forecast to expand more (ICAO, 2019). According to data availability on waste and emissions from sustainability reports, waste management accounts for less than 3% of the total CO_2 emissions of an airport (table 10.1 in appendix).

Under the growing awareness of the consequences of climate change and the implementation of local and national stricter regulations, more sustainable approaches are being put into practice by the air transport industry to deal with environmental issues. Improved waste management is one of them and aims at promoting waste reduction, reuse and recycling, with the aim of minimizing disposal to landfills (Dimitriou & Voskaki, 2010; Baxter et al., 2018). Among the waste treatment options, disposal to landfill is associated with the highest impact, since it is one of the main sources of methane emissions worldwide (IPCC, 2021). Furthermore, they are the last option to be considered according to the Waste Hierarchy and the European directive on landfill of 1999 (Directive 1999/31). Diverting waste from them has been one of the most widespread approaches when dealing with waste management.

2.3.1 *Types of waste generated in airports*

The most common types of waste generated in an airport are listed and described in table 2.1.

Table 2.1 Type of waste generated in airports (ICAO, 2018; Sebastian & Louis, 2021; direct interviews with SEA).

Type of waste	Description
Municipal Solid waste (MSW)	Food waste, glass, residual waste, plastic, metals, cardboard, aluminium and paper (the first three are the most difficult to deal with according to the National Academies of Sciences, 2018); they come from public areas and offices, tenant activities, airplanes and cargo operations
Deplaned waste	Any waste generated aboard an airplane, that is unloaded at the airport
Construction and demolition waste (C&D)	Concrete, wood, metals, soil, asphalt, plastic, pipes... They come from any activity of renovation, demolition and construction at the airport

Hazardous and Industrial waste	Oils, solvents and other chemicals and potentially toxic and corrosive waste coming from airplane and other vehicle maintenance, repairing, washing, cleaning and fuelling operations in hangars
Green waste	Grass, trees, leaves, soil coming from landscaping activities in the surrounding areas of the airports
Waste electrical and electronic equipment (WEEE)	WEEE coming from commercial activities, offices and IT systems
Hospital waste	Waste from hospitals, first aid units and drugstore present in the airport
Lavatory waste	Waste from the lavatories of airplanes, which might contain pathogens and chemicals
Liquid, aerosols, gels (LAGS) and prohibited items in hand luggage	Waste from passengers' security checks in airport (e.g. water bottles, some metal items). Generally speaking, they belong to the MSW flow
Waste from customs confiscations	Prohibited products found in luggage after plane's landing (e.g. organic substances of animal origin which are sent to incineration or non importable products)
Biohazardous waste	Any kind of waste potentially contaminated by COVID-19 or other diseases

Many are the areas in an airport and the stakeholders (passengers, tenants, various employees, airlines…) involved in the generation of one or more of these streams, and this makes the overall waste management in an airport even more challenging. Furthermore, because of the pandemic, airports had to recently deal with another type of waste, the biohazardous waste, i.e. any kind of waste potentially contaminated by COVID-19 or bio-hazards in general, which affected negatively the subsequent treatments of the waste, increasing the amounts sent to landfill and incineration (Sebastian & Louis, 2021).

The amount of waste generated in an airport is usually proportional to the total number of passengers that an airport can serve, but there are some airports where this trend is not met as it can be seen in figure 2.3. The amount of waste produced in a day, looking at some of the existing airports, can vary from 71.5 g/passenger (Vilnius Airport) up to 1.5 kg/passenger (Hamad International Airport). Some airports generate volumes equal to the ones produced by a small city (Pitt et al., 2002).

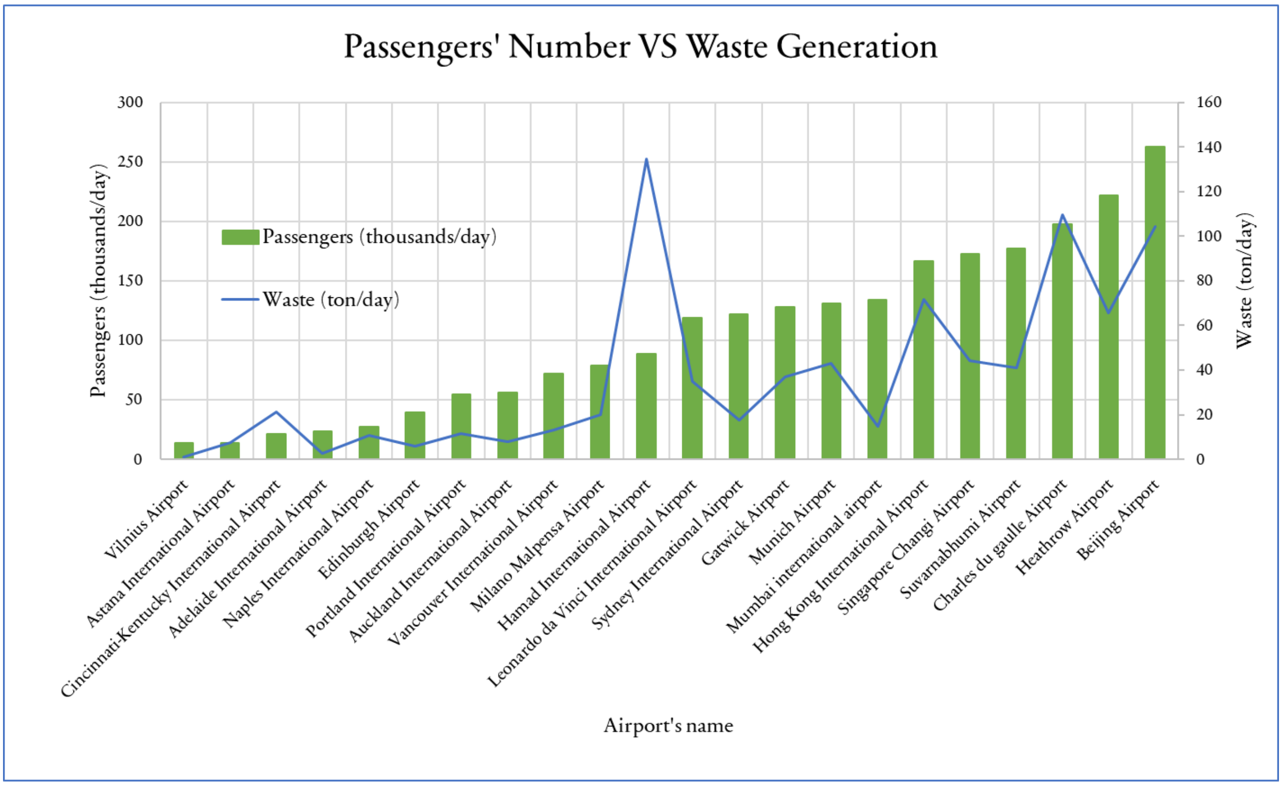

Figure 2.3 The figure shows how the waste generation varies with increasing passengers' number. The x-axis shows some worldwide airports ordered from lower to higher number of passengers. Values refers mostly to year 2019 in order to avoid the use of data affected by Covid pandemic (Sources: see table 10.2 in appendix).

Also the amount of waste that is sent to recycling differs a lot, going from 11.5% (Astana International Airport) up to 79% (Munich International Airport) (Sarbassov et al., 2020).

2.3.2 Waste management in airports

Depending on the airport, there exist two possible waste management systems: centralized and de-centralized. In the first case, the airport itself is in charge of providing the materials for the collection of the waste throughout the airport and deals with external public or private companies for its transportation and final treatment. In the second case, every activity within the airport is responsible for managing its own waste and makes its own contracts (Baxter et al., 2018).

Waste management therefore varies from airport to airport and the treatment and final disposal of each stream of waste also depends on its composition and quality, availability of waste treatment facilities as well as on the local regulatory framework. Some airports still send more than 75% of their waste to landfill (Sebastian & Louis, 2021).

The total waste management's cost in an airport is given by the sum of many cost and revenues items (Hershkowitz et al., 2006):

1. Equipment costs (for waste collection vehicles, roll off containers, sweeping equipment, dumpsters and bins; they can either be rented or purchased);
2. Transport costs (for the transport of the waste to the final destination plant; they include the costs connected to fuel, labour and maintenance operation);
3. Management costs (they include costs for cleaning, emptying the bins, labour and costs for the management of an on-site treatment plant if present; they also incorporate the costs connected to planning and decision making activities, including the ones for waste initiatives);
4. Disposal costs[2] (fees for processing a waste in external recycling plant or burning it in waste to energy (WTE) plant or disposing it in a sanitary landfill; fees for recycling can be null or even negative (i.e. when the plant pays the airport for its waste and not vice versa));
5. Revenues (sometimes an airport can sort some recyclable fractions and sell them directly thus obtaining a revenue, which is usually higher as sorting doesn't need to be carried out at the plant anymore).

2.3.3 Waste initiatives

In addition to the setting of targets to reduce the overall emissions connected to airport activities, many airports nowadays have implemented initiatives regarding waste. In addition to provide training to employees and staff for correct waste management, some airports purchase environmentally friendly products (such as compostable, recyclable, recycled or packaged in bulk products) and implement Pay As You Throw (PAYT) schemes to tenants. An example is the Seattle-Tacoma International Airport which, in order to increase recycling, applies pay-per-toss fees to tenants for the use of unsorted waste dumpsters, while leaves free the use of recycling and composting ones (National Academy of Sciences, Appendix 20, 2018). Some other airports donate the food in excess coming from the tenants' activities in order to reduce the generation of organic waste, bringing social benefit to local communities (e.g. soup kitchens and shelters). Cooking oils are sometimes used for biodiesel production, packaging for cargo are being reduced and reused, local composting or anaerobic digestion for the production of biogas are implemented by some airports in order to deal with organic waste while some other own incinerators to produce heat to be used inside the airport. Many airlines have also set targets to

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[2] This disposal costs are set by the plant itself and they take into account all the costs that the plant has to deal with including the ones for the disposal of the residues and the revenues from selling energy or secondary raw materials/ recycled materials. They can be considered comprehensive of all the costs and benefits of treating a type of waste from the plant onwards (Rigamonti et al., 2019).

reduce the production of waste during flights (National Academies of Sciences, 2018; Sebastian & Louis, 2021).

2.3.4 Municipal solid waste in airports

In the next paragraphs and chapters, the focus will be only on MSW's stream in airports, since it is the main objective of the study of this thesis.

In particular, the target is the MSW coming from the public areas of the airports such as terminals (with duty free shops, restrooms, restaurant and café areas), arrivals and departures sectors (check-in areas, packaging counters, retail outlet, eateries…).

For this specific type of waste, a key aspect which contributes to a better waste management is the one related to people's behaviour and awareness, including both passengers, employees and janitorial staff. The latter needs to be trained in order to carry out a proper waste collection and separation, while passengers and employees are the main responsible for the quality of the sorting, depending on their choices every time they throw a waste. This can affect importantly the subsequent treatments: each treatment facility can operate when certain thresholds of contamination are not crossed, otherwise the treatment has to be discarded, leaving available only treatments with lower environmental performance such as incineration and landfill (National Academies of Sciences, 2018).

Possible factors leading to bad separate collection in an airport are:

- people coming from numerous places in the world with different habits;
- people caring less or putting less attention;
- people being in a rush;
- people unsure of which bin the waste has to be discarded in;
- waste signage unclear or written in other languages;
- types of waste which, depending on the location, have to be discarded in a different bin;
- multi-material waste which requires further sorting (e.g. juice cartoon with plastic cap);
- waste bin of different shape, size and colours.

Efforts on waste separation have been carried out by airports through the implementation of separate bins for each fraction and through helping signage. Nevertheless, airports state that people's participation in improving the waste management in public areas is one of the main challenges they have to face for the reasons mentioned above (National Academies of Sciences, 2018).

According to a study by Hershkowitz et al. of 2006 concerning MSW in some U.S. airports, more than 75% of MSW is either recyclable or compostable, with paper being the main waste type

(40%). If these amounts would effectively be sorted in the right way, the relative amount sent to landfill or incineration would be strongly reduced, lowering the related impacts. The same study also subdivides the MSW into three different areas of origin for this waste flow ("Terminal public area waste", "Airline waste" and "Retail and restaurant waste") but doesn't provide a specific value referred to public places only as all three categories actually include a portion that should be taken into consideration for public areas.

2.4 Waste sorting

The management of the MSW includes different steps: collection and separation of the waste, transportation and storage, several treatments in specific facilities with the aim of recovering recyclable materials and/or energy and final disposal. An example of a waste management scheme valid both for households' and public places' waste is shown in figure 2.4. In this figure it is possible to tell apart two main streams: the one of separate collection, where waste is initially sorted in different fractions, and the one of the mixed bag collection, where the waste is unsorted (this stream can include either residual waste or all the fractions if source separation is not implemented). In addition to the two, there could be an intermediate situation where some fractions are collected separately (monomaterial), while some other are collected together (multimaterial).

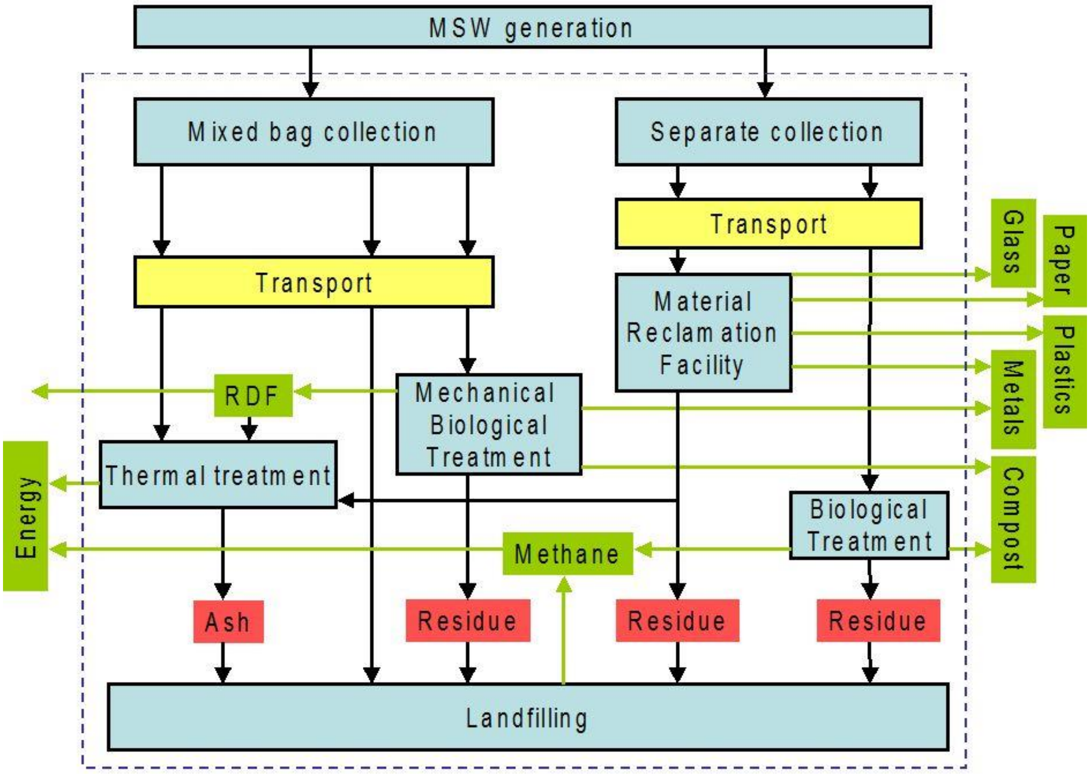

Figure 2.4 Example of MSW scheme (Abeliotis, K.,2011).

Waste sorting (or waste segregation) occurs among the different steps. Sorting the waste means separating the fractions of MSW so that each of them can undergo the required treatment. The most common fractions are paper and cardboard, glass, plastic, metals and organic waste. Depending on the local context and framework, waste sorting can happen in different points of the waste management scheme.

In many cases, when source separation is implemented, it happens in the same place where the waste is generated, i.e. at the household level or in public places. People are directly responsible for the separation of the different fractions.

In other cases, such as the mixed or grouped MSW collection, it can happen later on in central facilities. Material recovery facilities (MRF) or transfer stations are commonly used in developed countries to get recyclable items while manual picking is frequent in the developing ones. Over time, these central facilities have become more advanced with lots of options to detect the different materials, with increasing efficiency and automation. This has made this type of sorting process easier even though MRF usually have higher percentages of residues and impurities than other facilities which operate with only sorted fractions due to cross contamination. Some manual sorting is also required to improve the efficiency and overcome errors. MRF in any case helps in achieving higher recycling targets, they save materials from disposal and they are usually implemented to complement source separation or replace it when it's not possible or it doesn't appear to be effective (Cimpan et al., 2015).

Alternatively, the mixed waste stream can also be sent to mechanical-biological treatment (MBT) plants to improve its properties and subsequently to WTE plants for energy recovery.

Waste sorting is indeed a relevant step in the management of MSW. As a matter of fact, it's the divide between the amount of waste that can be recycled and turned into new products and the one that will have to be incinerated or disposed of in landfills.

2.4.1 Impacts of the sorting step

Each step in the MSW management plays a role in the overall environmental and economical impacts of a selected waste management scheme. Nevertheless, the contribution of each of them is not the same: two studies (de la Barrera & Hooda, 2016; Fitzgerald et al., 2012), which analysed the CO_2-eq emissions of the collection, sorting and recycling step of two different MSW collection's alternatives, showed that sorting in MRF is the step with relatively lower emissions, especially if compared to collection (where fuel consumption plays an important role) and recycling (where significant emissions are avoided due to energy and material savings).

The emissions and the energy consumption connected to sorting also depend on the type of collection and they increase whenever mixed bag collection is applied or some material are grouped together as more energy and fuel are required to separate them afterwards (de la Barrera & Hooda, 2016; Fitzgerald et al., 2012; Pressley et al., 2015). This shows the strong connection between the collection and the sorting step: when monomaterial collection is put into place, post-sorting is minimal and most of the impacts come from the use of more trucks for collection, while when multimaterial collection is chosen, the impacts are partially moved to the post-sorting step.

Generally speaking, it is still under investigation whether the best overall alternative in terms of costs (collection and various treatments) and ecological impacts comes from sorting the waste at the source or from collecting it as a mixed stream, with post-treatments to recover the various fractions. The answer also depends on the local context where for instance the grouping of the materials in the multimaterial collection is made according to different criteria, collection costs might be higher or lower, regulations might prevent some options and recyclable materials from mixed waste collection might not get the same market value and quality as the source separated ones (Cimpan et al., 2015; Yıldız-Geyhan et al., 2016). The type of plants available in the area might also have an influence. Furthermore, the choice has a social impact too as it can affect people's awareness and attitude towards recycling and reduction depending on if they are personally involved in these practices or not (Jacobsen et al., 2020).

2.4.2 Alternative ways of waste sorting

In recent years many studies about artificial intelligence and waste management have been carried out and lots of them focus on waste sorting (Alcaraz-Londoño et al., 2022; Lin et al., 2022). Researchers have been suggesting ways to automatically sort waste through different methods and have created some prototypes to study their effects. These methods can be distinguished in two categories: the first includes devices which rely on sensors such as IR sensors (used to detect the waste), moisture sensors (used to separate dry and wet waste), inductive proximity sensors (to detect metals), LDR sensors (to distinguish plastic from paper) and/or others. Hassan et al. (2018), Jayson et al. (2018), Pai et al. (2022) and Sharanya et al. (2017) provide examples in this direction; the second category relies on cameras collecting images of the waste, which is then classified and sorted in the correct trash bag through different types of machine learning algorithms (Jacobsen et al., 2020; Pamintuan et al., 2019; Xueming et al., 2022). In addition, some of these prototypes also have sensors which allow to know when the bin is full and needs to be emptied.

The idea behind these methods is to improve the waste sorting at the source of waste generation, thus leading to higher amounts and higher quality of recyclable materials and reduced hazards for people involved in the waste sector. Moreover, these strategies might reduce or eliminate some of the treatments (such as an intermediate plant for segregation) before a waste can be transported to a recycling plant, thus reducing the relative impacts (Kamlesh et al., 2021).

In the literature it's not clear yet if automatic sorting can provide benefits to the overall waste management system in terms of decreased environmental burdens and/or reduced costs. The collection and transport steps might be affected as well. That's one of the issue this thesis will try to address.

WiSort bin, the automatic prototype studied in this thesis, will try to answer some of the questions by assessing what happens when automatic sorting is applied to a public place such as an airport.

This is not the first attempt of evaluation in public places as Jacobsen et al. (2020) tested their prototype "Waste Wizard" in a zoo, a retail store and during a festival. The main aim was to explore people's knowledge and perception in sorting the waste where waste segregation is more demanding for people. People were stimulated to use the bin and were asked to guess the right bin before throwing the waste, knowing that the automated bin was able to sort between plastic and metal on the one side and general waste on the other. Sorting efficiency turned out to be of 85.7%, very similar to 85.2%, the average percentage of time people guessed correctly the bin.

The experiment also showed how people had some difficulties in sorting the waste even though they were used to do that at home, especially when misleading signage were present on the items they had to throw away or because different rules applied with respect to their hometown. Sometimes the reason was that sorting the waste was not considered a priority or it was time-consuming or because they believed it to be useless as later on they thought waste would be mixed again. People showed interest in how easy an automatic system would simplify the task for them.

This thesis will explore more and widen the effects of such applications in the public areas of Milano Malpensa airport.

2.5 Frameworks for the cost and environmental analyses

Many studies available in the scientific literature have been carried out to perform cost analysis and environmental assessments to evaluate different waste management strategies. Costs are usually investigated with tools such as cost benefit analysis (CBA) and life cycle costing (LCC), while environmental impacts by means of life cycle assessments (LCA). Sometimes these methodologies focus only on the economic part or on environmental and/or social aspects, while other times they combine them in order to obtain a more complete description of a system. Hoogmartens et al. (2014) and Carlsson Reich (2005) provide an overview of all these assessment tools. In the waste management field, Lam et al. (2018) established for instance a life cycle cost benefit analysis framework in order to assess different food waste management alternatives at Hong Kong International airport: in this framework three type of costs and benefits were included, i.e. economical, environmental and social; the latter two were included through economic evaluations into the CBA. Environmental costs were obtained through the monetization of the results of an LCA while the social one were based on opportunity costs of land and disamenity costs. Another study by Zhang et al. (2021) analysed the waste classification schemes of different countries through independent economical and environmental assessments and then compared the results with a radar chart analysis. Elagroudy et al. (2011) performed a comparative LCC and an environmental assessment on three different waste management scenarios in Iraq and a ranking of the alternatives based on the results was done in order to select one. Other studies that deals with waste management evaluation frameworks are the ones of European Commission (1997), US EPA (1997), Feng et al. (2009), Gomes et al. (2008) Medina-Mijangos et al. (2021), Medina-Mijangos & Seguí-Amórtegui (2021) and Woon & Lo (2016).

Alternatively to full LCA and CBA\LCC, in the scientific literature other simplified ways to assess the environmental and/or economical sustainability of solid waste management (SWM) systems have been suggested. Rigamonti et al. (2016), for instance, recommend the use of three indicators whenever it is not viable to carry out detailed analyses: a material recovery indicator (to determine the amount of recycled materials over the total collected waste), an energy recovery indicator (to take into account all those sources of energy recovered and made available from waste) and a cost indicator (to estimate the total costs of each studied alternative). Other studies (Michel Devadoss et al., 2021; Sarbassov et al., 2020) rely on the SWM-GHG calculator to evaluate the greenhouse gases (GHGs) emissions connected to different waste management options. This tool was developed by IFEU[3] and allows to perform an LCA based on the climate change impact category (IFEU, 2008). One of the two (Sarbassov et al., 2020) was applied to study the emissions connected to the management of the MSW at Astana International Airport.

The framework used by Zhang et al. (2021) was chosen as a reference for this thesis. An LCA with the inclusion of all impact categories according to the EF 3.0 method was performed in order to study the environmental impacts of the implementation of WiSort bin and a more simplified analysis of the costs was carried out with the available costs data.

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[3] Institut für Energie-und Umweltforschung Heidelberg GmbH

3 CASE STUDY: WASTE MANAGEMENT AT THE MILANO MALPENSA AIRPORT

The case study of the thesis is the airport of Milano Malpensa, an Italian intercontinental airport both for passengers' and freight transport located in the Lombardy region (northern Italy) within the municipality of Ferno and Somma Lombardo in the province of Varese. It is managed by the company SEA SpA, together with the airport of Milano Linate, and it serves more than 28 million passengers every year. On average more than 600 flights per day take off and land in this airport (SEA, 2020). Figure 3.1 shows additional information regarding passengers' geographical origin.

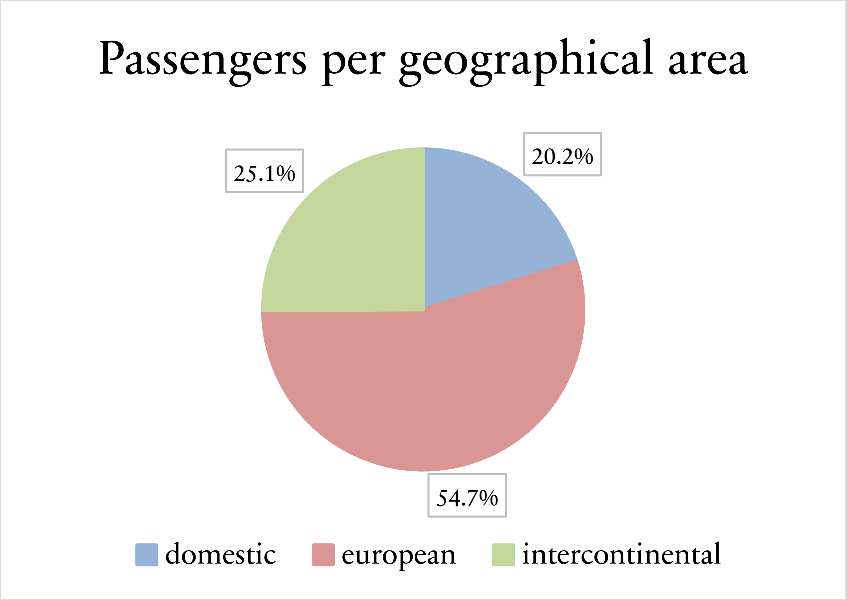

Figure 3.1 Passengers divided per geographical area at Milano Malpensa Airport in 2019 (SEA, 2021).

The airport has two terminals (T1 and T2) which serve different airlines and flight operators. Each of them can be divided into two main areas: landside and airside. The landside is the area of the airport before the passengers' security checks, while the airside covers all the areas after them, including the gates, most of the shops and restaurants, the cargo areas, the aircraft runaways, airplanes and buildings on the airside (fig 3.2). This division is explained in order to clarify some aspects in the next chapters, since they can have different regulations and different companies and municipalities are involved.

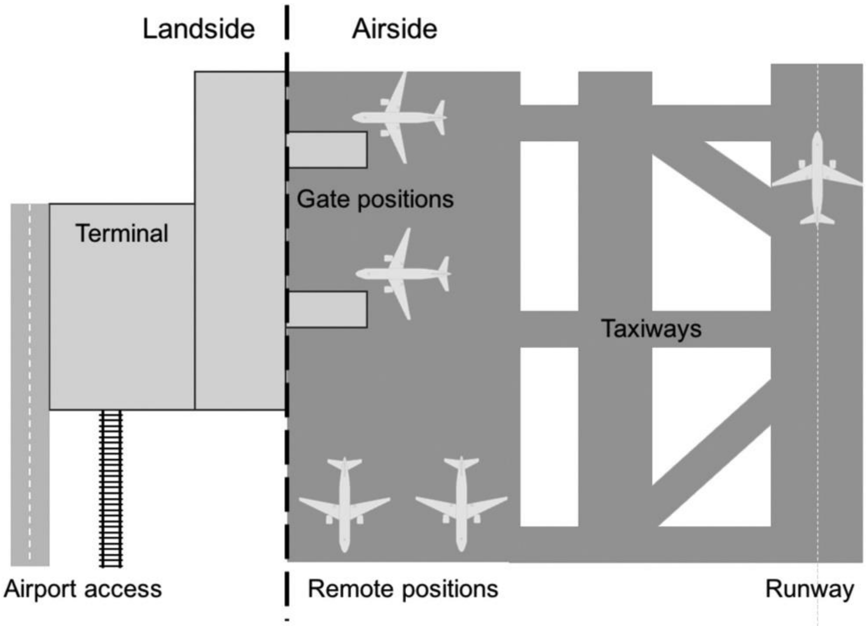

Figure 3.2 Area of a generic airport divided between landside (light grey) and airside (dark grey) (Schmidt, 2017).

3.1 The airport's waste data and management

The types of waste produced in the airport are the same described in table 2.1 of paragraph 2.3.1. They can be grouped in two main categories according to the Italian legislation[4]: municipal solid waste and special waste. Their amounts and description are provided in table 3.1.

Table 3.1 Four categories of waste and relative amounts for the airport of Malpensa (SEA, 2021). Data refer to year 2019, considered the last representative one.

Type	Category	Amount (ton)	Description
Municipal solid waste	Sorted	2444.00	e.g. paper and cardboard, glass, plastic, metal, wood, toners, batteries, organic waste, sweeping waste…
	Unsorted	4502.00	e.g. deplaned waste, residual waste and bulky waste
Special waste	Hazardous	114.00	e.g. exhausted oils, oily emulsions, oil and diesel filters, sanitary waste…
	Non hazardous	210.00	e.g. ferrous scrap, expired medicines, alkaline batteries

The total waste generated in one year at the airport amounts to 7.270 tonnes. MSW accounts for 95.5%, while special waste for the remaining 4.5%. Values refer to year 2019, which has been considered the last representative year. The reason can be deduced from figure 3.3, where the trends of waste generation and passenger's number are shown for the last decade. They both show an increase until 2019, then they both drop in years 2020 and 2021 for the COVID-19 pandemic

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[4] Decree 152/06 and subsequent modification and integrations

due to the restriction on travelling. The same figure highlights again how the two factors are highly correlated.

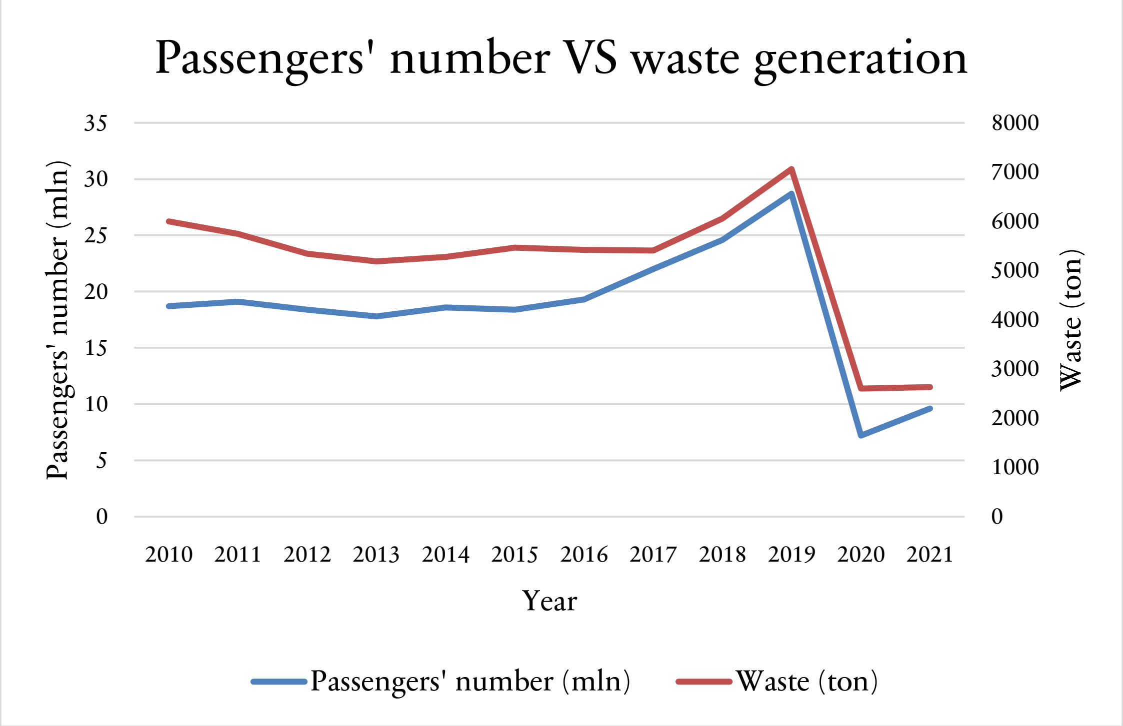

Figure 3.3 The figure shows the trend of passengers' number and waste from 2010 to 2021. Data from SEA sustainability reports.

MSW composition at the Milano Malpensa airport is shown in figure 3.4 and table 3.2. Unsorted waste corresponds to 70.7% of the total MSW. The high percentage is partially explained by the fact that it also includes deplaned waste, which accounts for around 45% of the total unsorted waste. Deplaned waste is usually collected unsorted due to economic reasons and reduced timing between flights and it is assimilated to the MSW, except for the food waste coming from airplane's galleys which is managed directly by the catering companies according to the law[5] and thus not directly by the airport. The sorted waste accounts for 29.3% and the main fractions are organic waste and paper. Sorted MSW is managed by the municipalities and carried to plants for recovery and recycling, while unsorted MSW is sent to incineration for energy recovery. There's no direct landfilling.

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[5] D.M. 22 maggio 2001

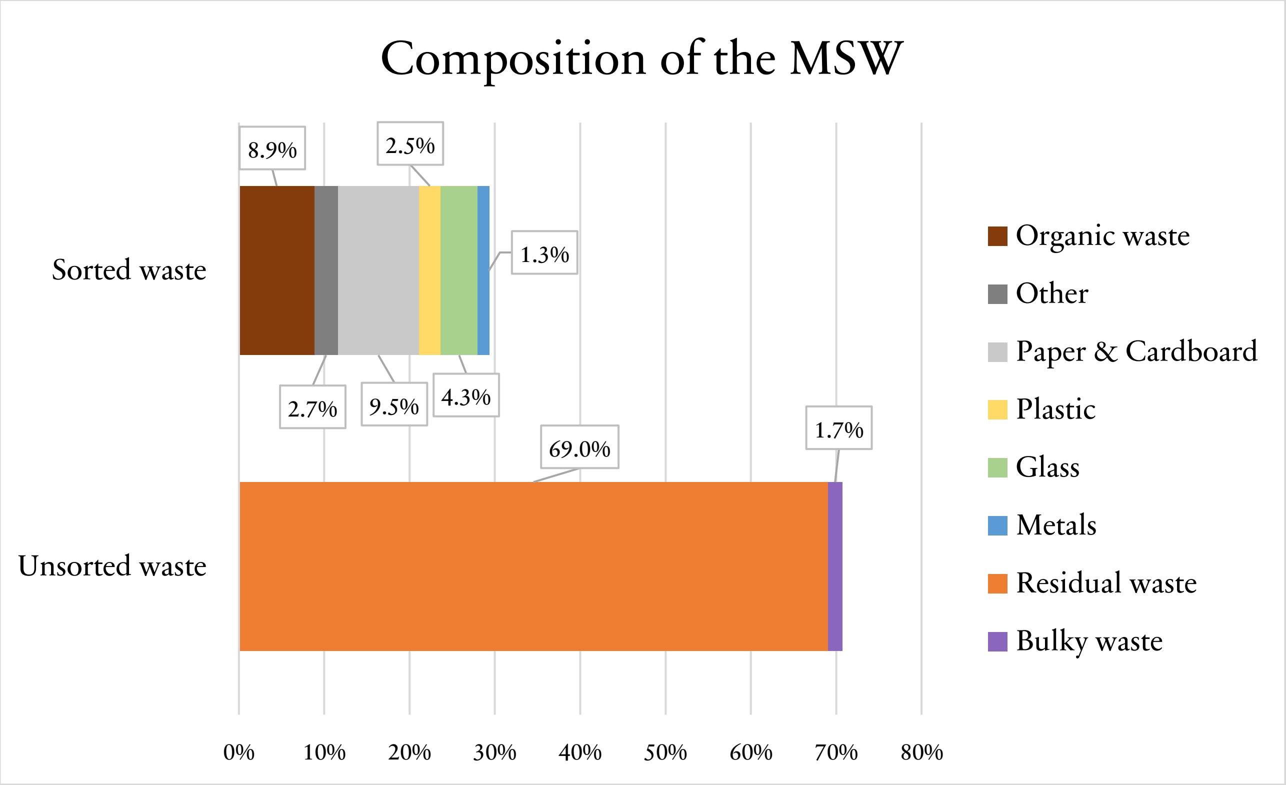

Figure 3.4 Composition of the MSW collected at the Malpensa airport. Sorted waste accounts for 29.3% and unsorted waste for 70.7%. “Other” includes green waste, WEEE, wood waste, toners and sweeping waste. Data refer to year 2019 and were provided by SEA.

Table 3.2 Composition of the MSW and European waste code (EWC) for each fraction. In addition, it is shown the number of journeys made from the airport's waste storage area to the final treatment plant for each fraction. Data refer to year 2019 and were provided by SEA. Note that these values refer to T1 (landside + airside) + airside of T2 (area of competence of Ferno-Lonate) so the overall amounts do not correspond to the ones shown in table 3.1. Nevertheless, the composition of the MSW can be considered representative for the airport.

COMPOSITION OF MSW (2019)					
UNSORTED WASTE	**EWC**	**ton**	**%**	**N° journeys**	**%**
Residual waste	200301	4,023.43	69.0%	644.00	42.9%
Bulky waste	200307	97.72	1.7%	34.00	2.3%
Mixed packaging	150106	0.00	0.0%	0.00	0.0%
Sweeping waste	200303	0.00	0.0%	0.00	0.0%
TOT (unsorted)		**4,121.15**	**70.7%**	**678.00**	**45.2%**
SORTED WASTE	**EWC**	**ton**	**%**	**N° journey**	**%**
Bulky waste	200307	0.00	0.0%	0	0.0%
Sweeping waste	200303	110.14	1.9%	19	1.3%
Food waste	200108	516.30	8.9%	416	27.7%
Glass packaging	150107	251.28	4.3%	66	4.4%
Paper	200101	554.15	9.5%	194	12.9%
Cardboard	150101	0.00	0.0%	0	0.0%
Mixed packaging (plastic)	150106	148.62	2.5%	67	4.5%
Metals	200140	77.84	1.3%	33	2.2%
Green waste	200201	0	0.0%	0	0.0%
Wood packaging	150103	47.26	0.8%	20	1.3%
Lead batteries	160601	0	0.0%	0	0.0%
Exhausted oils	130208	0	0.0%	0	0.0%
Animal and vegetable oils	200125	0	0.0%	0	0.0%
WEEE 1	200123	0	0.0%	0	0.0%
WEEE 2	200136	0	0.0%	0	0.0%
WEEE 3	200135	0	0.0%	0	0.0%
WEEE 4	200136	0	0.0%	0	0.0%
WEEE 5	200121	0	0.0%	0	0.0%
Toner	80318	1.837	0.0%	3	0.2%
Used clothes	200110	0	0.0%	0	0.0%
Paint, inks, adhesives	200127	0	0.0%	0	0.0%
Medicines	200132	0	0.0%	0	0.0%
Batteries	200133	0.073	0.0%	4	0.3%
Inert	170904	0	0.0%	0	0.0%
TOT (sorted)		**1,707.50**	**29.3%**	**822**	**54.8%**
TOT (sorted+unsorted)		**5,828.65**	**100.0%**	**1500**	**100.0%**

For what concerns waste management, the airport falls into the category of centralized system as described in paragraph 2.3.2. Moreover, according to some direct interviews with SEA, it has implemented different waste initiatives: first of all, it has set targets for separate collection with the aim of achieving 61% in 2026 (starting from a reference value of 49.7% in year 2020). The percentage of separate collection is obtained by considering both municipal and special waste that can be recovered over the total amount collected, excluding deplaned waste; the airport has also joined some European and pilot projects in order to increase the collection of specific categories of recyclable materials (e.g. selective collection of PET bottles) and it is about to start some composition analysis of the deplaned waste of some airlines with the aim of promoting its separate collection in the future. The airport is also planning to implement a door to door collection for tenancies in the future. Recently, the airport has also introduced innovative machines which are able to scan the LAGs at the passengers' security checks. This action of waste prevention will allow passengers to carry their items containing liquids (especially water bottles) without the need of discarding them and buying new ones.

3.2 Waste in the public areas of the airport

Waste coming from public areas is 2.21% of the total MSW and accounts for 153.5 ton/year. This value includes the waste bins scattered in the airport but not the ones provided by restaurant and cafeterias from the passenger side. Wisort bin would be able to intercept both.

The main type of bin used in the public areas to promote the separate collection of the waste is the quadripartite bin, capable of collecting plastic, paper, glass & metals and residual waste (fig. 3.5). Nevertheless, some areas have only tripartite bins with two possible arrangements: the first which allows the collection of plastic, paper, glass & metals (fig. 3.6) and the second where only residual waste can be collected (fig. 3.6). Even though they should be located close to each other in order to be similar to the quadripartite ones, it is not the case due to repositioning carried out by passengers or operators (without the permission of the managing authority). The consequence is a limitation to the quality of the material in the bags. In fact, a passenger standing in front of a tripartite bin with the first arrangement might discard non recyclable items in it (thus increasing the level of impurity) or, if in front of a tripartite bin with the second arrangement, might discard recyclables item in it (thus preventing the recovery of those items). Tripartite bins correspond to an old and less conscious purchase of the airport for the collection of waste that will be progressively phased out and replaced with the quadripartite ones.

Figure 3.5 Quadripartite bins of Malpensa airport.

Figure 3.6 Tripartite bins of Malpensa airport.

Furthermore, there are some containers for batteries and toners collection. Organic waste is collected in canteens, restaurant kitchens and some passengers' cafeterias but it's not part of the collection in public places for hygienic and management reasons.

At the moment the level of separate collection is really variable and materials often result mixed in each of the four bags (see paragraph 4.3.1 and 4.3.2). As a consequence, this limits, if not prevents at all, the recycling of the content of the bags, which are delivered to incineration as the most suitable option. The causes of that, as mentioned in the previous paragraphs (2.3.4), are the bad separate collection performed by the passengers and the absence of a possible sorting carried out by the operators afterwards. Interviews to airport's managers of SEA also revealed that reasons why there isn't always a good source separation are the absence of investments on monitoring activities from the company (as it would be too expensive), bad education of operators and reduction of the costs of operators related to correct management of the separate collection. An improvement of the source separation could be beneficial to the airport because disposal costs could be reduced and the perception of the quality of the service from the passengers would change positively. It would also be a way to address sustainability issues.

3.3 Waste physical flow

In this paragraph the physical flow of the MSW waste coming from public areas is described. The description is useful for the subsequent LCA and cost analysis.

MSW coming from the airport is managed by two municipalities, which in turn assign the responsibility to private companies. The municipality of Ferno-Lonate regulates T1+T2 airside while for T2 landside the municipality of reference is Somma Lombardo.

The study takes into consideration the waste flow starting from T1 as WiSort bin was installed there. Terminal 2 was temporary closed at the time of the experimentation.

MSW is collected every day from public areas by the cleaning companies. The operators empty the bins more than once during the day (up to 9 times/day in holiday periods), usually when there are fewer passengers (according to boarding times) and movements with waste bags and carriages are easier. Trash bags are then stored in designated areas on the same floor the material is collected, then they are brought every day to dedicated dumpsters located outside the ground floor of the airport where tenancies and other operators bring their own waste too.

Field observations at the airport showed that some operators of those cleaning companies are less precise in the collections of the bags and they do not always consider the colour of the bags and its content (by keeping them separated) thus compromising the source separation performed by the passengers.

From there, they are carried to a waste separation area (WSA), located within the boundaries of the airport, through urban collection trucks, which can compact the waste. Except for glass and aluminium, all other waste types get compacted. At the WSA the waste is put into roll-off containers which are also able to compress it and reduce volumes further. The roll-off containers are then carried away by bigger trucks to the final treatment plants. The reduction in volume allows to have on average one truck leaving the waste separation area per day instead of 4/5 per day (in order to reduce emissions and costs). Trucks work with diesel oil. The collection &

transport company is responsible only for collecting and carrying the waste to the different plants, in agreement with the municipality and the plants.

The initial physical flow of each waste fraction from the public areas to the WSA is shown in figure 3.7. The plants where the waste is delivered are shown in figure 3.8. Details about the plants are given in table 3.3. It is possible to observe that plastic, besides residual waste, is sent to energy recovery too and not to recycling, as it would be preferable according to the waste hierarchy. The reason is that the airport has some difficulties in meeting the requirements for plastic recycling: for example they can not select this fraction that well so it usually includes items that for their size or type of material should not be present[6]. As a result, plastic is actually classified as mixed packaging (EWC 15 01 06) and thus sent to energy recovery.

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[6] These requirements are imposed by Corepla, the Italian consortium of plastic packaging recycling. For instance, depending on the type of agreement, there are limits on size (max 20% w/w of big items (larger than format A2) or PET/HDPE/PP liquid containers not larger than 5l) or materials (absence of plastic strapping, expanded polystyrene, cellophane and others) or level of impurities above a certain threshold (max 20% w/w of extraneous fraction) (Corepla, 2020).

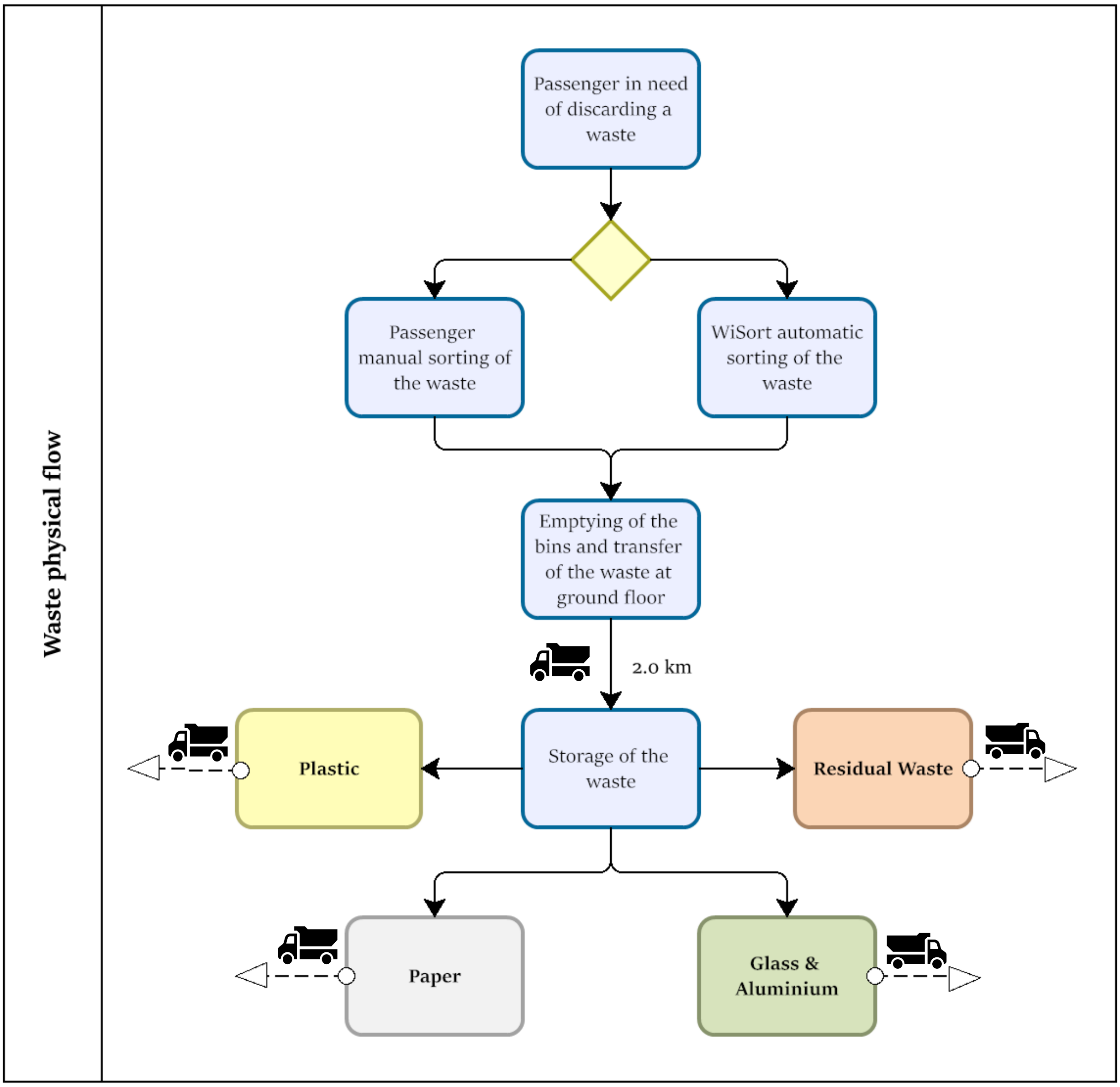

Figure 3.7 Initial part of the physical flow of MSW, common to every waste fraction. It already includes the alternative option, i.e. when WiSort bin automatically sorts the waste for the passenger. Storage of the waste refers to the WSA of the airport. Bizagi Modeler (version 4.0.0.014) was used to create the figure.

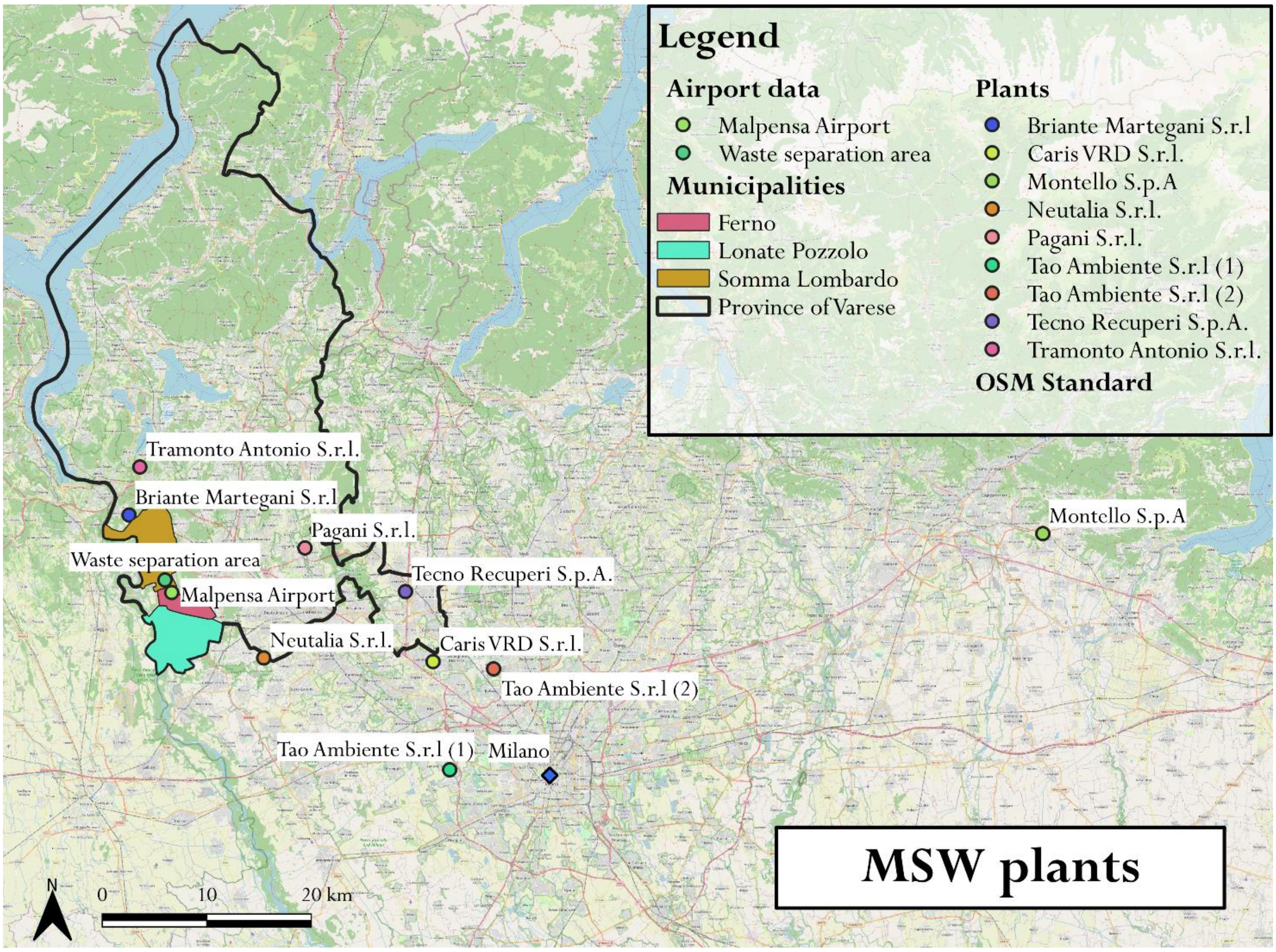

Figure 3.8 The image shows the destination plants of the different MSW fractions. QGIS 3.16 was used to create the map.

Table 3.3 Details of the plants for waste processing. Names were provided by SEA. Option 2 for plastic is just an assumption if it is assumed that plastic is sent to recycling instead of energy recovery.

Fraction	Plant	Description
Residual waste	1. Neutalia Srl	1. WTE plant with energy recovery
Food waste	1. Neutalia Srl 2. Montello SpA[7]	1. Transfer station 2. Plant for anaerobic digestion
Plastic	1. Tramonto Antonio Srl 2. Caris VRD Srl	1. MBT plant for plastic energy recovery (production of solid recovered fuel (SRF) for cement kiln/power plant) 2. Alternative assumed plant for plastic material recovery (selection of plastic polymers)
Paper	1. Pagani Srl	1. Plant for paper and carboard recovery (selection of pulp paper)

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[7] Information available on Neutalia website (retrieved March 03, 2023 from https://www.neutalia.it/bandi-appalti).

Glass & Aluminium	1. Tecno Recuperi SpA	1. Plant for glass and aluminium recovery (separation of glass and aluminium)
WEEE	1. Tao Ambiente Srl	1. Plant for WEEE recovery (selection plant)
Non MSW metals and Bulky waste	1. Briante Martegani Srl	1. Plant for metal scraps and bulky waste recovery (selection plant)

3.4 Description of the WiSort Bin

WiSort bin is a prototype of a smart bin capable of sorting the waste automatically into different fractions. Its structure can be divided in two parts: the lower part, where four normal trash bags are placed alongside each other (storage part) and the upper part where there's an opening which allows the waste to be inserted on a shuttle (loading part) (fig. 3.9 and 3.10). Once the waste has entered the bin, a sensor is able to detect its presence and three camera takes one picture of the waste each. The information coming from the cameras is used by a single board computer integrated in the bin, which is able to extract features using a deep learning model to identify the type of waste. This model is pretrained with waste images coming from publicly available recyclable waste datasets and every time a new waste item is inserted (such as the ones coming from the experimentation), its images are stored and used to expand the training dataset. Once the waste item has been identified, then a motor activates the shuttle and makes it move until it gets above the correct trash bag letting the waste fall in it. The bin is also capable of measuring the weight of the items inserted in the shuttle and it has sensors which allow to know when a waste bag is full.

Figure 3.9 Digital image of WiSort bin.

Figure 3.10 WiSort bin at the central satellite of Malpensa Airport (initial configuration).

The bin is connected with a normal plug to the electric system and it is also connected to the internet for remote diagnosis (such as debugging, software modifications etc.) so that less direct intervention is needed. Data on size, materials and energy consumption of the bin are provided in table 3.4. The bin has also a screen in the front which can show images and give environmental information connected to the bin.

For the experimental campaign at the airport the bin was designed to separate the waste into paper, glass & aluminium, plastic and residual waste (i.e. to be coherent with the quadripartite bins present in the airport). Every time the waste item is not identified as one of the first three categories, the shuttle lets it end up in the bag of residual waste. WiSort bin can also detect the filling quantity of each of the four waste bags and automatically contact the collection company for prompt emptying.

At the moment the protype can process only one item at a time. A green light inside the opening suggests that the waste can be inserted, then the light becomes blue when pictures from the camera are being taken and red when the shuttle starts moving. At this point the opening will close and it doesn't allow any other item to be inserted until the machine is ready again. As a safety measure, if a passenger doesn't remove the hand from the opening, flashes of intermitted yellow and red light are emitted inside the opening.

Table 3.4 Main features of the WiSort bin.

WiSort bin data	**Values**
Size (L, H, W)	▪ (1.35 m, 1.90 m, 0.48 m)
Materials	▪ Wood (20.9 kg) ▪ Aluminium (26.4 kg) ▪ Steel (5.2 kg) ▪ Plastic (PVC) (4 kg) ▪ Copper (0.01 kg) ▪ Electronics (boards. sensors. motor. cables) (5 kg)
Energy consumption (measured)	▪ Power (Min[8] 85 W. Max[9] 114 W) ▪ Current (Min 0.75 A. Max 1.4 A) ▪ Voltage (239 V) ▪ Power factor (Cos(phi)=0.47)
Expected lifetime	▪ 10 years

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[8] When WiSort bin is at rest (i.e. switched on but it is not processing a waste)

[9] When WiSort bin is sorting a waste (Max represents the maximum value during this phase)

3.5 Location of the WiSort bin

The central satellite of T1 of the airport was chosen as the area for the experiments in agreement with SEA. This satellite has 10 departing gates. The flights from this satellite include some airlines which connect Italy to the Schengen area and some low cost companies with different destinations around the world. It was therefore assumed sufficiently heterogeneous to catch different habits and behaviours.

Figure 3.11 shows a map of the satellite, where it is possible to notice the presence of a kiosk for passenger right in front of the WiSort bin, which was an additional source of waste besides personal stuff and food brought from home. WiSort bin was placed in point A in front of a wall and nearby there were many rows of passengers seats.

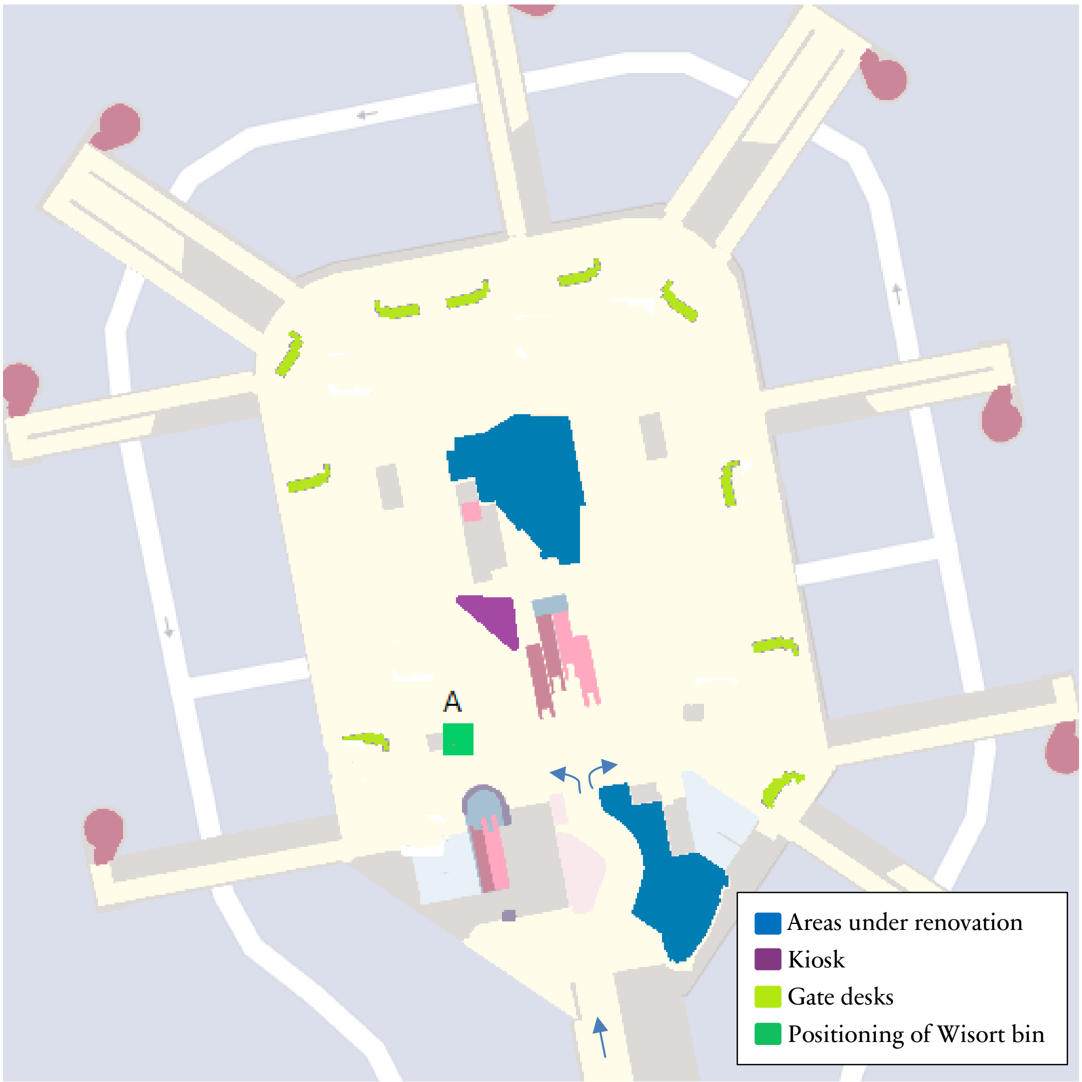

Figure 3.11 Simplified map of central satellite of Malpensa airport retrieved and modified from https://www.milanomalpensa-airport.com/it/guida-per-il-passeggero/mappa-aeroporto.

4 FIELD EXPERIMENTS

4.1 *Overview of the experiments and analyses*

The main aim of the thesis was to assess the potential advantages and disadvanteges of having WiSort bins installed in the public areas of the airport. Many tests and analyses were designed in order to find an answer from various perspectives. A brief overview is given in table 4.1 and 4.2. Nevertheless, not all of them were actually tested due to the limited time of the experimentation and because of some issues occurred with the first ones. The latter are reported in chapter 8 as possible tests for future experimental campaigns. The experiments on the field, which were carried out in February and March 2023, enabled the collection of real data, which were then used as a starting point for the subsequent analyses. For each experiment the duration period is also indicated.

Table 4.1 Overview of the experiments.

EXPERIMENT	PERIOD	AIM	PERFORMED?
Waste composition analysis - Part 1	8 days	To obtain the waste composition and the sorting accuracy of the normal quadripartite bins of the airport	Yes
Waste composition analysis – Part 2	-	To obtain the sorting accuracy of WiSort bin in order to compare it with the one of the normal quadripartite bins	No
User experience experiment - Part 1	4 days	Automatic bin close to the normal one. Collecting positive and negative feedbacks about the usage of the bin also with respect to the normal ones	Yes
User experience experiment- Part 2	3 days	Automatic bin far away from the normal one. Collecting positive and negative feedbacks about the usage of the bin also with respect to the normal ones	Yes
Awareness experiment	-	To understand if people are encouraged to use the bin if it shows them its environmental benefits and to discover if people are aware or want/need to be informed about the environmental benefit of such a bin	No
Rewarding experiment	-	To discover if people are encouraged to use the bin if they get a reward	No

Table 4.2 Overview of the analyses carried out with the data collected from experiments and interviews with SEA.

ANALYSIS	AIM
Life Cycle Assessment (LCA)	To evaluate the environmental impacts of three different waste management scenarios starting from MSW generation in the public areas of the airport until final disposal
Cost analysis	To determine the cost of managing MSW from public areas under three different waste management scenarios

The following paragraphs and chapters will describe in depth each of them.

4.2 Experiment 1: waste composition analysis

This is the most important experiment of the experimental campaign, since the environmental and cost analyses were based on these data. The waste composition analysis is the direct identification and measurement of the waste present in the trash bags of the conventional bins at the airport.

This analysis was initially done in order to determine the average composition of the waste generated in the public areas of the airport. Then it was chosen as a method to discover whether WiSort bin was able to sort the waste more precisely than the passengers' manual sorting and to determine the entity of this sorting improvement (i.e. whether the improvement was significant or negligible).

4.2.1 Metrics definition (sorting accuracy and source separation)

Two metrics were determined for the comparison of the quadripartite bins with the WiSort bin: the sorting accuracy and the source separation rate. Four types of sorting accuracies have been defined in order to describe the effectiveness of the WiSort bin from different point of views:

- Classification accuracy by item
- Classification accuracy by weight
- Bag accuracy by item
- Bag accuracy by weight

Each of them can be specified for each fraction (defined here as "x"). The choice of using the item as the reference unit in some of the formulas was made in order to be more consistent with the way the prototype performed the sorting, i.e. item by item.

The formula used for the classification accuracy by item (for fraction x) is the following:

$$Classification\ accuracy\ by\ item_x = \frac{number\ of\ items\ of\ x\ correctly\ sorted}{total\ number\ of\ items\ of\ x} \times 100$$

If, for instance, “x” is plastic, given the four bags of WiSort bin, then the numerator expresses the number of plastic items present in the plastic bag, while the denominator is the total number of plastic items introduced in the bin (which is given by the sum of the plastic items present in all the four bags, so items incorrectly sorted are included too). The classification accuracy thus gives a value of the precision of the WiSort bin in sorting each single fraction in terms of number of items correctly sorted. The same accuracy can be calculated for the normal bin and can be seen as an indirect measure of the sorting ability of the passengers (still in term of items).
The formula can also be expressed in terms of weight in this way (for fraction x):

$$Classification\ accuracy\ by\ weight_x = \frac{total\ weight\ of\ x\ correctly\ sorted}{total\ weight\ of\ x} \times 100$$

The formula is similar to the previous one, but in this case it is obtained by considering the weight and not the number of items of a certain fraction. This formula is more precise because the final aim is to sort correctly most of the “mass” of the waste introduced in the bin: items can have different weight, so for instance the accuracy by weight can be strongly affected by few heavier items that are sorted correctly (or not).
The bag accuracy by item for fraction x is defined as:

$$Bag\ accuracy\ by\ item_x = \frac{number\ of\ items\ of\ x\ in\ the\ bag}{total\ number\ of\ items\ in\ the\ bag} \times 100$$

In this formula the total number of items in the bag includes the impurities, i.e. the other fractions incorrectly sorted there. So, contrarily to the other formulas, the focus here is the amount of a fraction in a bag with respect to what is contained in the bag (rather than the same fraction contained in other bags).
The bag accuracy by weight for fraction x is defined as:

$$Bag\ accuracy\ by\ weight_x = \frac{total\ weight\ of\ x\ in\ the\ bag}{total\ weight\ of\ the\ bag} \times 100$$

While the first two accuracies give an insight of the performance of the machine learning model in sorting the waste and they indicate the dispersion of one material among the four bags, the other two are more representative of the dispersion of the impurities in each bag. For instance, if the classification accuracy by item for plastic is low and the plastic bag accuracy by item is high, this means that most of the items inside the plastic bag are indeed plastic, but there is a lot of plastic scattered in the other bags too.

These values of accuracy were determined for each waste composition analysis on the four bags of a quadripartite bin and the distribution of values was then represented with boxplots.

Such values of accuracy were calculated for each of the four fractions in order to take into account that the automatic bin might be better at identifying some types of waste than others.

The other metric used is the source separation rate. It is defined as:

$$Source\ separation\ rate = \frac{sum\ of\ weights\ of\ correctly\ sorted\ fractions}{sum\ of\ the\ weights\ of\ the\ four\ bags} \times 100$$

The source separation rate is a measure of the overall amount of separately collected fractions over the total collected waste. For the case study it is the sum of paper, glass & aluminium and plastic correctly sorted, divided by the total amount of waste of the four bags (correctly and incorrectly sorted, including the residual waste). It doesn't necessarily correspond to the percentage of waste that is sent to recycling, since in this case for example plastic is sent to energy recovery. This means that in this case the source separation rate will be higher than the percentage of waste sent to recycling. This rate is already representative of the real amount that can be recycled, since at the numerator the effective weight of the recyclable fractions is used (impurities are excluded).

The resulting values of these indicators and the measured average waste composition for the normal quadripartite bins are shown in paragraph 4.3. Since the time for the experimentation was limited and the calculation of the indicators requires a sufficiently high number of observations (i.e. waste composition analyses) in order to be representative, it was not possible to determine the values of the same indicators for WiSort bin. Indeed, the time available was used for the calibration of the automatic bin with images of waste items directly generated at the airport in order to train the machine learning algorithm for this specific case study.

4.2.2 Methodology for waste composition analysis

The average waste composition was determined by randomly picking trash bags at the airport, both from the airside and landside zones during the entire experimental period (2 months, by choosing different days and times of the day) in order to have a representative value, which was obtained by averaging the result of the single analysis of the bags. The zones selected included check-in areas, restaurant and bar areas and shops areas.

The methodology that was applied for the analysis of the content of the bags is the following: each of the four bags (paper, plastic, glass & aluminium, residual waste) was emptied and each item inside the bag was classified in term of amount, waste fraction, unitary weight and it was also observed if it was a packaging material or not. The total weight for each fraction in the bag was then obtained. This information allowed to calculate the metrics defined above. More fractions than the four collected by the bins were taken into account in order to better define the composition of the waste and to include additional ones ending up in those bins:

- Plastic, with a focus on the polymer (PET, PP, PE, PVC, PS and OTHER (P7))
- Paper and carboard
- Glass divided in green, brown and clear
- Aluminium
- Steel
- Food waste
- Residual waste
- Other (e.g. batteries, cloths…)
- Liquid

Table 4.3 provides details about the assumptions made to assign each waste item to a fraction. The identification was made easy thanks to the specification of the material and type of disposal present on most of the products[10]. Generally speaking, the rules for a good separate collection provided by the Italian packaging consortia were taken as reference model (Corepla, n.d.; Comieco, n.d.). In addition, the following criteria were applied in order to be coherent with the principle of functioning of the WiSort bin (i.e. image classification):

- in the case of items containing other items (e.g. a chips plastic package containing some chips, biscuits paper package with internal plastic box…), when calculating the metrics by item (classification accuracy and bag accuracy by item), each item was classified by the external material it was made of, while for metrics by weight (classification and bag accuracy by weight), the weight of each component was measured and assigned to the correct fraction. To give an example, the bag accuracy by item formula considers the chips package (plastic waste) with chips inside (food waste) as one item of plastic, while the bag accuracy by weight considers the weight of the two fractions and so it takes into account that in the bag that single item is actually made of two items.
- in the case of plastic/paper bags with a lot of items inside (e.g. lunch bag with water bottle, apple, sandwich and napkins inside), which showed the negligence of the passenger in sorting the items contained, the bag was considered as one item of residual waste for the item metric, while the weight metric considers as before the weight and the waste fraction of each single item.

This highlights a drawback of the WiSort prototype: even though it aims at relieving the passengers from doing the sorting by themselves, at the moment it is not able to handle situations like those described above. A sorting process done through image classification doesn't allow to understand whether an item contains other items, so an unwanted and unavoidable impurity is introduced in the bag the item is sent to. Anyway the use of the accuracy by weight metric allows in the end to have a value of accuracy which also takes into account the impurities.

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[10] According to the Decree 116/2020 it is mandatory in Italy to show this kind of information on packaging products.

Table 4.3 Assumptions made for the waste composition analysis.

ITEM TYPE	ASSUMPTION
PET bottle with PP label and HDPE cap	It is classified as one item of PET (isolated caps not attached to the bottles were though considered as additional items of PE)
Cigarette package	The package is made with paper but it usually has a thin plastic casing which commonly is not separated by the passenger and cannot be separated by the WiSort bin. Thus the item is considered as one item of paper. Even though it was not a common situation, if cigarettes are contained in the package they inevitably end up in the paper bag even though they are residual waste
Paper glass with plastic cover	Whenever this item is not thrown separated, it is consider as one item of paper (paper glass is 7-11 g while plastic casing is 2 g)
Mixed package[11]	They are considered residual waste
Composite package[12]	According to Comieco, the paper packaging consortium, their disposal depends on the municipality (Ferno-Lonate in this case). Assumptions made: • composite material c/pap84 (e.g. juice/water box) are considered residual waste (item like this usually show as indication for disposal "follow the rules of your municipality") • composite material c/pap81 (e.g. coffee paper glass) are considered paper (item like this usually show as indication for disposal "to paper")
Tissues (clean and used)	They are considered residual waste
Napkin (clean and used)	They are considered paper
Plastic fork, spoon, knifes	They are considered residual waste
Liquid (of bottles/can)	They are considered in the waste composition analysis to give an idea of the presence of this type of waste but they are excluded in the above defined metrics (e.g. a plastic bag with only plastic bottles full of water would have 100% bag accuracy by item and by weight). This assumption underlines that water is not considered as an impurity: indeed passengers do not have alternative ways of disposing the liquids before throwing the bottles/cans.

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[11] Mixed package (EWC 15 01 06): item made of two or more materials that can be separated manually from each other (e.g. bread package which is half paper and half plastic, toothbrush package).

[12] Composite package (EWC 15 01 05): item made of two or more materials that cannot be separated manually (e.g. polylaminated items such as juice box). Common type found at the airport were c/pap84 and c/pap81. "c" means "composite", "pap" means that the predominant material is paper, the number indicates the additional material ("84" means it includes plastic and alumnium, "81" it includes plastic).

4.3 Experiment 1 results

4.3.1 Waste composition analysis

This paragraph reports the findings of the waste composition analysis performed in the public areas of the airport. At the end of the experimental period, 21 independent waste composition analyses were performed making sure, as mentioned before, that bags were selected from different areas (total weight of the waste analysed was 92 kg).

Figure 4.1 shows the average composition of the waste generated in the public areas. It is possible to observe that the most relevant fractions are food waste (25.7%), liquids (22.3%) and paper (17.3%). Liquids come mainly from plastic/glass/composite bottles or cans which are thrown by the passenger without being emptied before and in minor part from coffee liquid residues. The presence of this waste category might increase the contamination when liquids spread out in the bag, especially by wetting paper elements which then might stick to other items. Food waste, which is relevant because of the higher water content if compared to the other fractions, is at the moment not part of the separate collection in the public areas of the airport, but amounts to ¼ of the total waste, suggesting that additional bins for this specific fraction should be added. Moreover, organic waste collection is already carried out by restaurants and canteens, so the food waste collected in the public areas could join this flow and this could also benefit the quality of the other bags. Since organic waste was found in all bags, an additional indication on the RW bag could be added to encourage people to throw it with this fraction and not with the others.

Items not recoverable, i.e. residual waste, are not a big fraction (8.1%) and it can be highlighted that they also include some materials which could be recyclable when a proper treatment is applied: this is the case of composite materials (e.g. juice and water boxes), whose collection is not active in the municipality of Ferno-Lonate at the moment (SAP, 2013). Also mixed packages (e.g. toothbrush package, paper glass with plastic cover) end up in this fraction whenever they are not manually separated by the person. All these kinds of items make the source separation more difficult (composite materials are usually a source of uncertainty for people, indeed it was common to find them both in the residual waste bag and paper one, and mixed packages require an additional effort for the passenger). The WiSort bin could simplify the task in the first case (since it could sort according to the rules of the municipality) but, in the second case, these items which are potentially recyclable risk to be lost anyway.

The category “other” includes mainly pieces of textile material or WEEE, but the percentage of this fraction is almost negligible (1.4%).

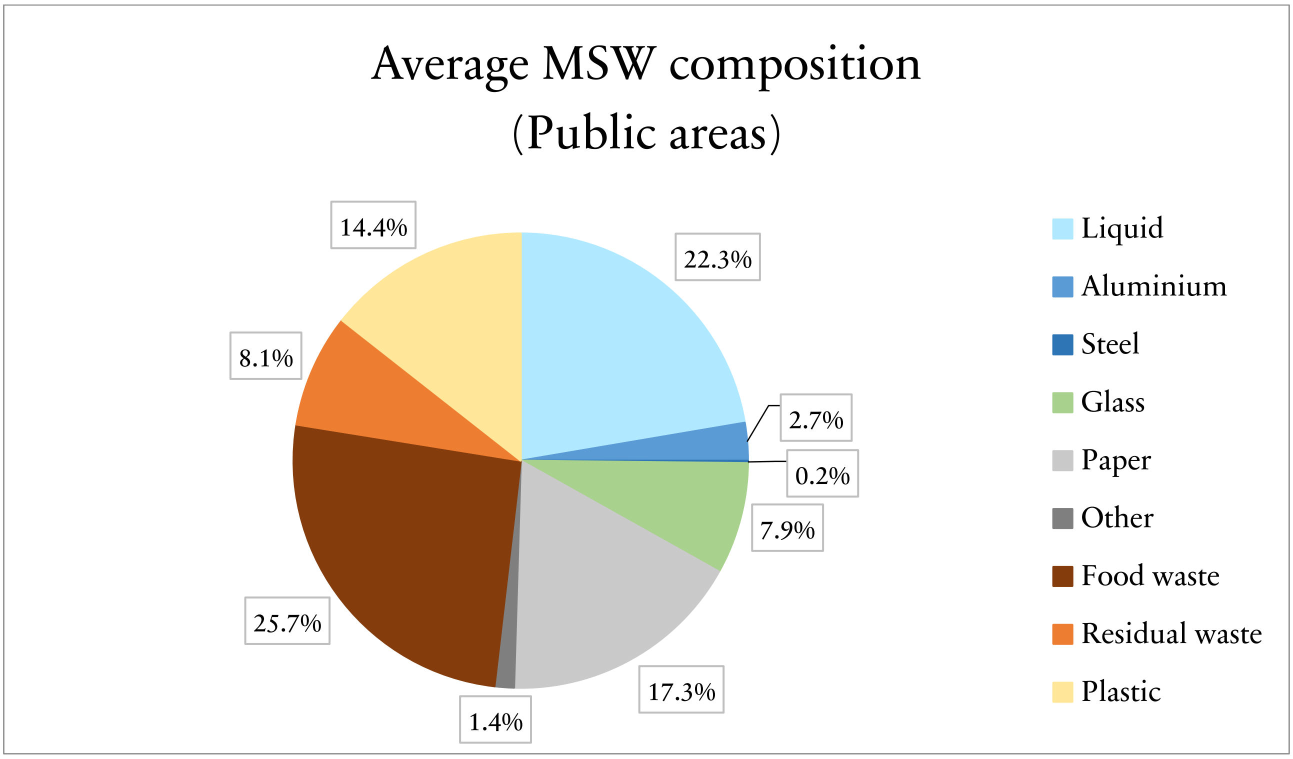

Figure 4.1 Average MSW composition of the public areas of the airport.

Table 4.4 shows the average composition of the MSW rescaled with the exclusion of liquids.

Table 4.4 Average MSW composition of the public areas rescaled without the liquids. The total amount is 119.2 tons/year.

Fraction	%
Aluminium	3.5%
Steel	0.2%
Glass	10.2%
Paper	22.3%
Other waste	1.8%
Food waste	33.1%
Residual waste	10.4%
Plastic	18.5%

Overall, the potential recoverable fraction amounts to 87.9% (recyclables + food waste) when the liquids are excluded. The value at the moment is 54.8%, since food waste counts as residual waste (which also includes the category "other") and this is also the potential quantity recoverable by the WiSort bin[13]. The two values are similar to the ones retrieved by Hershkowitz et al. (2006), which are 74% and 54% respectively (even though they refer to the overall MSW of airports). The same authors found that paper was 40% w/w, a much higher value than the one of Malpensa

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[13] 54.8% is also the maximum level of source separation achievable in the public areas of the airport

airport, but this is probably due to the fact that all the paper sheets and documents produced in the offices of the airport never end up in the bins of the public areas.

During the waste composition analysis, it was also taken into account whether an item was a packaging material or not. On average, 42.1% of the total waste is packaging waste[14] (ISPRA 2021 report shows an average value of 55% for MSW). For what concerns plastic, glass and aluminium, they were all considered as packaging materials, since non packaging ones have been classified as RW. Paper packaging is 43.3% w/w and it is higher than the 29% reported by ISPRA 2021 report. Common non-packaging items in the paper bag were napkins and paper sheets. In the RW category, packaging accounts for 23.4% and it is because of the presence of the composite and mixed materials mentioned above.

Figure 4.2 and 4.3 shows the average composition of the plastic and glass category.

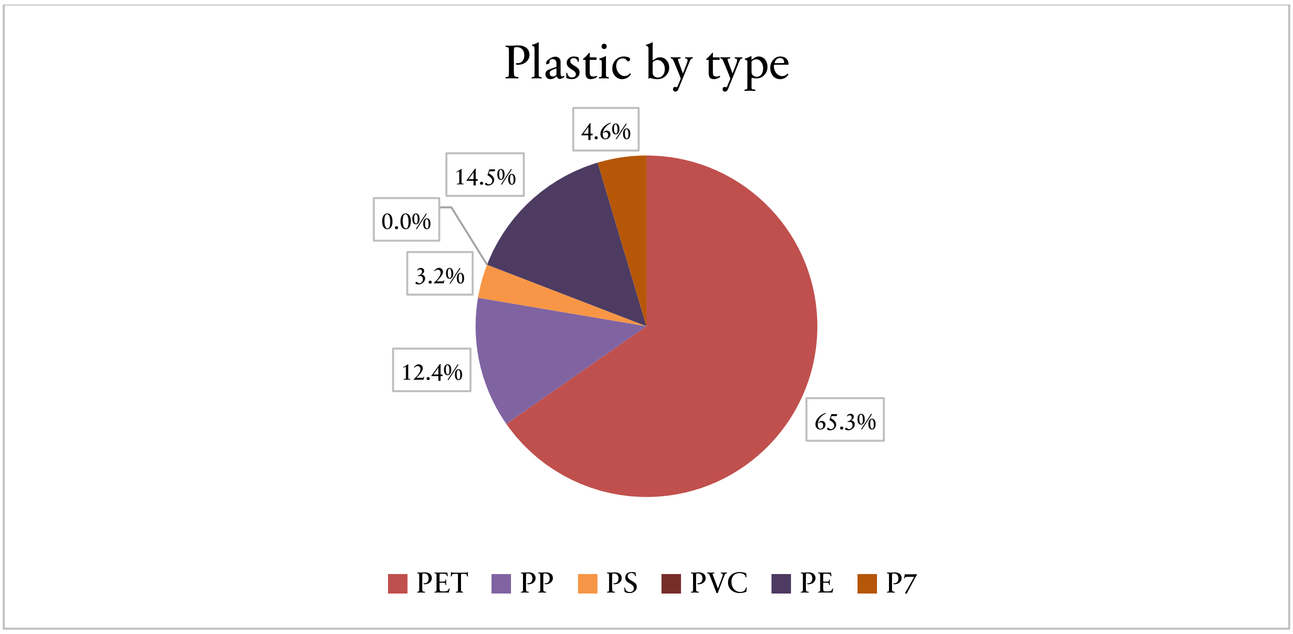

Figure 4.2 Average composition of plastic.

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[14] Percentage in w/w excluding liquids

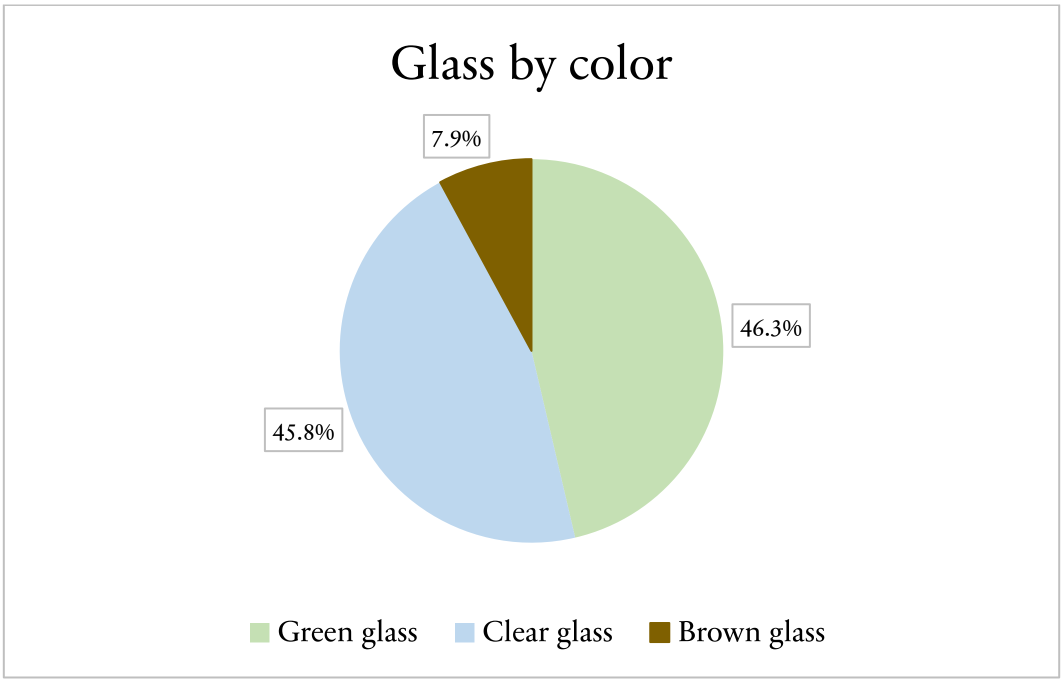

Figure 4.3 Average composition of glass.

Figure 4.4 shows the average composition of the four bags of a quadripartite bin. This figure allows to understand the average level of bag accuracy by weight in those bags: 65.3% for RW, 59.8% for paper, 78.5% for plastic (liquid included) and 59.3% for glass/aluminium (liquid included).

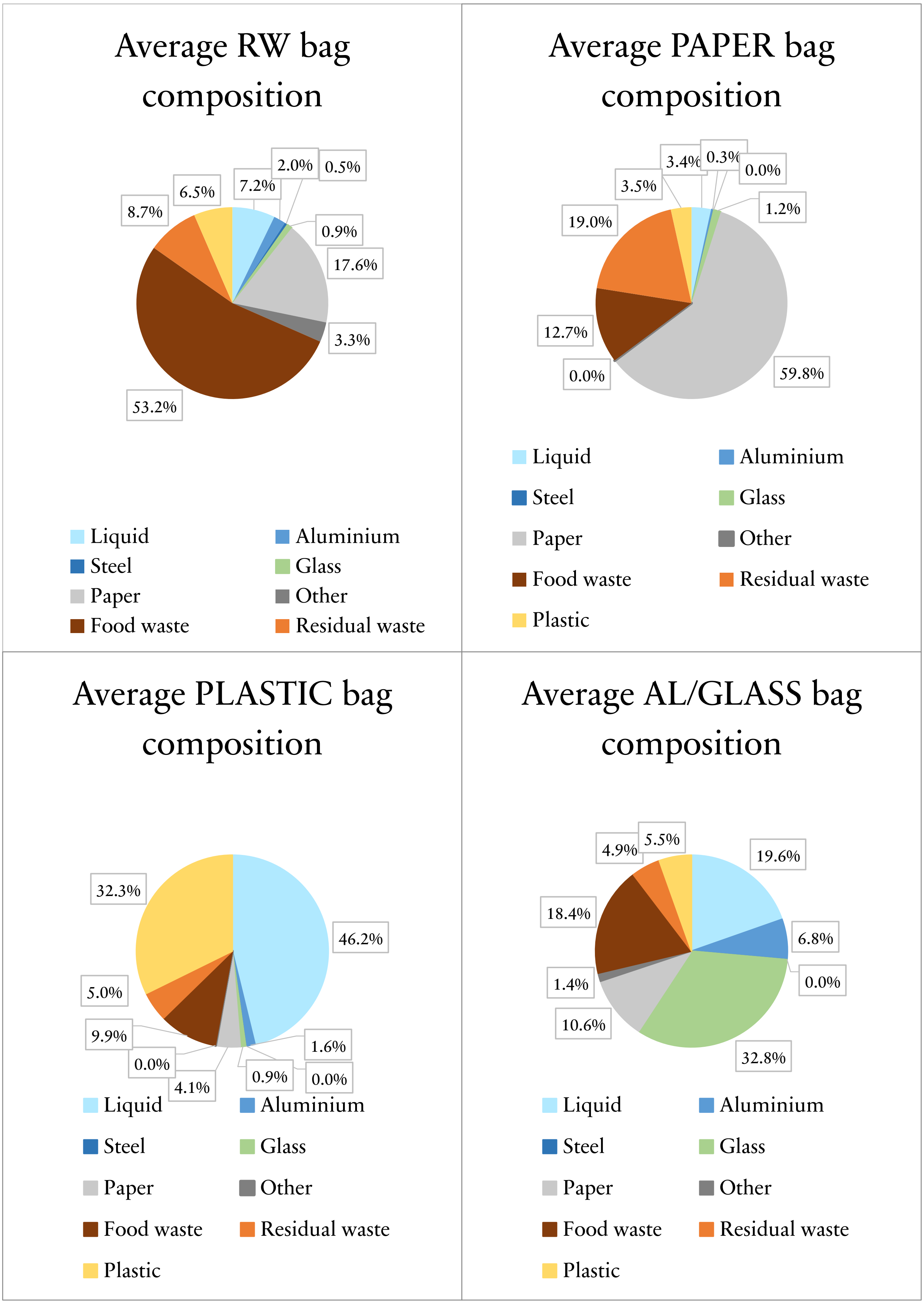

Figure 4.4 Average waste composition of the four bags of a quadripartite bin.

It wasn't unusual to find quadripartite bins where the colour of the bags wasn't matching the colour of the collected fraction. This highlights the above mentioned lack of care of some operators.
Some pictures of the bags analysed are shown in figure 4.5.

Figure 4.5 Photos of some bags analysed for the waste composition analysis. In order of appearance two bags of RW, two of paper, one of plastic and one of glass/aluminium.

4.3.2 *Sorting accuracy and source separation*

This paragraph reports the obtained values of the metrics "sorting accuracy" and "source separation" described in paragraph 4.2.2. The values refer to the normal quadripartite bins analysed for the waste composition analysis, so they can provide an indication of how good/bad the passengers do the sorting and the level of source separation they can achieve. Twenty values for each metric were obtained.

Figure 4.6 to 4.8 show the different values of accuracy. They are represented with boxplot, in order to show their variability. Each graph has a fifth boxplot where an aggregated value over the four fraction is given (i.e. each point of this latter boxplot is an average of the four values of accuracy from the other four fractions of one quadripartite bin). It must be highlighted that the bags were collected at different times of the day, so the weight of the bags was quite variable. It was uncommon to find full bags as the operators usually remove them before this happens. It happened that sometimes, given a quadripartite bin, some of the four bags were fuller than others (usually the one of glass & aluminium was emptier). There were two cases where the glass & aluminium bag was empty. This situation was taken into consideration as well: indeed, some aluminium items (e.g. aluminium foil for food, aluminium cans) were present in the other bags, meaning that the separate collection had not been properly done.

First of all, it is possible to notice a great variability for all the types of accuracy, with a particular emphasis on the accuracy by weight.

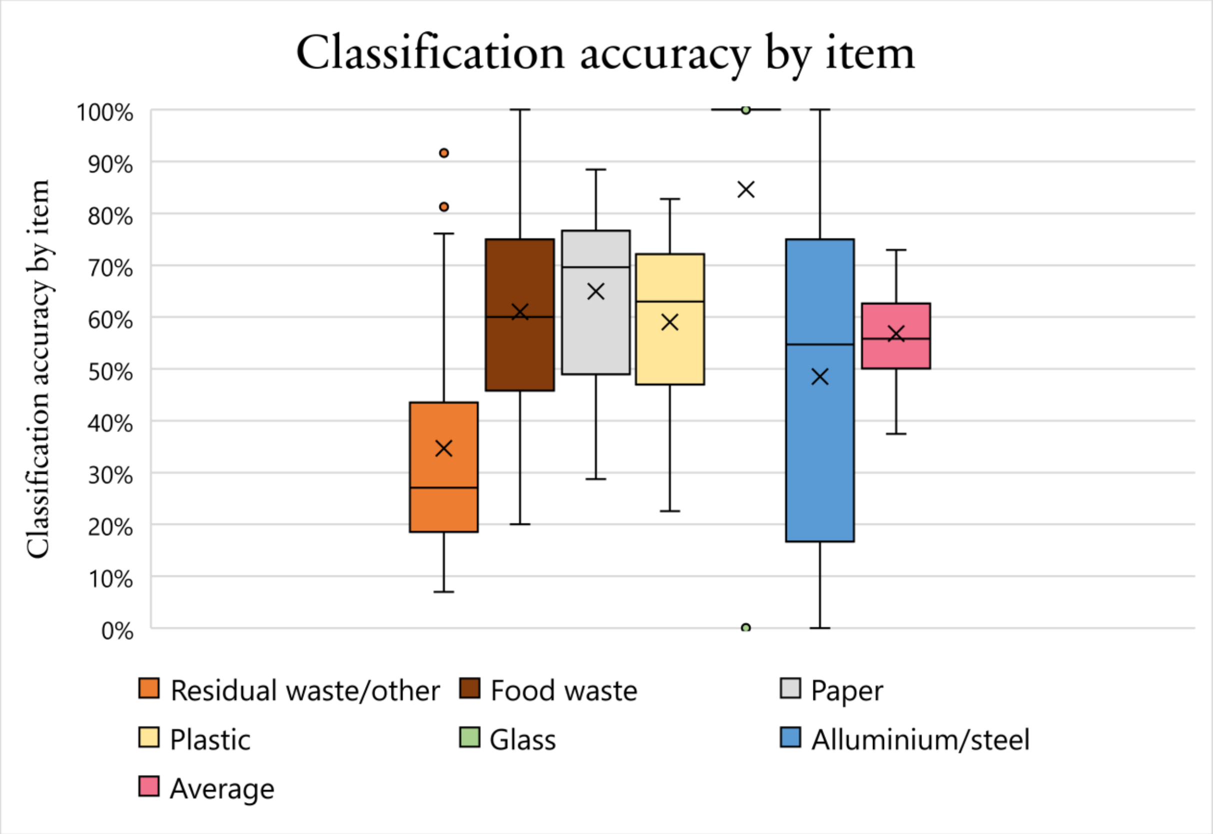

Figure 4.6 Classification accuracy.

From the figure of the classification accuracy by item (fig. 4.6) it is possible to notice that on average almost 4 items of RW out of 10 are classified correctly by the passenger as RW: this indicates the poor willingness of passengers in caring about the source separation, since the other 6 items will inevitably contaminate the other fractions. Passengers are better at classifying the other fractions with 5 to 6.5 items out of 10 correctly sorted and with 8.5 items out of 10 for glass. Glass is the easiest to classify. The average value (which is represented by an “x” in the boxplot) is always affected by the presence of particularly high or low values in the dataset, while the median (horizontal line in the boxplot) is not, because it represents the value which leaves behind and ahead 50% of the data. It is possible to notice that the median value for RW bag is lower than the average, while it is higher for the other bags.

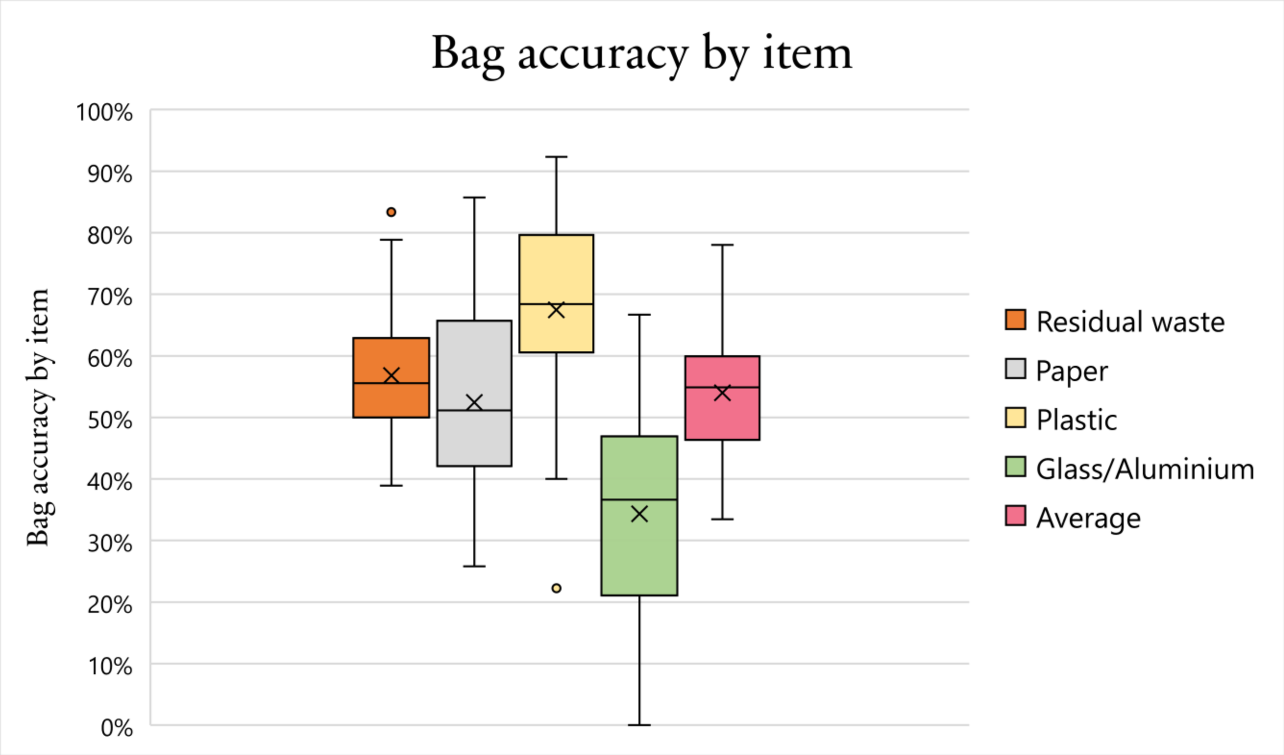

Figure 4.7 Bag accuracy by item.

Figure 4.7 shows the accuracy by item for each bag. The highest value is achieved with plastic: almost 7 items out of the 10 inside the bag are plastic items. The bag with the lowest performance is the aluminium & glass one, with 3.5 items out of 10. It happened to find bags with no correct items inside (as it can be seen with the corresponding boxplot having a minimum value of 0%). Paper and RW show on average around 5/6 items out of 10.

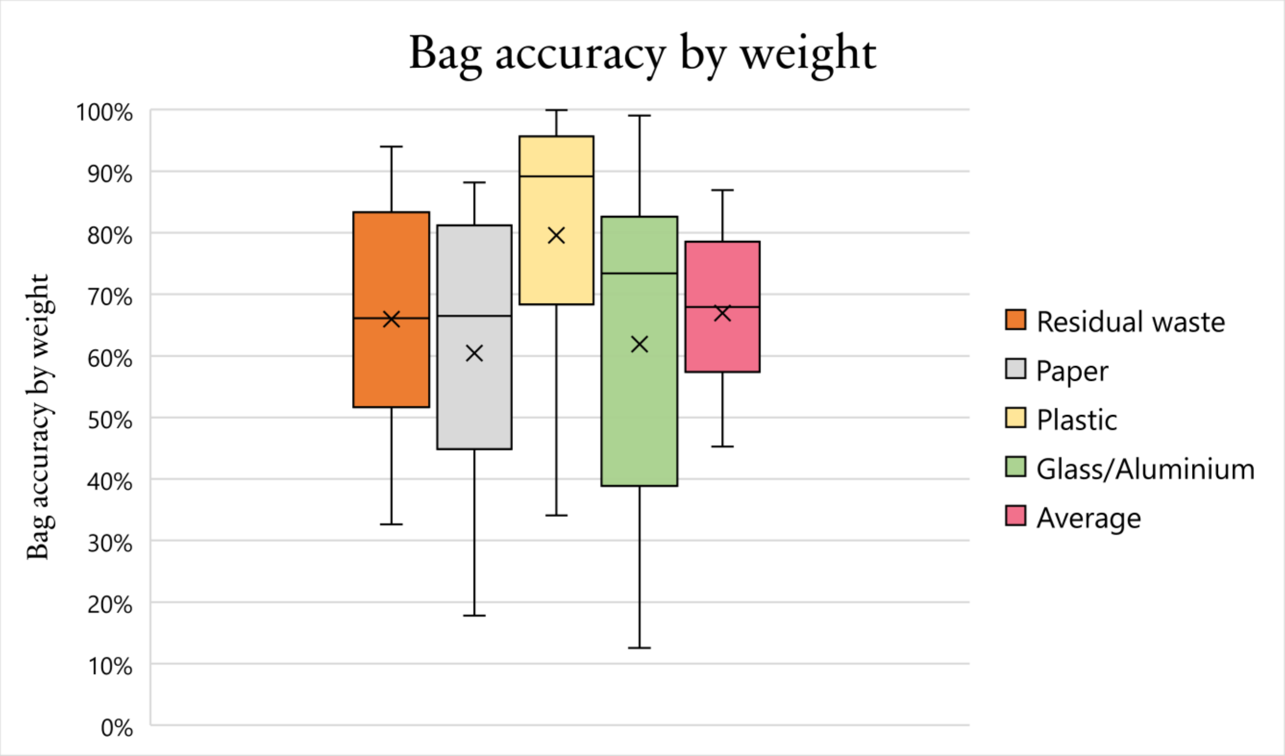

Figure 4.8 Bag accuracy by weight.

In figure 4.8 the accuracy by weight is shown. The highest value corresponds to the plastic bag with an average accuracy of almost 80%, followed by RW, glass & aluminium, and paper. This is the graph with the highest variability: to give an example, the accuracy for glass & aluminium ranged from 12% up to 99% w/w. It must be underlined though that the accuracy by weight for plastic and glass/aluminium bag considers in the numerator of the formula (paragraph 4.2.1) the sum of the weight of the fraction and the weight of the liquid (inside the bottles/can) because, as said before, the liquid is not considered completely as impurity. An average value of accuracy by weight which doesn't consider the liquid at the numerator would be 32.3% and 39.6% respectively (it can be seen from figure 4.4).

A comparison between the classification accuracy and the bag accuracy by item shows that on average (blue boxplot) 5.7 items out of 10 are classified correctly by the passenger and 5.4 out of 10 are the number of items correct in every bag. It is also possible to observe that while on average 6.6 items of glass or aluminium are classified correctly, only 3.4 items are correct in the glass/aluminium bag, meaning that a lot of impurities are thrown in this bag by the passengers.

A comparison can now be done between the two values of bag accuracies (by item and by weight). The average value (blue boxplot) by weight is higher than the one by item (54% vs 67%). This indicates how the number of correct items might not be representative of the actual weight sorted in the bags. Moreover, the accuracy by weight indicator describes better the situation of items inside other items with the correct classification of each of them, considering impurities as well. A possible but more complex solution to items containing other items could be the use of a weighting sensor (which actually was already installed on the WiSort bin but not used during the experimentation): a biscuit package full of biscuits could for example be sent to the residual waste bag instead of the paper one every time the weighting sensor detects a weight above the average value of a biscuit package (in this way an impurity inside the paper bag (i.e. the biscuits) can be avoided but at the expense of the possibility of recycling the paper package).

The boxplot in figure 4.9 shows the value of the source separation metric.

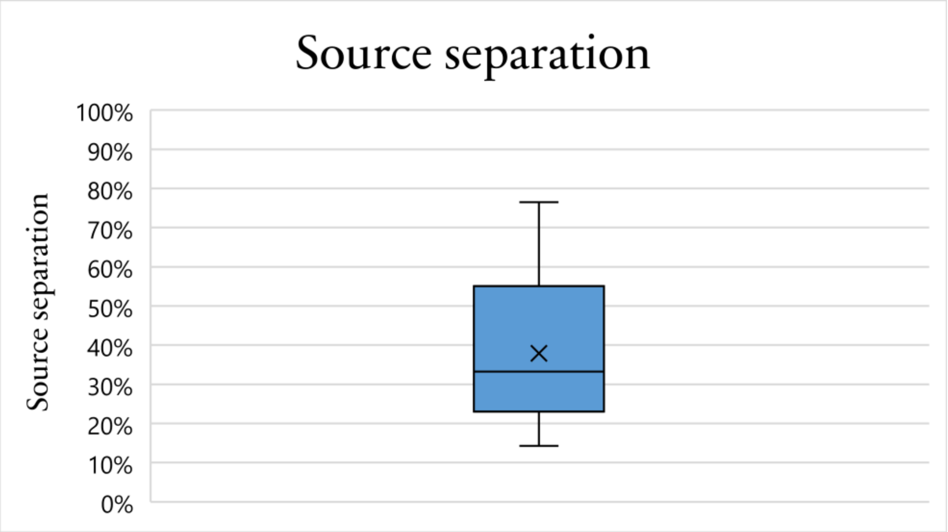

Figure 4.9 Source separation rate at Milano Malpensa.

The average value is 37.9%, while the median one, not influenced by the highest and lowest value, is 33.3%. Also this boxplot shows a great variability in the observations. Considering that the actual maximum amount of recyclables of the airport is 54.8% (i.e. 65.3 ton/year), this means that 45.2 ton out of 119.2 ton could be separately collected at the moment.
The potential of WiSort bin in this way can be double: to increase the level of source separation and to keep it consistent.

4.4 Experiment 2: user experience

Once the WiSort bin was installed at the airport, the initial test was to understand how the bin was perceived by the passengers and to collect feedbacks from them (about the design, the easiness of use, the drawbacks, the main limitations, the improvements that could be made and so on). The test was performed during 8 days distributed over a period of one month and a half, with two different configurations: in some days only the WiSort bin was located in point A, while in some others a normal tripartite bin (for residual waste only) was put next to the WiSort bin. In this way, it was possible to study the influence of a normal bin (to which people are used to) close the automatic one. In the second configuration, since the two types of bin were located next to each other, a passenger could either decide to choose the automatic bin or the traditional one.

People using any of the two bins were directly interviewed by the undersigned in order to catch their point of view and to ask for a comparison when possible.

The presence of the screen showing images of waste, recycling and pollution had the aim of catching the attention of the people and making them better understand that what they had in front of them was a waste bin.

Results are reported in the next paragraph.

4.5 Experiment 2 results

In this paragraph, feedbacks from passengers are reported. Most of the passengers fell in the 40-60 age category, probably due to the fact that the days during which the test was performed were weekdays and people mainly moved for work reasons. During the first two days of this test, the configuration with the normal bin nearby was adopted in order to see which bin was mostly chosen.

It was observed that almost the totality of passengers in need of throwing a waste opted for the normal bin. As a matter of fact, passengers didn't notice the WiSort bin or were not able to understand what it was. The interviewed passengers reported that the bin was not eye-catching enough (this was probably enhanced by the fact that the bin was painted in white and leant on a white wall), that the signage on it was not clear (e.g. the fact that it was possible to introduce only one item at a time) or that the structure of the bin was not helpful (e.g. shape not easily attributable to a waste bin or the round opening let some people think that it was possible to throw water bottles only[15]). The screen at the top made one passengers think that WiSort bin was some kind of "informative" device (rather than a waste bin). Nevertheless, when people were informed by the undersigned about the project at the end of the short interview, they showed curiosity and interest in such a type of device. Therefore, the communication part of the WiSort bin was not working properly.

For these reasons, after two days it was decided to partially modify the design of the bin according to the feedbacks of the passengers in order to make it more noticeable, more instantly recognizable and to provide more information on its use. Figure 4.10 shows the new design of the bin. It was decided to add an explicit indication of the four selected fractions. A QR code was added on the front to invite passengers to scan it and leave feedbacks in addition to two signage (in Italian and English) explaining how the bin had to be used.

Passengers' behaviour was again observed. At the beginning the configuration was still the one with the normal bin aside (4 days). There was a fair improvement even though in many cases

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[15] In Italy the are waste devices with similar shape on the outside of some supermarkets where people can throw water bottles and get some discount on the grocery shopping (see for an example Coripet eco-compactors (Coripet, 2022)).

people still tended to use the normal one: indeed, it was for them much more intuitive and the WiSort bin was still not enough eye-catching. Nevertheless, more people got attracted by the automatic bin and tried to use it. Some people stared at it while drinking or eating at the table of the kiosk. Some decided to use it instead of the normal one and, when approached by the undersigned, they were curious to know the operating principle and found it a really interesting idea. Passengers thought it could relieve them from an annoying task and this type of device could make a good impression as a way to collect waste. One person thought that the quality of source separation was already good enough not to justify such a type of bin.

Figure 4.10 WiSort bin with the new design.

In the other additional 3 days dedicated to this test, the second configuration without the normal bin aside was tested. The absence of the normal bin didn't seem to increase the number of people using the automatic one and this was probably due to the presence of other bins at the kiosk and the difficulty of acknowledging WiSort as a waste bin, as said before (this happened when people passed nearby without looking specifically at the signage on the bin). Despite that, a certain number of people used the WiSort bin as in the other configuration and those who used it had a positive impression. The images on the screen contributed to make people more aware about the drawbacks of not recycling. The main limitation for the passengers was the long time needed for the sorting.

As it usually happens with a prototype, some jam occurred too. Since the calibration phase was in progress during this test, some incorrect sorting happened and made some passengers a bit disappointed.

An indirect feedback collected during this experiment is that the passengers tend to use the closest bin they find without considering its typology. Indeed, the normal bin located beside the automatic one was a tripartite bin for residual waste only: some people just put waste item in without taking a look while some others, even if they stopped to try to figure out in which of the three parts of the bin it was correct to throw the waste, they then just left the waste item (which most of the time was recyclable) there without checking if nearby there was another bin with separate fractions. This highlights the importance of the design of normal bin as well: when a tripartite bin has plastic, paper, glass & aluminium but not residual waste, a passenger will probably introduce a residual waste item in one of the three parts thus randomly introducing an avoidable impurity.

In the next version of the prototype an interesting thing would be to manufacture it with a transparent front so that people can see how the automatic sorting is performed and get curious in knowing if the sorting is done correctly or not and maybe even might be more willing to introduce more items in.

5 LIFE CYCLE ASSESSMENT

In order to compare from an environmental perspective the actual situation with the one in which WiSort bin is implemented, a Life Cycle Assessment was performed. “LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)” (ISO, 2006). In this specific case, a waste management oriented LCA has been performed as the service studied is a waste management system. An LCA typically includes four phases: the goal and scope definition, the life cycle inventory (LCI), the life cycle impact assessment (LCIA) and the interpretation of the results. These four phases are sequential but they are all interconnected and the process is iterative.

5.1 Goal and scope definition

In the first phase of an LCA, the reason and the final purpose of the study, the intended audience, the technical information, the methods applied and the assumption made are given.

In this study, the intended application is to compare three alternative waste management scenarios for the waste produced in the public area of the airport:

- **scenario 0** (**S0**): it is assumed that all the waste from public areas is sent to the WTE plant managed by Neutalia Srl (Busto Arsizio, VA). The choice was based taking into account that the bad sorting performed by the passengers and inaccuracies of the operators at the moment prevent a good recovery. The waste composition of each bag is inferred from the experiment 1;
- **scenario 0 with recycling** (**S0-r**): in this scenario material recovery is introduced where possible: paper and glass/aluminium bags are sent to selection and material recycling, plastic bag is sent to selection for being recovered as SRF while residual waste bag is still sent to the WTE plant managed by Neutalia Srl; the waste composition of each bag is the same of scenario S0;
- **scenario 1** (**S1**): the waste is supposed to be automatically sorted by WiSort bin which can increase the quality of the materials in the bags (classification accuracy by weight equal to 90%) thus providing higher amounts of recyclables sent to recycling. Waste bags are treated in the same way of scenario S0-r except for plastic bags which are sent to a sorting plant for PET selection.

Details about the three scenarios are provided in paragraph 5.2.1, 5.2.2 and 5.2.3. These three scenarios were built with the aim of answering the following questions: which waste management scenario is better? Is it really more environmentally friendly sending waste to

recycling (S0-r) instead of sending it to incineration (S0)? The use of an automatic bin (which uses energy to sort the waste unlike a normal bin) is outbalanced by the benefits of a higher recycling rate (more materials sent to recycling)?
As functional unit, 1 ton of waste with composition given by the results of the waste composition analysis performed in experiment 1 was chosen: 223.3 kg of liquids, 28.5 kg of aluminium, 79.5 kg of glass, 173.5 kg of paper, 256.9 kg of food waste, 94.3 kg of RW and 144.1 kg of plastic (same of fig. 4.1). Steel (0.2%) has been aggregated in the aluminium category and consider as such due to its lower amount. The category "other" (1.4%) has been considered as the residual waste. Liquids have also been considered because passengers that want to throw away not empty bottles do not have the possibility to "separate collect" them in other ways. Indeed, most of the liquids were found inside PET/glass bottles or cans. The functional unit is a reference value which allows a correct comparison among scenarios and it is the value all the input and output data will be referred to.

The system boundaries for the estimation of the impacts start from the moment the waste is generated and discarded into the bin at the airport to when it becomes a new resource or leaves the system as emission or inert material. This choice is the so called "zero-burden approach" i.e. the impacts of the upstream processes and activities connected to the supply chain of the product before it becomes a waste are not considered, also because they are common to all the subsequent waste management options. In addition to the all subsequent phases of waste management, the life cycle of the bin (both normal and WiSort one) and the polyethylene (PE) bags used to contain the waste have been included in the system boundaries. Schemes which show the processes included in the system boundaries are shown in fig. 5.1, 5.2 and 5.3 of paragraph 5.2.1, 5.2.2 and 5.2.3 respectively.

The LCA performed for this study can be classified as an attributional LCA. SimaPro 9.3.0.3 was used as LCA software to support data processing.

Cases of multi-functionality related to the recovery of energy and materials in the valorisation of the waste were solved by expanding the system boundary (Finnveden et al., 2009) to include: (1) the avoided production of electricity from conventional fossil fuels due to the incineration of the waste; (2) the avoided production of raw material/fuel due to recycling/recovery as SRF of waste.

For what concern the life cycle of the normal and automatic bin it was decided to use the EPD® approach due to uncertainty in the modelling of their end of life (distances of treatment plants and type of treatments and related impacts). The approach considers only the impact of the transport to a selection plant and the selection process when recycling is chosen while it considers all the impacts related to disposal to landfill and the ones of incineration but without the benefits of energy recovery (The International EPD® System, 2021). Details can still be found in the LCI tables 5.2 and 5.10.

The assessment considered a wide spectrum of impact indicators, related to different impact areas: environment, human health and resources consumption. More specifically, 16 indicators evaluated at the midpoint level were selected from the impact characterisation method Environmental Footprint Impact Assessment Method, version 3.0 (Fazio et al., 2018; Saouter et al., 2020), grouped as follow:

- 8 indicators concerning the impact on the environment, i.e., Climate Change (CC), Ozone Depletion (OD), Photochemical Ozone Formation (POF), Acidification (A), Aquatic Freshwater Eutrophication (EUf), Marine Eutrophication (EUm), Terrestrial Eutrophication (EUt), and Freshwater Ecotoxicity (ECf));
- 4 indicators assessing the impact on the human health, i.e., Ionising Radiation, Human Health (IR), Particulate Matter (PM), Human Toxicity non-cancer effects (HTnc), and cancer effects (HTc);
- 4 indicators relating to resource consumption, i.e., Land Use (LU), Water use (WU), Resource Use, minerals & metals (RUm), Resource Use, fossil and nuclear energy carriers (RUf).

Regarding data quality, the foreground system was mainly described with primary data when available. In particular, data collected from the experiments at the airport (such as the waste composition, materials of the bins and the bags for the collection of the waste) and transport information (such as type of trucks, distances…) are primary data[16] provided by Malpensa or Wisort; the waste treatment were modelled using Northern Italy plants data collected during previous studies of AWARE research group[17]. Regarding background system, data from literature papers and datasets from ecoinvent database (version 3.8) were used.

5.2 *Life cycle inventory*

According to the LCA methodology, the life cycle inventory stage involves the compilation and quantification of the main inputs (material and energy) and outputs (waste and emissions) for each waste management scenario throughout all stages involved in the system boundaries.

Paragraph 5.2.1, 5.2.2 and 5.2.3 show the detailed life cycle inventories for scenarios S0, S0-r and S1 respectively.

5.2.1 LCI of S0

In scenario S0 the waste is sorted manually by passengers, who use the normal quadripartite bins, and its subsequent management consists of collection, transport, treatment in a WTE plant

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[16] Primary data are specific data referred to the case study and collected on the “field”

[17] https://www.aware.polimi.it/

(Neutalia Srl). System boundaries are shown in fig. 5.1, while table 5.2 shows the average composition of each of the four bags for scenario S0.

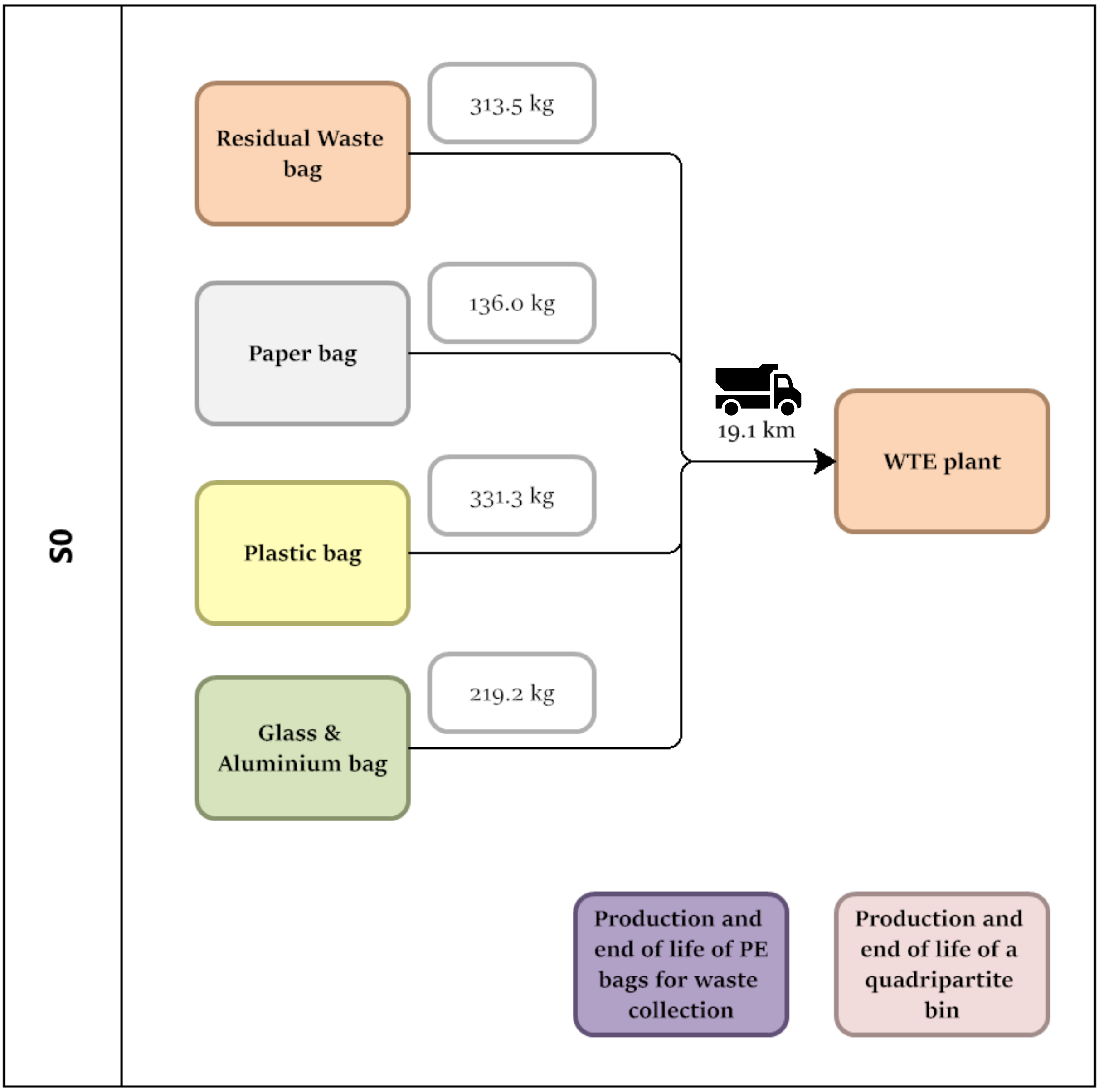

Figure 5.1 S0 system boundaries. Bizagi Modeler (version 4.0.0.014) was used to create the figure.

Table 5.1 Average waste composition of the bags of a quadripartite bin under S0 and S0-r. Values within parenthesis show the average composition of the bags but rescaled to 1000 kg (1 ton) which was used in SimaPro software. The second last row shows the average weight of a bag relative to 1 ton of waste obtained from the waste composition analysis, while the second last column shows the average weight of each fraction (same values of figure 4.1). The last row and column show the average value of bag accuracy by weight and classification accuracy by weight, respectively.

S0 and S0-r	**RESIDUAL WASTE BAG (kg)**	**PAPER BAG (kg)**	**PLASTIC BAG (kg)**	**GLASS/CAN BAG (kg)**	**Total weight per fraction (kg)**	**Classific. accuracy by weight**
	a	**b**	**c**	**d**	**e**	
Liquid	**22.6** (72.1)	**4.6** (33.9)	**153.0** (462.0)	**43.0** (196.2)	**223.3**	**-**
Aluminium	**7.9** (25.3)	**0.4** (3.3)	**5.2** (15.6)	**14.9** (67.9)	**28.5**	**52.3%**
Glass	**2.8** (8.8)	**1.7** (12.2)	**3.1** (9.2)	**72.0** (328.4)	**79.5**	**90.6%**
Paper	**55.2** (176.1)	**81.3** (598.1)	**13.6** (41.2)	**23.3** (106.3)	**173.5**	**46.9%**
Food waste	**166.8** (531.9)	**17.3** (127.2)	**32.7** (98.6)	**40.2** (183.5)	**256.9**	**64.9%**
Residual waste	**37.9** (120.7)	**25.9** (190.5)	**16.8** (50.6)	**13.8** (63.0)	**94.3**	**40.1%**
Plastic	**20.4** (65.0)	**4.7** (34.7)	**107.0** (322.9)	**12.0** (54.6)	**144.1**	**74.3%**
Total weight per bag	**313.5** (1000)	**136.0** (1000)	**331.3** (1000)	**219.2** (1000)	**1000.0**	**-**
Bag accuracy by weight	**65.3%**	**59.8%**	**78.5%**	**59.3%**	-	-

Tables 5.2, 5.3 and 5.4 show the LCI of scenario S0 processes, of a quadripartite bin and a PE bag respectively. For what concerns the modelling of the bin, primary data on material and size were used and closest ecoinvent modules were chosen according to the availability of those in the ecoinvent library. In most cases, the option “market for” was used so that both production and transport phase were considered.

Table 5.2 LCI of S0 with values referred to 1 ton of waste with the composition of table 5.1 column e (functional unit).

PROCESS	VALUE (for 1 ton)	ECOINVENT DATASET AND ASSUMPTIONS
NORMAL BIN PRODUCTION AND END OF LIFE		
Normal bin life cycle	0.017 unit	Relative portion of the normal bin allocated to 1 ton of waste. The value was calculated according to: • amount of waste collected in a day by a quadripartite bin (12.9 kg knowing that it collects on average 4.29 kg and by assuming the four bags are replaced three times in a day); • expected lifetime of a quadripartite bin (12.5 years). See corresponding module in table 5.4
PE BAG PRODUCTION AND END OF LIFE		
Polyethylene (PE) bag for waste collection	400.8 kg	Total weight of PE bags needed for 1 ton of waste. It was assumed a number of bags equal to 932 according to the average weight of the waste inside the four bag of a quadripartite bin (4.29 kg) and a weight of the single bag equal to 43 g. See corresponding module in table 5.5
TRANSPORT		
Transport from airport to WSA	2 km	Lorry 16-32 ton, Euro 6 for all bags (primary data)
INCINERATION		
INPUT		
Transport from WSA to WTE plant (Neutalia Srl)	19.1 km	Lorry 16-32 ton, Euro 6 (primary data)
Incineration	1 ton (waste) + 400.8 kg (PE bags)	The composition of the ton of waste is the average composition of the MSW obtained from experiment 1 (table 5.1 column e). Indeed, in S0 the totality of waste is sent to incineration (bags of RW, plastic paper, glass/aluminium). Moreover, it is considered the total weight of the PE bags used to contain 1 ton of waste. See module of incineration in appendix (table 10.4 and 10.5).

Table 5.3 LCI relative to the production and end of life of one quadripartite bin.

PROCESS	VALUE (for unit)	ECOINVENT DATASET AND ASSUMPTIONS
NORMAL BIN PRODUCTION		
INPUT		
Chromium steel	40 kg	40 kg is the weight of a quadripartite bin (assuming 100% made of steel). *Steel, chromium steel 18/8 (GLO) market for*
Sheet rolling	40 kg	Processing of steel assumed to be representative for the shape of the quadripartite bin. *Sheet rolling, chromium steel (RER) processing*
NORMAL BIN END OF LIFE		
Transport from airport to close ferrous scraps recycling plant (Acciaierie Venete SpA)	141 km	Lorry 16-32 ton, Euro 6 (assumed considering that waste of the airport are transported with such Euro class). It is assumed that it is sent directly to recycling. According to EPD® approach, it is taken into account the transport to the recycling plant for ferrous scraps. Benefits of steel recycling are excluded. *Transport, freight, lorry 16-32 metric ton, euro 6 (RER) market for*

Table 5.4 LCI relative to the production and end of life of one PE bag.

PROCESS	VALUE (for unit)	ECOINVENT DATASET AND ASSUMPTIONS
PE BAG PRODUCTION		
INPUT		
Polyethylene (PE) bag for waste collection	43 g	Value of weight directly measured during experiment 1. Bag of 70l capacity. *Packaging film, low density polyethylene (GLO) market for* modified according to the assumption that the production phase happens within Europe.
PE BAG END OF LIFE		
	-	*It has been modelled according to the end of life of the waste inside these bags (see other LCI tables).

5.2.2 LCI of S0-r

In scenario S0-r the waste is sorted manually by passengers, who use the normal quadripartite bins, and its subsequent management consists of collection, transport, treatment in sorting and recycling plants (paper and glass/aluminium) and the WTE plant of Neutalia Srl (residual waste). Plastic, in agreement to what specified in paragraph 3.3, is sent to energy recovery (preparation of SRF for cement kiln in substitution of pet coke). In this scenario, the chosen waste management plants are the same that the airport uses for the other MSW produced in the airport (table 3.3 of paragraph 3.3).

System boundaries are shown in fig. 5.2. Waste values for each bags are the same of scenario S0 (table 5.1).

The presence of the liquid, which was not negligible, was handled by assuming its treatment in the sewage at the first plant the waste is sent to.

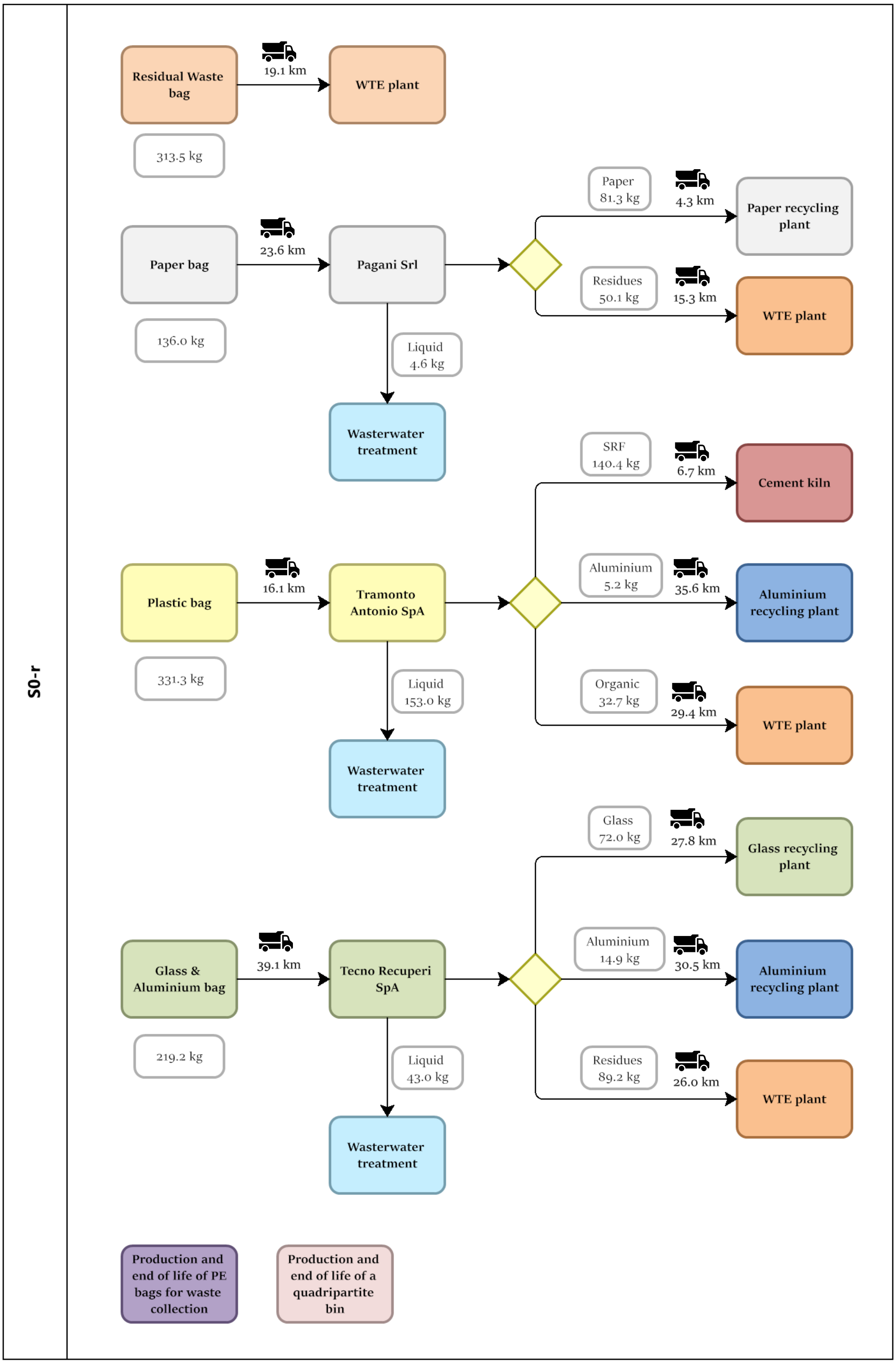

Figure 5.2 S0-r system boundaries. Bizagi Modeler (version 4.0.0.014) was used to create the figure.

Table 5.3 and 5.4 shows the LCI of a quadripartite bin and PE bags (same of scenario S0) while table 5.5 the LCI of the processes of scenario S0-r.

Table 5.5 LCI of S0-r with values referred to 1 ton of waste with the composition of table 5.1 column e (functional unit).

PROCESS	VALUE (for 1 ton)	ECOINVENT DATASET AND ASSUMPTIONS
NORMAL BIN PRODUCTION AND END OF LIFE		
Normal bin life cycle	0.017 unit	Relative portion of the normal bin allocated to 1 ton of waste. The value was calculated according to: • amount of waste collected in a day by a quadripartite bin (12.9 kg knowing that it collects on average 4.29 kg and by assuming the four bags are replaced three times in a day); • expected lifetime of a quadripartite bin (12.5 years). See corresponding module in table 5.3
PE BAG PRODUCTION AND END OF LIFE		
Polyethylene (PE) bag for waste collection	400.8 kg	Total weight of PE bags needed for 1 ton of waste. It was assumed a number of bags equal to 932 according to the average weight of the waste inside the four bag of a quadripartite bin (4.29 kg) and a weight of the single bag equal to 43 g). See corresponding module in table 5.4
TRANSPORT		
Transport from airport to WSA	2 km	Lorry 16-32 ton, Euro 6 for plastic and RW (primary data)
Transport from airport to WSA	2 km	Lorry 3.5-7.5 ton, Euro 6 for paper and glass/aluminium bags (primary data)
Transport from WSA to WTE plant (Neutalia Srl)	19.1 km	Transport related to RW bags to Neutalia Srl. Lorry 16-32 ton, Euro 6 (primary data)
TREATMENTS		
Incineration of residual waste bag	313.5 kg (waste) +12.6 kg (PE bags)	Only RW bags goes to incineration. The composition of the content of the residual waste bags is the one of table 5.1 column a. Moreover, it is considered the weight of the RW bags (calculated as $43g/(10^6\ g/ton) \times 932\ bags/ton \times 313.5\ kg/ton$. See module of incineration in appendix (table 10.4 and 10.5).

Treatment of plastic bags	331.3 kg +13.3 kg (PE bags)	Plastic bags goes to a sorting plant for preparation of SRF sent to a cement kiln. The composition of the content of the plastic bags is the one of table 5.2 column c. It is also considered the weight of the plastic bags (calculated as $43g/(10^6\ g/ton) \times 932\ bags/ton \times 331.3\ kg/ton$. See inventory data in table 5.6
Treatment of glass/aluminium bags	219.2 kg + 8.8 kg (PE bags)	These bags goes to a sorting plant for separation and recycling of glass and aluminum. The composition of the content of the glass/aluminium bags is the one of table 5.2 column d. It is also considered the weight of the glass/aluminium bags (calculated as $43g/(10^6\ g/ton) \times 932\ bags/ton \times 219.2\ kg/ton$. See inventory data in table 5.7
Treatment of paper bags	136 kg + 5.5 kg (PE bags)	These bags goes to a sorting plant for separation and recycling of paper. The composition of the content of the paper bags is the one of table 5.2 column b. It is also considered the weight of the paper bags (calculated as $43g/(10^6\ g/ton) \times 932\ bags/ton \times 136\ kg/ton$. See inventory data in table 5.8

Table 5.6 Inventory table for plastic bag treatment for S0-r with values referred to 1 ton of waste inside plastic bag as indicated in table 5.1 column c in brackets.

PLASTIC SELECTION		
PROCESS	**VALUE (for 1 ton)**	**ECOINVENT DATASET AND ASSUMPTIONS**
INPUT		
Transport from WSA to plastic selection plant (Tramonto Antonio Srl)	14.1 km	Lorry 16-32 ton, Euro 6 (primary data)
Electricity consumption at plastic selection plant	14.2 kWh/ton	Value taken from Rigamonti et al. (2014) considering the treatment without Near-infrared range (NIR) sensors because separation of PET for recycling has not been considered in this scenario.
Treatment of the liquids contained in the bag	462.0 kg	It is assumed that the liquids contained in the bag are treated in a wastewater treatment plant. *Wastewater, average (Europe without Switzerland) market for*
OUTPUT		

Treatment of food waste separated at Tramonto Antonio: incineration at Neutalia Srl	98.6 kg	At the plant (Tramonto Antonio Srl) the waste inside the bag is subjected to the following treatments: • size reduction • non ferrous metal separation for recycling • sieving (food waste separation) The food waste is firstly transported to Neutalia Srl for 29.4 km (assumption because this is the closest WTE plant). Then it is incinerated (see incineration module in appendix with table 10.4 and 10.5). Lorry 16-32 ton, Euro mix of north Italy, 2017 (ACI, 2018)
Treatment of aluminium separated at Tramonto Antonio: recycling	15.6 kg	Aluminium is firstly transported to a foundry for 35.6 km (it was assumed an average distance from two local foundries (Fonderia Emi Srl and Fonderia Gussoni Srl). Then it is recycled (see "aluminium recycling" module in table 5.7). Lorry 16-32 ton, Euro mix of north Italy, 2017 (ACI, 2018)
Treatment of plastic waste fraction, glass, residual waste, paper and PE bags: co-combustion in a cement kiln (Holcim Comabbio)	322.9+50.6+41.2+9.2 kg (waste) +400.8 kg (PE bags)	The Solid Recovered Fuel produced by Tramonto Antonio is transported to the cement kiln managed by Holcim (Comabbio) for 6.7 km. This plant has been chosen because it is close and it accepts SRF as input. For the co-combustion of SRF in a cement kiln see appendix with table 10.6. Lorry 16-32 ton, Euro mix of north Italy, 2017 (ACI, 2018)

Table 5.7 Inventory table for glass/aluminium bag treatment for S0-r with values referred to 1 ton of waste inside glass/aluminium bag as indicated in table 5.1 column d in brackets.

GLASS/ALUMINIUM SELECTION		
PROCESS	**VALUE (for 1 ton)**	**ECOINVENT DATASET AND ASSUMPTIONS**
INPUT		
Transport from WSA to a glass/aluminium selection plant (Tecno Recuperi Srl)	37.1 km	Lorry 16-32 ton, Euro 6 (primary data)
Electricity consumption at selection plant	15.9 kWh/ton	Average value for the separation of glass and aluminium from two Italian glass/aluminium selection plants (Rigamonti et al. 2013)

Treatment of the liquids contained in the bag	192.2 kg	It is assumed that the liquids contained in the bag is treated in the wastewater treatment plant. *Wastewater, average (Europe without Switzerland) market for*
OUTPUT		
Treatment of paper, food waste, RW and plastic waste (PE bags included) separated at Tecno Recuperi Srl: incineration at Neutalia Srl	106.3 + 183.5 +63.0 +54.6 kg (waste) +400.8 kg (PE bags)	At the plant (Tecno Recuperi Srl) the waste inside the bag is subjected to the following treatments: • glass and aluminium separation for recycling • impurities separation (paper, food waste, RW and plastic) The impurities are firstly transported to Neutalia Srl for 26 km (assumption because this is the closest WTE plant). Then they are incinerated (see module of incineration in appendix with table 10.4 and 10.5). Lorry 16-32 ton, Euro mix of north Italy, 2017 (ACI, 2018)
Treatment of aluminium separated at Tecno Recuperi Srl: recycling	67.9 kg	Aluminium is firstly transported to a foundry for 30.5 km (it was assumed an average distance from two local foundries (Fonderia Emi Srl and Fonderia Gussoni Srl). Then it is recycled (see “aluminium recycling module” below). Lorry 16-32 ton, Euro mix of north Italy, 2017 (ACI, 2018)
Treatment of glass separated at Tecno Recuperi Srl: recycling	328.4 kg	Glass is firstly transported to a glass work for 27.8 km (it was assumed an average distances from 4 local plants for glass recycling (Vetrobalsamo SpA, O-I Manifacturing SpA, Vidrala Italia Srl and Vetropack Italia Srl). Then it is recycled (see module below). Lorry 16-32 ton, Euro mix of north Italy, 2017 (ACI, 2018)
GLASS RECYCLING		

Recycling of glass at recycling plant	328.4 kg	The glass recycling module was created taking into account: • repartition of glass into different colours according to percentage obtained from experiment 1 (54.2% green + brown glass and 45.8% clear glass); • use of inventory data related to glass recycling from two Italian glassworks which produce glass packages with a percentage of glass cullet equal to 76% for green glass and 49% for clear glass (Assovetro, 2021); • Avoided products with 1:1 substitution coefficient and glass production according to the typical market conditions in Europe (*Packaging glass, green/white (RER) market for*)
ALUMINIUM RECYLING		
Recycling of aluminium at recycling plant	67.9 kg	The aluminium recycling module was created taking into account that: • Aluminium separated from glass is processed in a pyrolytic kiln for removal of paint and adhesive substances with efficiency of 95.2% and then melted in a saline rotatory furnace with efficiency of 83.9%) (Rigamonti et al. 2013); • Aluminium recycling was modeled according to ecoinvent dataset *Aluminium, wrought alloy (RER) alluminio secondario, post-consumer, prepared for recycling, at remelter);* • Avoided products with 1:1 substitution coefficient and production of aluminium according to the global market conditions (69% primary aluminium e 31% secondary aluminium) (*Aluminium, wrought alloy (GLO) market for*).

Table 5.8 Inventory table for paper bag treatment for S0-r with values referred to 1 ton of waste (functional unit).

PAPER SELECTION		
PROCESS	**VALUE (for 1 ton)**	**ECOINVENT DATASET AND ASSUMPTIONS**
INPUT		
Transport from WSA to a paper selection plant (Pagani Srl)	21.6 km	Lorry 16-32 ton, Euro 6 (primary data).
Electricity consumption at paper selection plant	1.5 kWh/ton	Value taken from Rigamonti et al. 2013)
Treatment of the liquids contained in the bag	33.9 kg	It is assumed that the liquids contained in the bag is treated in the wastewater treatment plant. *Wastewater, average (Europe without Switzerland) market for*
OUTPUT		
Treatment of glass/aluminium, RW, food waste and plastic waste (PE bags included) separated at Pagani Srl: incineration at Neutalia Srl	3.3 +12.2 + 127.2 +190.5 + 34.7 kg (waste) +400.8 kg (PE bags)	At the plant (Pagani Srl) the waste inside the bag is subjected to the following treatments: • paper separation for recycling • impurities separation (glass/aluminium, RW, food waste and plastic) The impurities are firstly transported to Neutalia Srl for 15.3 km (assumption because this is the closest WTE plant). Then they are incinerated (see module of incineration in appendix with table 10.4 and 10.5) Lorry 16-32 ton, Euro mix of north Italy, 2017 (ACI, 2018)
Treatment of paper separated at Pagani Srl: recycling	598.1 kg	Paper is firstly transported to a paper recycling plant for 4.3 km (it was assumed an average distance from two local plants (FM Cartiere SpA Srl and Cartiera Olona Srl). Then it is recycled (see module below). Lorry 16-32 ton, Euro mix of north Italy, 2017 (ACI, 2018)
PAPER RECYCLING		

Recycling of paper at recycling plant	598.1 kg	The paper recycling module was created taking into account that: • A recycling process with 89% efficiency and consumption data indications from Rigamonti et al. (2013); • Avoided product considering the Italian market conditions (62% recycled paper and 38% virgin paper) (Comieco, 2022); • the substitution ratio between secondary and primary pulp was chosen equal to 1:0.833 according to number of times of possible reuse of paper (Rigamonti et al. 2013) .

5.2.3 LCI of S1

In scenario S1 the waste is automatically sorted by WiSort bin with a supposed 90% w/w classification accuracy for each fraction (plastic, paper, glass, aluminium, food waste, RW).

The choice of 90% accuracy was based on findings related to other automatic bins already on the market or experimental prototype mentioned in literature (Bin-e, (n.d.); CleanRobotics, (n.d.); Jacobsen et al., (2020) and Pamintuan et al., (2019)).

According to the separation rate, the composition of the 4 waste bags (plastic, residual waste, glass/aluminium, paper) was built according to the following hypotheses (table 5.9):

- the amount of each fraction (plastic, residual waste, glass/aluminium, paper) was kept unchanged with respect to the two other scenarios (last column of table 5.1 and 5.9 are indeed equivalent);
- for plastic, paper, glass/aluminium 90% w/w was supposed to be correctly selected in the dedicated bag while the remaining 10% was allocated to the RW bag: to give an example with plastic, 90% of plastic weight (i.e. 129.6 kg out of 144.1 kg) was allocated to the plastic bag, the remaining to the RW bag;
- for residual and food waste 90% w/w was supposed to be selected in the residual waste bag, while the remaining 10% was allocated to the other three bags evenly;
- for what concerns the liquids, since they were mostly found inside bottles during observations in experiment 1, 90% w/w was allocated between the plastic and glass/aluminium bags in proportion to the relative weight of the two fractions (57% plastic and 43% glass/aluminium), while the remaining 10% was attributed to the RW bag.

In this scenario, the waste management consists of its collection, transport, treatment in recycling plants (paper and glass/aluminium) and WTE plants (residual waste). Plastic, in this scenario, is assumed to be sent to the closest pre-treatment plant for polymer selection (CARIS VRD Srl, Lainate, MI) where PET is separated for recycling while the other fractions are treated for SRF generation. The presence of liquids in the bags, which was not negligible, was handled by assuming their treatment in the sewage at the first plant the waste is sent to.

System boundaries, which include also the production and the end of life of the WiSort bin and PE bags for waste collection, are shown in fig. 5.3.

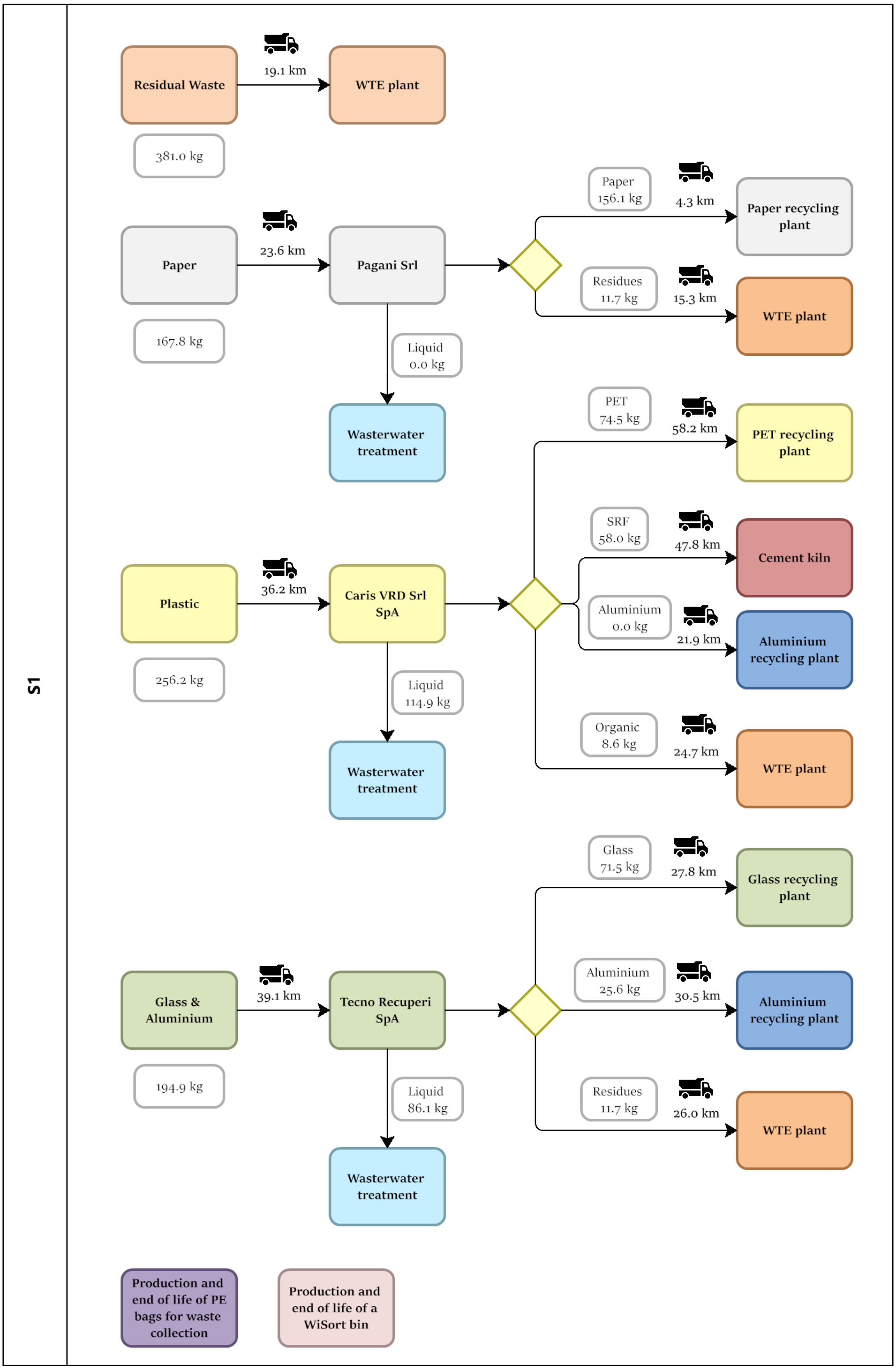

Figure 5.3 S1 system boundaries. Bizagi Modeler (version 4.0.0.014) was used to create the figure.

Table 5.9 Average waste composition of the bags of a quadripartite bin under S1. Values within parenthesis show the average composition of the bags but rescaled to 1000 kg (1 ton), which was used in SimaPro software. The second last column is identical to the last column of table 5.1.

S1	**RESIDUAL WASTE BAG (kg)**	**PAPER BAG (kg)**	**PLASTIC BAG (kg)**	**GLASS/CAN BAG (kg)**	**Total weight per fraction (kg)**	**Classific. accuracy by weight**
	a	**b**	**c**	**d**	**e**	
Liquid	**22.3** (58.6)	**0.0** (0.0)	**114.9** (448.4)	**86.1** (441.6)	**223.3**	-
Aluminium	**2.8** (7.5)	**0.0** (0.0)	**0.0** (0.0)	**25.6** (131.4)	**28.5**	**90.0%**
Glass	**7.9** (20.9)	**0.0** (0.0)	**0.0** (0.0)	**71.5** (366.9)	**79.5**	**90.0%**
Paper	**17.3** (45.5)	**156.1** (930.2)	**0.0** (0.0)	**0.0** (0.0)	**173.5**	**90.0%**
Food waste	**231.2** (606.9)	**8.6** (51.0)	**8.6** (33.4)	**8.6** (43.9)	**256.9**	**90.0%**
Residual waste	**84.9** (222.8)	**3.1** (18.7)	**3.1** (12.3)	**3.1** (16.1)	**94.3**	**90.0%**
Plastic	**14.4** (37.8)	**0.0** (0.0)	**129.6** (506.0)	**0.0** (0.0)	**144.1**	**90.0%**
Total weight per bag	**381.0** (1000)	**167.8** (1000)	**256.2** (1000)	**194.9** (1000)	**1000.0**	-
Bag accuracy by weight	**83.0%**	**93.0%**	**95.4%**	**94.0%**	**-**	-

Table 5.10 shows the LCI for the processes of scenario S1. The LCI of the PE bags is the same of table 5.4 while the LCI of WiSort bin can be found in table 5.11. For what concerns the modelling of the WiSort bin, primary data from WiSort startup about the composition of the prototype in terms of materials were used when possible and closest ecoinvent modules about production and supply of the single components were chosen according to the availability among ecoinvent datasets. The modelling of the electronic components of the bin is the one characterized by the highest uncertainty due to difficulties in finding completely corresponding modules and correct values of weights.

Table 5.10 LCI of S1 with values referred to 1 ton of waste with the composition of table 5.9 column e (functional unit).

PROCESS	VALUE (for 1 ton)	ECOINVENT DATASET AND ASSUMPTIONS
WISORT BIN PRODUCTION AND END OF LIFE		
Wisort Bin life cycle	0.0082 unit	Relative portion of WiSort bin allocated to 1 ton of waste. The value was calculated according to: • Amount of waste collected in a day by Wisort bin (33.0 kg by assuming that every minute a waste item is thrown into the bin (i.e. 1440 items/day) using 22.9 g as the average mass of an item (average value of weight measured during experiment 1)). • expected lifetime of WiSort bin (10 years). See corresponding module in table 5.11
PE BAG PRODUCTION AND END OF LIFE		
Polyethylene (PE) bag for waste collection	9 kg	Total weight of PE bags needed for 1 ton of waste. It was used a number of bags equal to 208 assuming they get 80% full before being emptied (full actual capacity of a bag inside the bin is 40 l) and assuming an average density of the waste equal to 0,15 kg/l and a weight of the single bag equal to 43 g. See corresponding module in table 5.4
TRANSPORT		
Transport from airport to WSA	2 km	Lorry 16-32 ton, Euro 6 for plastic and RW (primary data)
Transport from airport to WSA	2 km	Lorry 3.5-7.5 ton, Euro 6 for paper and glass/aluminium bags (primary data)
Transport from WSA to WTE plant (Neutalia Srl)	19.1 km	Transport related to RW bags to Neutalia Srl. Lorry 16-32 ton, Euro 6 (primary data)
TREATMENTS		
Incineration of residual waste bag	381.0 kg (waste) +3.4 kg (PE bags)	Only RW bags goes to incineration. The composition of the content of the residual waste bags is the one of table 5.9 column a. Moreover, it is considered the weight of the RW bags (calculated as $43 g/(10^6\ g/kg) \times 208\ bags/ton \times 381.0\ kg/ton$). See module of incineration in appendix with table 10.4 and 10.5

Treatment of plastic bags	256.2 kg +2.3 kg (PE bags)	Plastic bags goes to a sorting plant for preparation of SRF sent to a cement kiln. The composition of the content of the plastic bags is the one of table 5.9 column c. It is also considered the weight of the plastic bags (calculated as $43g/(10^6\ g/ton) \times 208\ bags/ton \times 256.2\ \ kg/ton$. See inventory data in table 5.12
Treatment of glass/aluminium bags	194.9kg + 1.7 kg (PE bags)	These bags goes to a sorting plant for separation and recycling of glass and aluminum. The composition of the content of the glass/aluminium bags is the one of table 5.9 column d. It is also considered the weight of the glass/aluminium bags (calculated as $43g/(10^6\ g/ton) \times 208\ bags/ton \times 194.9\ kg/ton$. For modelling see inventory data in table 5.7 modifying the composition of the bag according to values in brackets of column d of table 5.9
Treatment of paper bags	167.8 kg + 1.5 kg (PE bags)	These bags goes to a sorting plant for separation and recycling of paper. The composition of the content of the paper bags is the one of table 5.9 column b. It is also considered the weight of the paper bags (calculated as $43g/(10^6\ g/ton) \times 208\ bags/ton \times 167.8\ kg/ton$. For modelling see inventory data in table 5.8 modifying the composition of the bag according to values in brackets of column b of table 5.13

Table 5.11 LCI relative to the production and end of life of one WiSort bin.

PROCESS	VALUE (for unit)	ECOINVENT DATASET AND ASSUMPTIONS
WISORT BIN PRODUCTION		
INPUT		
Chromium steel	5.2 kg	The steel component in WiSort bin is mainly used for C-parts so hot rolling was thought to be more representative than sheet rolling (cold rolling) as processing method of the steel. *Steel, chromium steel 18/8, hot rolled (GLO) market for*
Wrought alloy of aluminium	26.4 kg	Aluminium is used for the modular structure of the bin (bars). *Aluminium, wrought alloy (GLO) market for*
Section bar extrusion for aluminium	26.4 kg	Processing of aluminium assumed to be representative for the aluminium parts of WiSort bin. *Section bar extrusion, aluminium (GLO) market for*
Plywood	0.0588 m^3	Plywood is used for the white external panels covering the machine. *Plywood (RER) market for plywood*

PVC	3.9 kg	PVC is used for external protection of wires, the hinge mechanism of the opening of the shuttle and cap protections applied on the extremities of the aluminum bars. The weight already excludes the PVC part contained in cables (described below). Suspension polymerization is the technology most commonly used. *Polyvinyl chloride, suspension polymerized (RER) market for*
TV screen	1 unit	*Display, liquid crystal, 17 inches (GLO) market for*
Electronic components **1. Sensors** **2. Light modules** **3. Raspberry pi** **4. Safety switches** **5. Electric motors and motor drivers** **6. Cables** **7. Plugs**	1. 29.6 g* 2. 0.7 g* 3. 46 g* 4. 58 g* 5. 1.5 kg 6. 1.40 m 7. 5 units*	1. Modelling was based on information found in Pirson & Bol (2021) and the average weight for integrated circuits suggested in the “Life Cycle Inventories of Electric and Electronic Equipment: Production, Use and Disposal” ecoinvent report was used. *Integrated circuit, logic type (GLO) market for* 2. *Light emitting diode (GLO) market for* 3. It was chosen the closest module available to description of a Raspberry Pi. *Printed wiring board, surface mounted, unspecified, Pb free (GLO) market for* 4. *Switch, toggle type (GLO) market for* 5. These components were modeled by considering the most relevant materials they were made of (and relative proportion in weight) and by using integrated circuits to model the electronic part. The weight of this component is a primary data. *Integrated circuit, logic type (GLO) market for* (0.62 kg); *Permanent magnet, for electric motor (GLO) market for* (0.22 kg); *Iron pellet (GLO) market for* (0.22 kg)*; Steel, chromium steel 18/8, hot rolled (GLO) market for* (0.44 kg). 6. Different types of cables were present so it was chosen the model that could be the most representative. The length of the cables is a primary data. *Cable, network cable, category 5, without plugs (GLO) market for* 7. Primary data. This is the modelling of the plugs connecting the tv, electronic components and socket together. *Plug, inlet and outlet, for computer cable (GLO) market for* *these numbers are secondary data
Electricity consumption	67.1 kWh/ton	Quantity obtained starting from the values measured during the experimentation (table 3.4 of paragraph 3.4), the time for processing one waste (confidential) and the total energy consumption in a day (given by the sum of the energy consumption at rest and the extra energy consumption when WiSort bin is processing one waste assuming that every minute a waste item is thrown into the bin)
WISORT BIN END OF LIFE (WEEE selection)		
Transport from airport to a close WEEE selection plant (Tao Ambiente Srl)	48.3 km	Lorry 16-32 ton, Euro 6 (assumed considering that waste of the airport are transported with such Euro class). WiSort bin was considered as a WEEE at its end of life and it is supposed to be sent to a selection plant for the separation of its components. EPD® approach is used so it is taken into account the transport of the automatic bin to the WEEE selection plant.

Treatment at selection plant (electricity consumption)	66 kWh/ton	The modelling of the selection process was based on Falbo et al. (2015) assuming WiSort bin as WEEE of type 4 (as this category includes vending machines which have been thought to be somewhat similar to the automatic bin). According to the EPD® approach, the selection process for the separation of the components of the bin is taken into account. It is assumed that all the components (except PVC and plywood that are assumed to be sent to a WTE plant) are sent to material recovery plants. Benefits of recycling and energy recovery are excluded while the impacts of combustion due to incineration are considered (see below).
Incineration of Plywood	0.0588 m^3	*Waste Polyvinylchloride (CH) treatment of, municipal incineration*
Incineration of PVC	3.9 kg	*Waste wood, untreated (CH) treatment of, municipal incineration*

Table 5.12 Inventory table for plastic bag treatment for S1 with values referred to 1 ton of waste inside plastic bag as indicated in table 5.9 column c in brackets.

PLASTIC SELECTION		
PROCESS	**VALUE (for 1 ton)**	**ECOINVENT DATASET AND ASSUMPTIONS**
INPUT		
Transport from WSA to plastic selection plant (CARIS VRD Srl)	36.2 km	Lorry 16-32 ton, Euro 6 (assumed equal to the other transports)
Electricity consumption at plastic selection plant	29.0 kWh/ton	Value taken from Rigamonti et al. (2014) considering a complete sorting plant including metal separation and NIR sensors.
Treatment of the liquids contained in the bag	448.4 kg	It is assumed that the liquids contained in the bag are treated in a wastewater treatment plant. *Wastewater, average (Europe without Switzerland) market for*
OUTPUT		

Treatment of food waste separated at Caris VRD Srl: incineration at Neutalia Srl	33.4 kg	At the plant (Caris VRD Srl) the waste inside the bag is subjected to the following treatments: • size reduction • separation of PET for recycling with sorting rate of 88% (COREPLA, 2023) • non ferrous metal separation for recycling • preparation of SRF to be sent to a cement kiln (made of plasmix, PET residues, paper, glass and RW) • sieving (food waste separation) The food waste is firstly transported to Neutalia Srl for 24.7 km (assumption because this is the closest WTE plant). Then it is incinerated (see module of incineration in appendix with table 10.4 and 10.5) Lorry 16-32 ton, Euro mix of north Italy, 2017 (ACI, 2018)
Treatment of aluminium separated at Caris VRD Srl: recycling	0.0 kg	Aluminium is firstly transported to a foundry for 21.9 km (it was assumed an average distance from two local foundries (Fonderia Emi Srl and Fonderia Gussoni Srl). Then it is recycled (see "aluminium recycling" module in table 5.7. Lorry 16-32 ton, Euro mix of north Italy, 2017 (ACI, 2018)

Treatment of selected PET in PET recycling plant	290.8 kg	Sorted PET is firstly transported to a PET recycling plant for 58.2 km (it was assumed an average distance from two local plants (Erreplast Srl and Aliplast SpA)). The PET recycling module was created taking into account that: • 75.5% of input PET is converted into secondary granulate while 24.5% is considered as scrap; consumption of electrical energy, heat (natural gas), water and sodium hydroxide were included according to Rigamonti et al (2013); • Avoided product: the production mix of PET in the European market was considered (70% primary and 30% recycled PET; Eunomia (2022)); • The substitution ratio between secondary and primary PET was chosen equal to 1:0.701 according to current price of the two granules types (Althesys, 2022). • Scraps generated during recycling process are transported for incineration to Neutalia as closest WTE plant (modelled according table 10.4 and 10.5 in appendix)
Treatment of plasmix, PET residues, glass, RW paper and PE bags: co-combustion in a cement kiln (Holcim Comabbio)	175.6+ 39.6+ 0.0+12.3+0.0 kg (waste) +9 kg (PE bags)	The Solid Recovered Fuel produced by Caris VRD Srl is transported to the cement kiln managed by Holcim (Comabbio) for 47.8 km. This plant has been chosen because it is close and it accepts SRF as input. For the co-combustion of SRF in a cement kiln see appendix (table 10.6). Lorry 16-32 ton, Euro mix of north Italy, 2017 (ACI, 2018)

5.3 Life cycle impact assessment and interpretation of the results

This is the third phase of an LCA, aimed at evaluating the magnitude and significance of the potential environmental impacts for the studied system. This phase involves the conversion of LCI results to common units (using characterization factors) and the aggregation of the converted results within the same impact category. The substances that contribute to an impact category are multiplied with a characterisation factor that expresses the relative contribution of the substance. For example, the characterisation factor for CO_2 in the impact category “Climate change” (GWP100) is equal to 1 kg CO_2 eq/ kg CO_2, while the characterisation factor of methane (fossil) is 29.8 kg CO_2 eq/ kg CH_4, (IPCC, 2021). The total result is expressed as impact category indicator (formerly characterisation result). Characterization factors are calculated using characterization models. Often, the characterization model is chosen among existing models: characterization models reflect the environmental mechanism by describing the relationship between the LCI results and category indicators (i.e. by formulas of all physical, chemical and / or biological processes linking the LCI results to the category indicator). The characterisation models adopted in this study are the one selected for the Environmental Footprint (EF) method 3.0 (Fazio et al., 2018), in accordance with the PEF guide, which is the most recent LCA reference handbook promoted by the European commission (European commission, 2021). The LCIA results are now reported for every scenario: in this way it is possible to observe how each process contribute to every impact category and the ones which are connected to the highest impacts or benefits. Finally, the three scenarios are compared in order to see if it is possible to rank them or the choice is dependent on the impact category.

5.3.1 Analysis of the impacts of S0

Table 5.13 reports the indicator value for each impact category with reference to the functional unit for scenario S0. If an indicator has a net positive sign, it means that for that category the studied system causes an environmental burden while, if it has a net negative sign, the system causes an environmental benefit. Fig 5.4 shows the contribution analysis for the scenario S0. Each impact category is represented by a column where it is possible to notice the contribution of each process involved in the scenario. The sum of the contributions (expressed in absolute value) of all processes for a category gives 100%.

Table 5.13 LCIA results for S0 relative to 1 ton of waste with the composition of table 5.1 column e (functional unit). Net impacts are highlighted in red while net benefits in green.

Impact category	Unit of measurement (for functional unit)	Total impact	Load (positive impacts)	%	Benefits (negative impact)	%
CC	kg CO2 eq	4.5E+02	5.8E+02	80.9%	-1.38E+02	-19.1%
OD	kg CFC11 eq	-1.5E-05	7.2E-06	25.7%	-2.08E-05	-74.3%
IR	kBq U-235 eq	-1.8E+01	1.2E+01	28.9%	-3.06E+01	-71.1%
POF	kg NMVOC eq	1.3E-01	6.7E-01	55.5%	-5.34E-01	-44.5%
PM	disease inc.	-3.6E-06	6.9E-06	39.6%	-1.05E-05	-60.4%
HTnc	CTUh	3.7E-06	5.7E-06	74.3%	-1.97E-06	-25.7%
HTc	CTUh	7.2E-07	7.2E-07	99.2%	-5.76E-09	-0.8%
A	mol H+ eq	-6.8E-01	7.1E-01	33.8%	-1.39E+00	-66.2%
EUf	kg P eq	5.2E-02	9.5E-02	68.6%	-4.36E-02	-31.4%
EUm	kg N eq	8.9E-03	1.7E-01	51.3%	-1.64E-01	-48.7%
EUt	mol N eq	4.7E-01	2.1E+00	56.3%	-1.63E+00	-43.7%

ECf	CTUe	-5.5E+02	3.0E+03	45.7%	-3.51E+03	-54.3%
LU	Pt	7.8E+01	6.1E+02	53.4%	-5.32E+02	-46.6%
WU	m3 depriv.	1.6E+01	1.1E+02	53.7%	-9.71E+01	-46.3%
RUf	MJ	4.0E+02	3.7E+03	52.9%	-3.27E+03	-47.1%
RUm	kg Sb eq	-3.7E-04	1.1E-03	42.9%	-1.48E-03	-57.1%

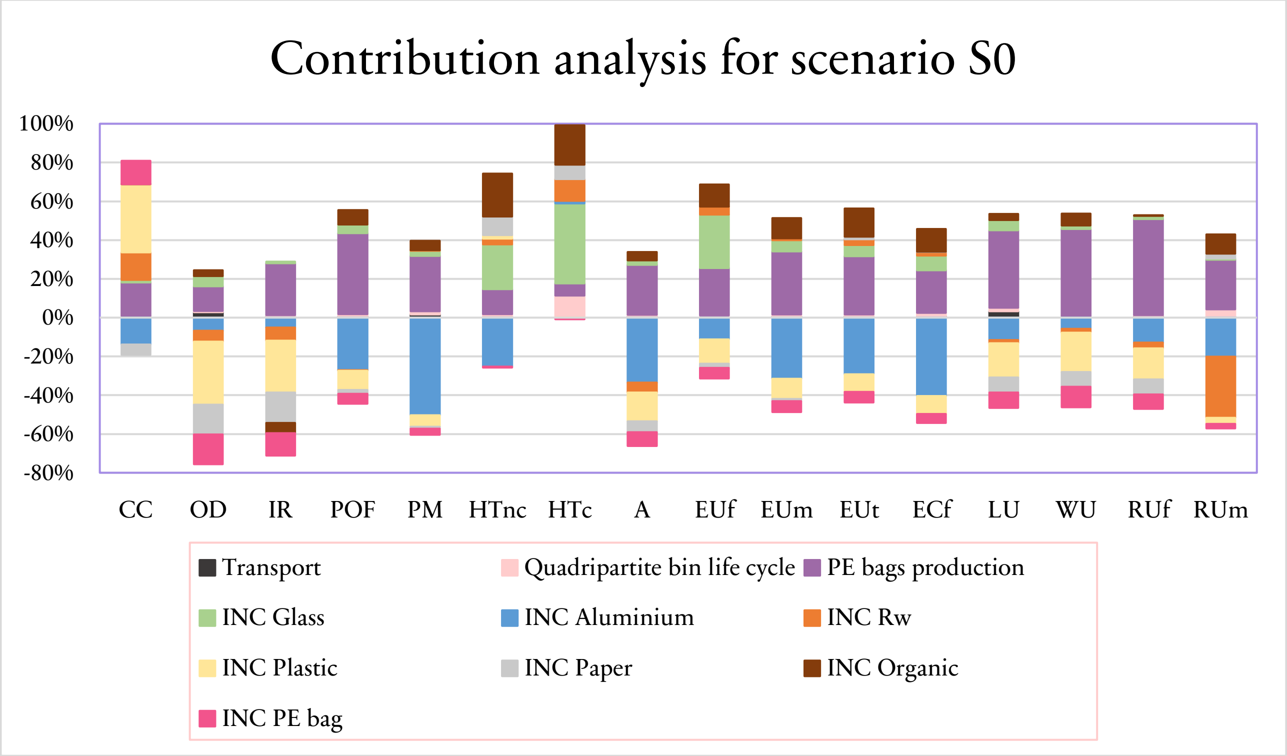

Figure 5.4 Contribution analysis for scenario S0. “INC” means incineration.

In scenario S0 there are 10 out 16 impact categories which contribute to an environmental burden (CC, POF, HTnc, HTc, EUf, EUm, EUt, LU, WU and RUf).

In six of them (POF, EUm, EUt, LU, WU and RUf) the main contribution to the burdens is the production of the PE bags used for collecting the waste at the airport (from 53.3% to 93.6% of the load). This is due to the high amount of the bags used for the collection of the waste since, according to experiment 1, it was very common to collect waste bags well before they were full.

The impacts of incineration are relevant (and net positive) for the CC, HTc, HTnc and EUf category. The highest contribution to the CC category is the emissions of fossil CO_2 due to the combustion of plastic and RW (higher carbon content than other fractions). Emissions of biogenic CO_2 (paper and organic) are equal to 0 in this category according to the characterisation factor of biogenic carbon dioxide adopted by the EF method. For what concerns HTc, HTnc and EUf, the main contributor is the incineration of glass, followed by the incineration of organic waste. Impacts in this case are associated to the landfilling of the fly ash (which causes long term leaching of metals in the ground) produced during the combustion because both glass and organic waste leaves a lot of solid residues to handle at the end of the incineration process.

For the other six categories (OD, IR, PM, A, ECf and RUm) the benefits overcome the impacts. This is mainly due to incineration of plastic and aluminium. Indeed, plastic has a high LHV which allows an higher recovery of electrical energy with respect to the other fractions while aluminium incineration allows the recovery of the material from the bottom ash (assuming that the recoverable amount is aluminium of size larger than 5 mm).

The impact of the production phase of a quadripartite bin is almost negligible (below 4.5%) in all categories except for the HTc and RUm one where it has a positive contribution of 11.3% and 9.0% respectively and it is associated to the process of steel production.

5.3.2 Analysis of the impacts of S0-r

Table 5.14 reports the indicator value for each impact category with reference to the functional unit for scenario S0-r while fig. 5.5 shows the contribution analysis.

Table 5.14 LCIA results for scenario S0-r relative to 1 ton of waste with the composition of table 5.1 column e (functional unit). Net impacts are highlighted in red while net benefits in green.

Impact category	Unit of measurement (for functional unit)	Total impact	Load (positive impacts)	%	Benefits (negative impact)	%
CC	kg CO2 eq	-9.2E+01	2.2E+02	41.5%	-3.1E+02	-58.5%
OD	kg CFC11 eq	-8.6E-05	4.3E-06	4.6%	-9.0E-05	-95.4%
IR	kBq U-235 eq	-3.7E+01	1.2E+01	19.4%	-4.9E+01	-80.6%
POF	kg NMVOC eq	-9.7E-01	5.2E-01	25.8%	-1.5E+00	-74.2%
PM	disease inc.	-3.3E-05	5.4E-06	12.3%	-3.8E-05	-87.7%
HTnc	CTUh	-4.9E-06	2.1E-06	23.3%	-7.0E-06	-76.7%
HTc	CTUh	8.8E-09	2.3E-07	51.0%	-2.2E-07	-49.0%
A	mol H+ eq	-2.8E+00	5.6E-01	14.4%	-3.4E+00	-85.6%
EUf	kg P eq	-5.3E-02	3.9E-02	29.8%	-9.2E-02	-70.2%
EUm	kg N eq	-3.3E-01	1.1E-01	20.4%	-4.4E-01	-79.6%
EUt	mol N eq	-3.3E+00	1.2E+00	20.9%	-4.4E+00	-79.1%
ECf	CTUe	-8.2E+03	1.6E+03	13.7%	-9.8E+03	-86.3%
LU	Pt	-2.0E+03	4.9E+02	16.5%	-2.5E+03	-83.5%
WU	m3 depriv.	1.7E+01	9.6E+01	55.0%	-7.8E+01	-45.0%
RUf	MJ	-4.9E+03	3.5E+03	29.3%	-8.4E+03	-70.7%
RUm	kg Sb eq	-1.4E-03	7.7E-04	25.9%	-2.2E-03	-74.1%

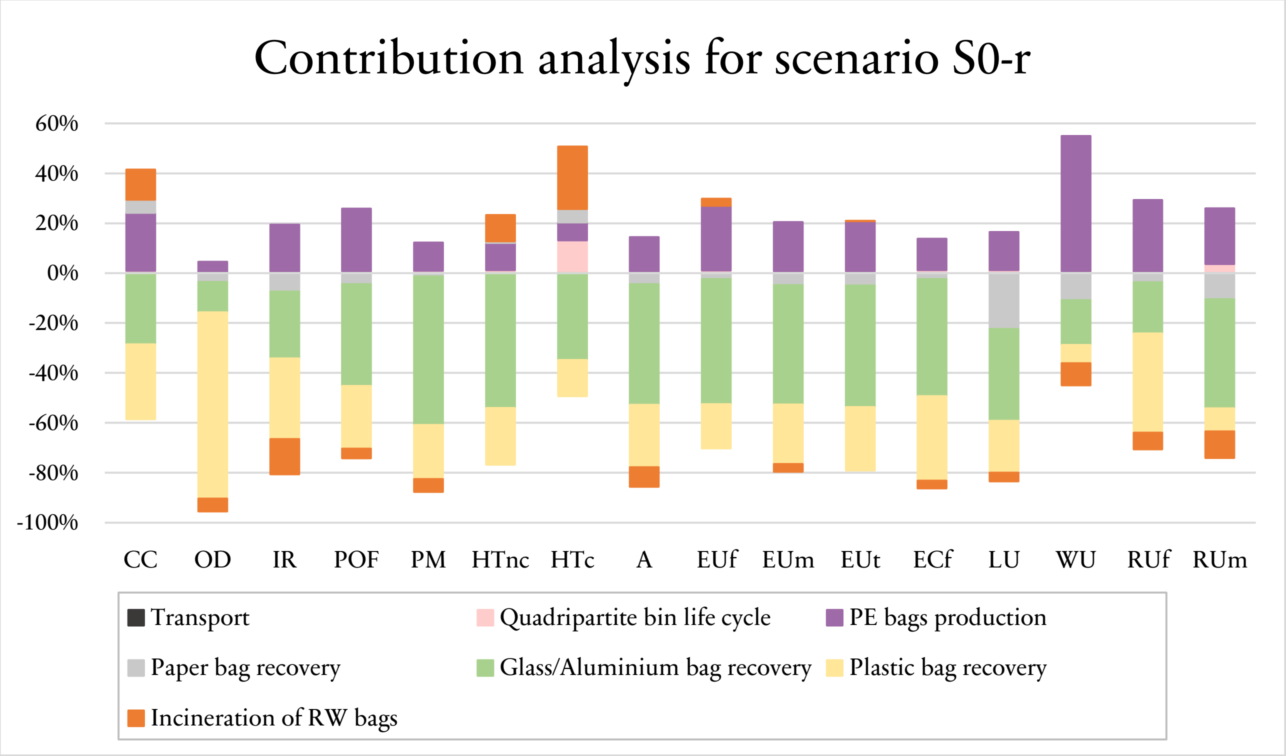

Figure 5.5 Contribution analysis for scenario S0-r.

In scenario S0-r only 2 categories out of 16 show a net impact on the environment (HTc and WU). The largest positive contribution in the HTc is given by the incineration process and it is still connected to the long term leaching of metals in the ground associated with landfilling of the fly ash (in this case the main contribution comes from incineration of residual waste bag which is composed mainly of organic waste with 49.3% of the load). The impact in the WU category are due to the production phase of the PE bags.

As regards benefits, in 10 out of the beneficial 14 categories (POF, PM, HTnc, A, EUf, EUm, EUt, ECf, LU and RUm) the main responsible is the glass/aluminium recovery with aluminium recycling as main share within this process (figure 5.6). Indeed, the recycling of aluminium avoids the production of a certain amount of primary aluminium (799 kg/ton), which is a very energy intensive process.

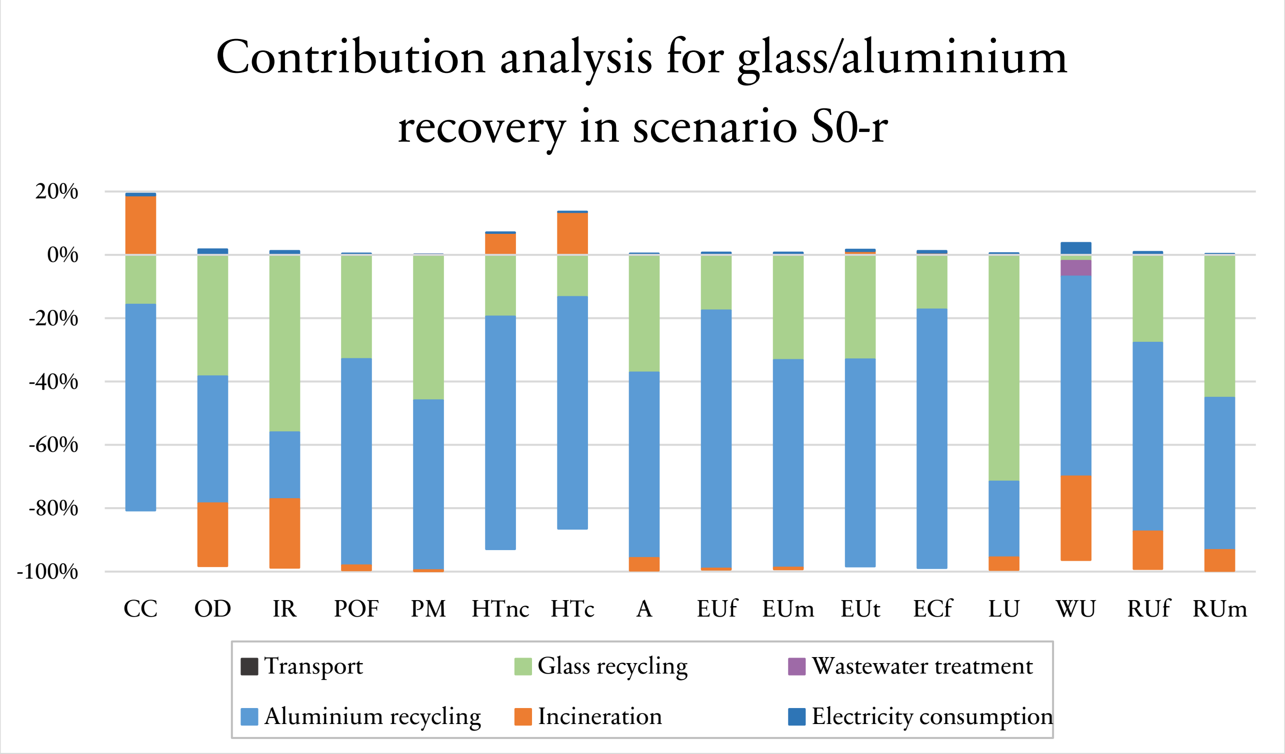

Figure 5.6 Contribution analysis for glass/aluminium recovery in S0-r.

In 4 out of the 14 categories (CC, OD, IR and RUf) the main responsible is plastic recovery. Indeed, in scenario S0-r it has been assumed that plastic is sent as SRF to a cement kiln and this allows to avoid the primary production of a certain amount of pet coke. The plastic recovery process is also beneficial in all other categories because the plastic recovery implies the recovery of aluminium impurities in the plastic bag at the selection plant (according to what happens in the dedicated plant Tramonto Antonio Srl).

Paper recovery is particularly beneficial only in the category LU due to the avoided production of paper from forests (26.8% of the benefits).

As in scenario S0, the impact of the production of the PE bags is important for every category and predominant (higher than 55% of the load) in 14 out of 16 (except for HTc and HTnc) while the production of the quadripartite bin has a very low contribution except in the HTc category (35.8% of the load).

5.3.3 Analysis of the impacts of S1

Table 5.15 reports the indicator value for each impact category with reference to the functional unit for scenario S1 while fig. 5.7 shows the contribution analysis.

Table 5.15 LCIA results for scenario S1 relative to 1 ton of waste with the composition of table 5.9 column e (functional unit). Net impacts are highlighted in red while net benefits in green.

Impact category	Unit of measurement (for functional unit)	Total impact	Load (positive impacts)	%	Benefits (negative impact)	%
CC	kg CO2 eq	-2.5E+02	1.8E+02	29.7%	-4.4E+02	-70.3%
OD	kg CFC11 eq	-4.7E-04	6.2E-06	1.3%	-4.8E-04	-98.7%
IR	kBq U-235 eq	-3.8E+01	8.0E+00	14.8%	-4.6E+01	-85.2%
POF	kg NMVOC eq	-1.5E+00	2.6E-01	13.2%	-1.7E+00	-86.8%
PM	disease inc.	-3.9E-05	2.6E-06	5.9%	-4.2E-05	-94.1%
HTnc	CTUh	-6.3E-06	3.1E-06	24.8%	-9.5E-06	-75.2%
HTc	CTUh	-1.9E-07	2.8E-07	37.5%	-4.7E-07	-62.5%
A	mol H+ eq	-3.2E+00	3.5E-01	8.9%	-3.6E+00	-91.1%
EUf	kg P eq	-8.4E-02	5.0E-02	27.0%	-1.3E-01	-73.0%
EUm	kg N eq	-4.4E-01	9.5E-02	15.0%	-5.4E-01	-85.0%
EUt	mol N eq	-4.5E+00	1.2E+00	17.0%	-5.6E+00	-83.0%
ECf	CTUe	-9.1E+03	2.2E+03	16.5%	-1.1E+04	-83.5%
LU	Pt	-2.7E+03	3.2E+02	9.5%	-3.0E+03	-90.5%
WU	m3 depriv.	-6.3E+01	4.3E+01	28.8%	-1.1E+02	-71.2%
RUf	MJ	-7.0E+03	1.4E+03	14.2%	-8.4E+03	-85.8%
RUm	kg Sb eq	1.1E-03	4.6E-03	56.8%	-3.5E-03	-43.2%

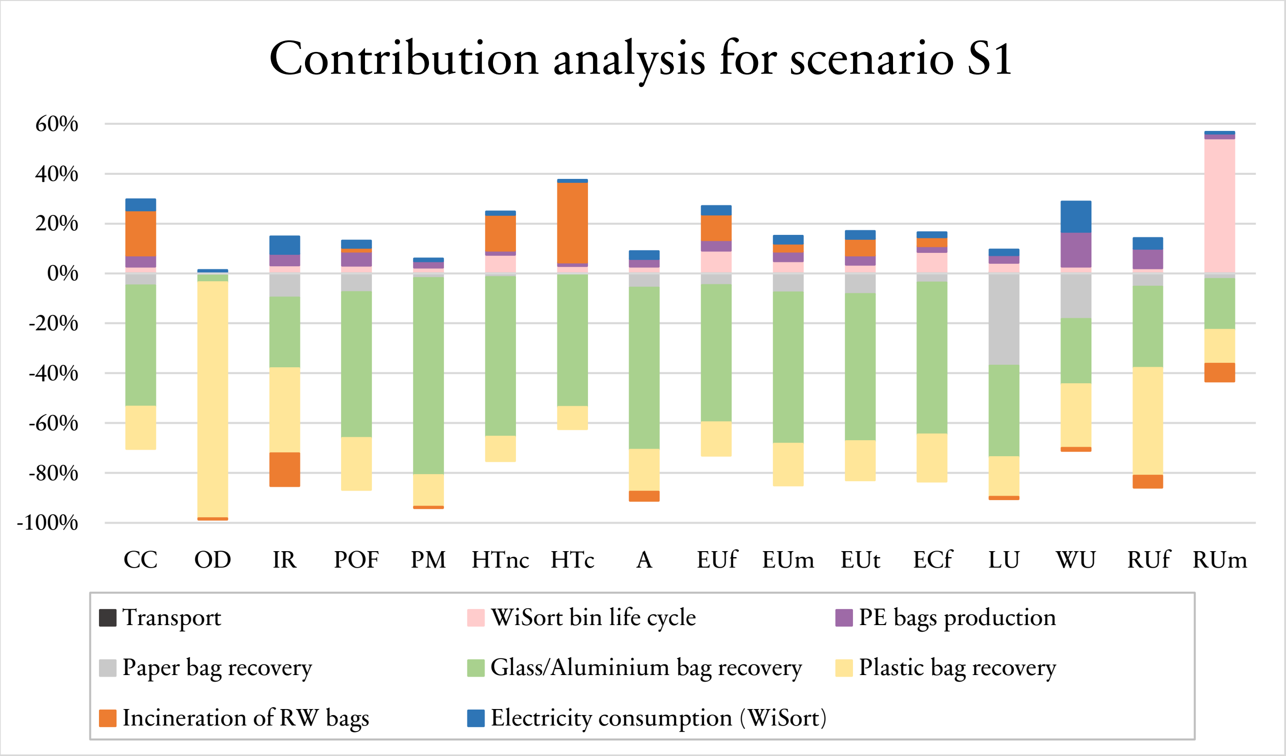

Figure 5.7 Contribution analysis for scenario S1.

In scenario S1 all impact categories except one (RUm) have a net benefit on the environment. The high environmental load for RUm is mainly due to the life cycle of WiSort bin, in particular to the electronic components with contain rare metals (as gold).

The overall benefits for the 15 out of 16 categories are mainly due to glass/aluminium recovery (in 11 categories out of 16, i.e. CC, POF, PM, HTnc, HTc, A, EUf, EUm, EUt, ECf and WU), plastic recovery (in 3 categories, i.e. OD, IR and RUf) and paper recovery (in 1 category, i.e. LU, where it accounts for 40.9% of the benefits).

In scenario S1 plastic recovery doesn't take into account the recovery of aluminium at the selection plant (Caris VRD Srl) as this fraction is equal to zero in the plastic bag so the benefits come from the production of SRF for the cement kiln and the recycling of the PET. PET recycling is the main contribution of the negative impacts (from 57.4% to 94.5% of the benefit) for 12 categories out of 16 (OD, POF, PM, HTnc, HTc, A, EUf, EUm, EUt, ECf, WU, RUm) as it can be seen from figure 5.8. The LHV of PET is the lowest among plastic so the separation of it from the other plastics allows to have a SRF with a higher lower heating value (LHV is also influenced by the other impurities of the plastic bag but in scenario S1 their amount is very low) and this is beneficial for the co-combustion process.

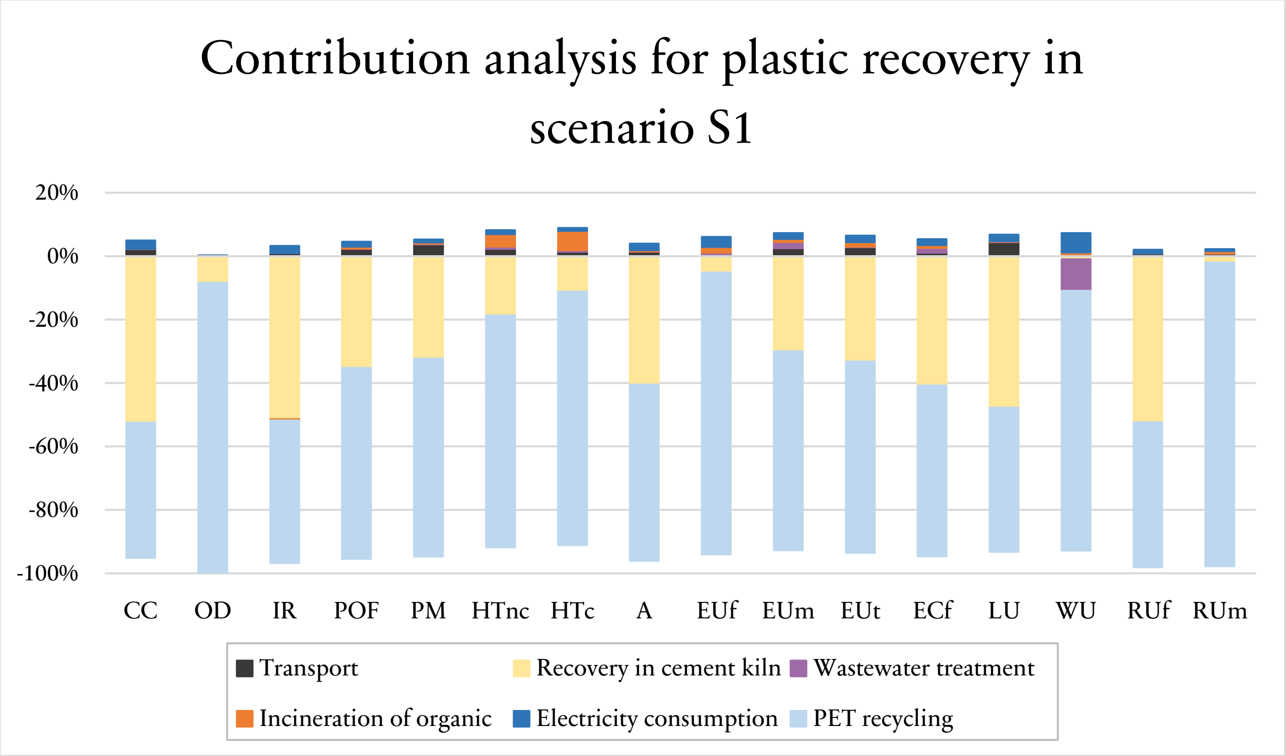

Figure 5.8 Contribution analysis for plastic recovery in S1.

Differently from scenarios S0 and S0-r, in scenario S1 it is possible to observe that the impacts of the production of PE bags for waste collection are reduced and this is due to the fact that the use of WiSort bin allows to monitor the filling condition of the bag and therefore it was assumed that bags are collected when full at 80% of their capacity with an optimization of the number of bags needed to collect 1 ton.

By looking at fig. 5.7 it is also possible to answer one of the initial questions of the LCA and affirm that the impact of the additional use of electricity required by the automatic bin (under the assumption of one item every minute) is more than outbalanced in each impact category by the benefits of the various types of recovery and for the RUm is almost negligible (1.3%).

5.3.4 Comparison of S0, S0-r and S1

Fig 5.9 shows the comparison of the three scenarios. Note that the figure has been created in a way that enhances the comparison in relative terms among the scenarios: since for each category there are three values (one for each scenario), 100% is given to the maximum value among them (considering them in absolute values) and the other two values are rescaled as a consequence.

The figure allows to see that scenario S1 is better than the other two scenarios in all categories except the one of RUm. In this last category, scenario S1 has a very high relative load mainly due to the production of the electronic components of the WiSort bin as explained in paragraph 5.3.3.

Scenario S0-r is better than scenario S0 for every category except the WU where it has a slightly higher absolute value (17.5 VS 15.6 m^3 water eq. deprived, i.e. +11.9%). In this scenario only two impact categories have an overall positive impact (HTc and WU) differently from scenario S0 which is burdensome for 10 out 16 impact categories (CC, POF, HTnc, HTc, EUf, EUm, EUt, LU, WU and RUf). According to such results, it is possible to conclude that the current management of the MSW coming from the public areas of Malpensa (complete incineration at Neutalia Srl) is not justified from an environmental point of view as the majority of the categories have an net impact rather than a benefit in scenario S0. It is important to encourage the selection and recycling of plastic, glass/aluminium and paper fractions, also promoting a better separation of them at the source.

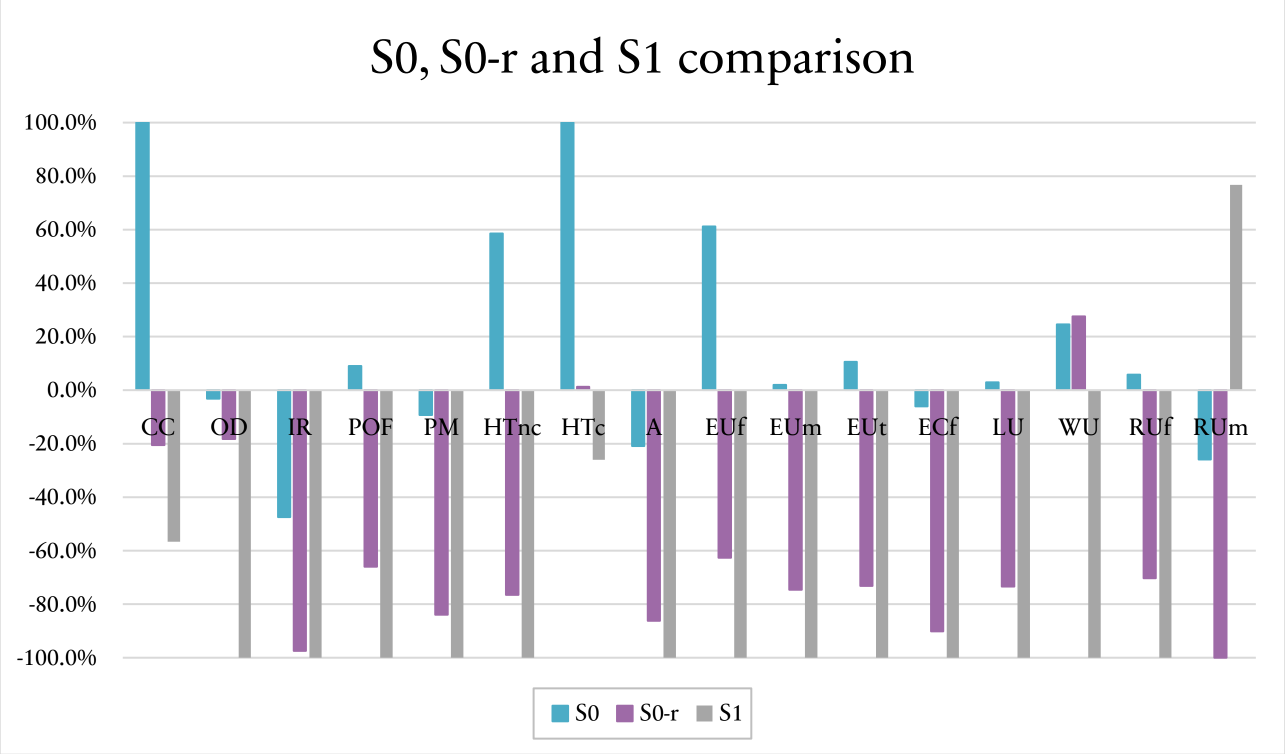

Figure 5.9 S0, S0-r and S1 comparison in terms of environmental impacts.

Figure 5.10 and 5.11 show the comparison of the three scenarios by keeping for each impact category the contribution of the processes involved. Fig. 5.10 shows the comparison for eight categories (CC, OD, IR, POF, PM, HTnc, HTc, A) while fig. 5.11 for the other ones (EUf, EUm, EUt, ECf, LU, WU, RUf, RUm).

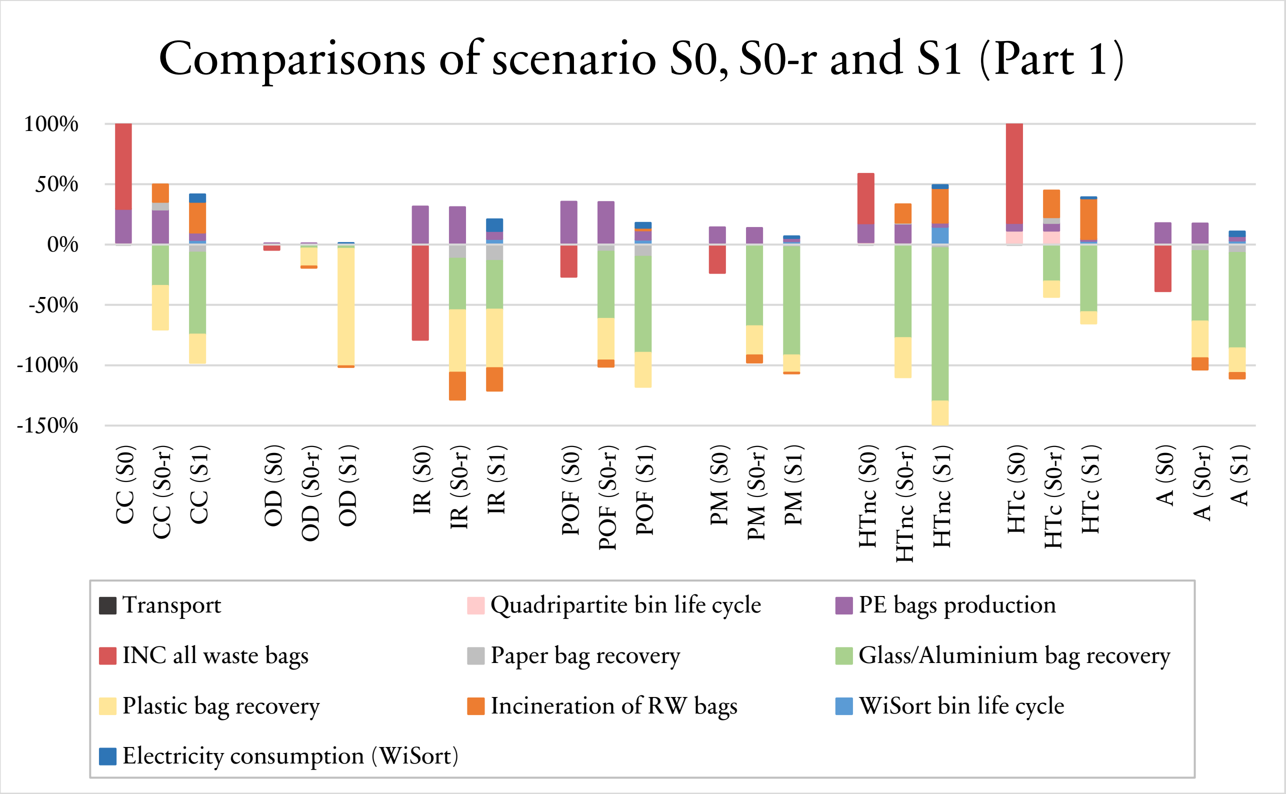

Figure 5.10 S0, S0-r and S1 comparison keeping the contribution analysis for each category and scenario. Results relative to the first 8 impact categories.

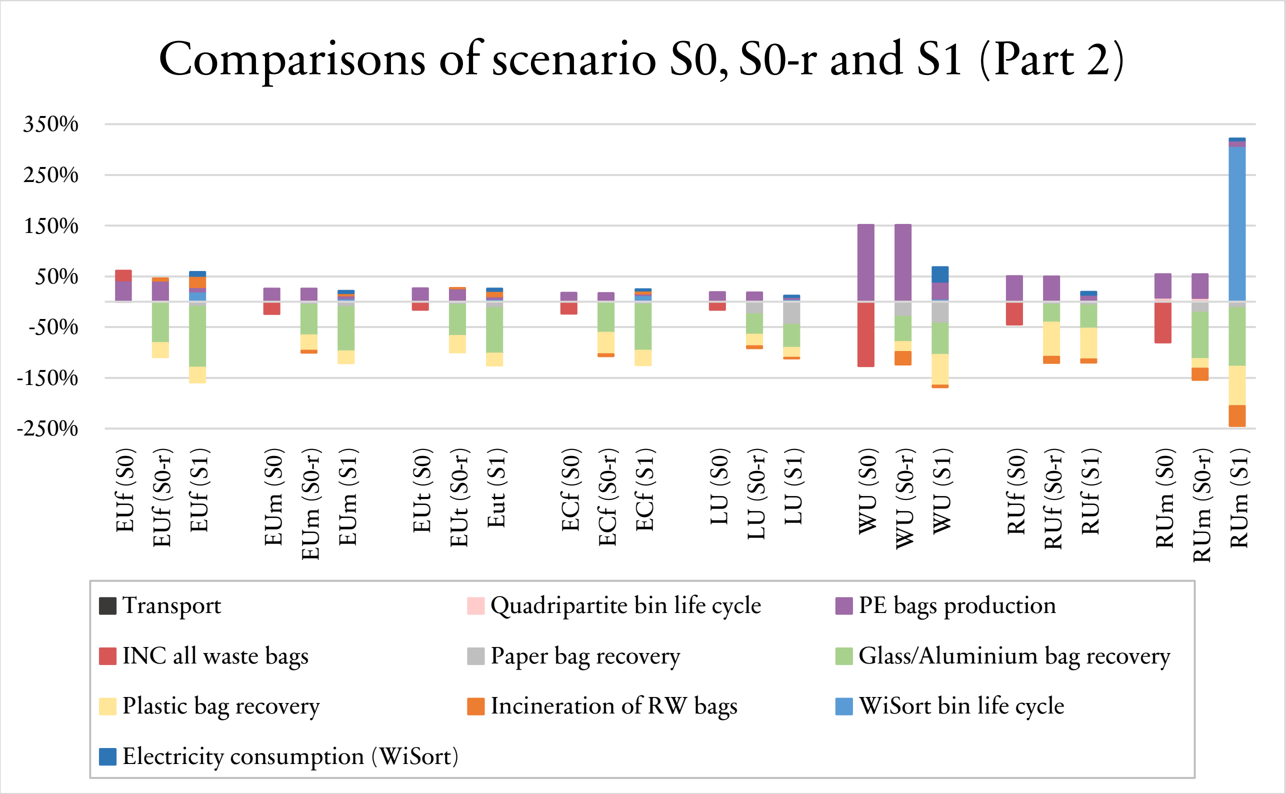

Figure 5.11 S0, S0-r and S1 comparison keeping the contribution analysis for each category and scenario. Results relative to the last 8 impact categories.

From figures 5.10 and 5.11, it is possible to see that for 9 categories out of 16 (IR, POF, PM, A, EUf, EUm, EUt, ECf and RUf) the main burden of scenario S0 is the production of the PE bags for the collection of the waste, while incineration provides a benefit in the same categories (except for EUf). From scenario S0-r and S1 contribution analysis, it is possible to notice that the choice of sending material to recovery is much more advantageous than the one of incineration and the main contributor to the overall benefit is the glass/aluminium recovery (in green with aluminium recycling as major benefit as highlighted in the previous paragraphs) except for the RUf category where the main contributor is plastic recovery (contribution in yellow). The benefit of material recovery is higher in scenario S1 because the amount of recyclable materials sent to recovery increases due to a better sorting performed by the Wisort bin. Indeed, with the exception of glass, whose quantity remains almost the same between manual and automatic separation (72 kg VS 71.5 kg), aluminium indeed goes from 14.9 kg to 25.6 kg (+72%) and plastic from 107.0 kg to 129.6 kg (+21%). Paper recovery is relevant only in the LU and WU category. The amount of paper correctly sorted also goes from 81.3 kg (scenario S0,S0-r) to 156.1 kg (scenario S1) (+92%).

For what concerns the RUm category, it is also possible to see once again the influence of the Wisort bin life cycle in scenario S1. It must be highlighted though that the life cycle of Wisort bin has been modelled according to the EPD® approach so the benefits of the recycling of the electric components of the bin are not taken into account. Those benefits might lower the impacts of this category. An investigation of them could be carried out to find an answer to this open issue. The choice of the EPD® approach was also made because of the high uncertainty and/or unavailability of modelling choices for these benefits with SimaPro.

In the CC, HTnc and HTc categories, incineration causes a high environmental burden in scenario S0, which is lowered in scenario S0r and S1 as only RW bags are directly sent to incineration. Glass/aluminium and plastic recovery are the main source of benefit in scenario S0r and S1.

The OD category shows a strong improvement from scenario S0 to S1 thanks to the recovery of plastic. The latter process is particularly favourable in scenario S1 due to the recycling of PET, which indeed goes from 69.9 to 84.7 kg (+21%) and therefore to the avoided production of a certain amount of virgin PET. In scenario S0-r the benefit only depends on the recovery of SRF from plastic bag in a cement kiln and recovery of aluminium residues in the plastic bag.

5.3.5 Sensitivity analysis

Finally, a sensitivity analysis on the level of accuracy (classification accuracy by weight) of WiSort bin was carried out to see the changes in the performance of scenario S1 relative to S0-r. Scenario S1, as said before, was created assuming a classification accuracy by weight of 90% (value selected from literature and other existing automatic bins), while the current corresponding value of accuracy for manual passengers selection for S0/S0-r is 61.5%[18]. The latter value indicates that passengers of Malpensa airport are capable of classifying correctly on average 61.5% of the mass of the waste they introduce in a quadripartite bin.

Three more values of accuracy for WiSort bin were tested: 70%, 80% and 95%. Figure 5.12 shows the results of this analysis.

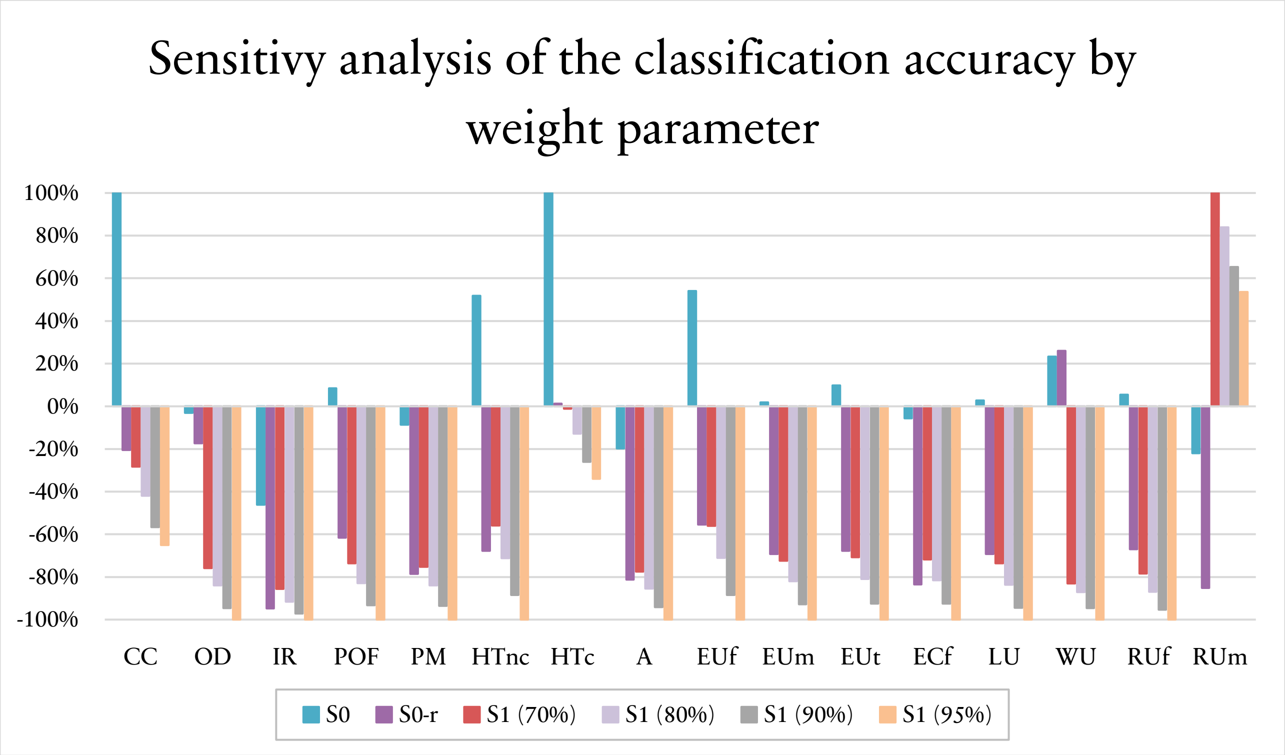

Figure 5.12 Sensitivity analysis results for the classification accuracy by weight parameter in the scenario S1.

Irrespective of the level of the classification accuracy by weight (i.e. 70%, 80% and 95%), scenario S1 provides an environmental benefit for all categories except for the RUm as already observed for scenario S1 with 90% classification accuracy by weight. These benefits grow with the level of accuracy. Nevertheless, it can be noticed that scenario S1 with 70% is worse than scenario S0-r for the IR, PM, HTnc, A, ECf and RUm impact categories and only slightly better for the others. This is due to two reasons: the first is the fact that the presence of the automatic bin and its consumption of electricity causes higher burdens than the ones of the quadripartite bin life cycle (as for scenario S1 with other values of classification accuracy by weight); the second is a reduction of the benefits because in scenario S1 with a 70% classification accuracy some fractions are sorted worse by WiSort bin than in scenario S0-r which describes the current manual separation. Indeed, even though the average value of classification accuracy by weight for scenario S0-r is 61.5%, the airport's values of that accuracy for plastic and glass are already higher than 70% (i.e. 74.3% and 90.6% respectively as it can be seen from table 5.1 of paragraph 5.2.1).

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[18] This value is the average value of the classification accuracies by weight taken from last column of table 5.1

Therefore, higher burdens and lower benefits make scenario S1 with 70% unfavourable with respect to scenario S0-r in those categories.

Scenario S1 with 80% is slightly worse than scenario S0-r for the IR and ECf categories and greatly for RUm as already observed also for the other scenarios. Nevertheless, the difference of the values of the indicator in the first two categories (IR and ECf) is less than 10% so the two scenarios can be considered comparable for those categories taking into account the uncertainty of the results connected to the estimation of the various impacts.

Scenario S1 even with a 95% accuracy determines an environmental burden in the RUm category due to the reasons already widely explained.

Starting from such preliminary results, it is already possible to say that in order to make a difference with respect to the actual waste management condition, the WiSort bin should at least have a value of classification accuracy by weight of 80%.

An final consideration on the modelling of the different waste treatments should be made: results of the analysis are dependent on the data of the specific plants, where the airport actually send its MSW for a proper management. Indeed, WTE plants with higher electrical efficiency (or with the chance of supplying the heat generated for district heating) than the plant managed by Neutalia Srl or selection plants with other types of treatment or efficiency might have led to different results. A sensitivity analysis on this topic could explore further the results and understand better the impacts of an automatic system under different circumstances.

6 COST ANALYSIS

A cost analysis was performed in order to understand the total management cost of the MSW at Malpensa airport and the economic costs and benefits of increasing the amount of recyclable materials collected from the public areas of the airport through the use of WiSort bin. As for the LCA, the analysis for public areas was performed under scenario S0, S0-r and S1.

The data sources regarding costs were ISPRA reports, Lombardy region data (PRGR) and direct interviews with SEA. The latter will be mostly expressed as aggregated values due to confidentiality. Due to COVID-19, a drastic reduction in the generation of waste was observed. For this reason, the calculations were made using 2019 waste data, considered the last representative available data, while for the costs the choice of the year was made in agreement with SEA in order to use the most unbiased data, usually choosing year 2019 or average data.

Four main categories of costs for the total MSW can be identified at Malpensa airport:

a) Cost for external transport (i.e. the costs for transporting the waste to the final destination plant);
b) Cost for disposal (i.e. the fees for processing the waste at the final plants);
c) Costs for cleaning operations (e.g. personnel costs for emptying the bins, moving the waste to ground floor);
d) Cost for internal operations (i.e. the costs of operators and trucks (fuel) for carrying the waste from ground floor to the airport's waste storage area, including the cost of management of this area);

The airport, as described in the above chapters, has two terminals (T1 and T2), each of them divided into landside and airside. At the moment for T1 (landside and airside) and airside of T2 there is an agreement with the municipality of Ferno-Lonate which has established that the MSW costs are paid based on the amounts produced. An average unitary external transport is 48 €/ton while disposal costs, which differ greatly from fraction to fraction, vary from -120 €/ton to 150€/ton. The landside of T2 is managed by the municipality of Somma Lombardo, which applies the TARI[19] for the management of the MSW coming from there. So in this case the costs for transport and disposal don't vary with the amount of each fraction produced and they are indirectly included in the TARI, which can be considered a fixed value as only small changes from year to year occur.

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[19] The TARI is a tax that each municipality has to collect from households and activities within its boundaries in order to completely cover the costs of collection, treatment and disposal of the waste. For commercial and industrial activities, it depends on the surface and the type of activity (MEF, n.d.).

Cleaning and internal operations costs adds up to these costs. Costs for cleaning operations refer only to the cost of the operators who have the job of emptying the bins in the public areas of the airport (both T1 and T2) throughout the day as the waste produced from activities (restaurants, cafés, shops) is directly brought to ground floor by the activities themselves (and so it is not a cost in charge of the airport). Costs for internal operations refer only to T1 (landside and airside) and airside of T2 as the same cost for landside T2 is already included in the TARI tax. The values of these costs are confidential so they are not reported here. Since these costs can be considered independent on the relative amount of each waste fraction (e.g. they don't change if more waste is sorted and less residual waste is produced), a unitary cost per ton was obtained by dividing them by relative amount of MSW. In this way an indicative value of cost per ton related to these activities can be attributed to every fraction and used to determine the overall cost of management of each fraction. Waste data which have been used to determine these two cost items are shown in table 6.1 and their amounts are displayed according to the area of competence of the two municipalities.

Table 6.1 Waste amounts referred to MSW generated in 2019. Column 4 values are taken from SEA Sustainability report 2021 and show the overall MSW of the airport. Column 2 data were provided by SEA and column 3 was deduced based on the other columns. The amount of waste from public places was estimated by SEA.

Malpensa airport (2019 ton)	T1+ airside T2	Landside T2	T1+T2
Sorted MSW	1.707.50	736.50	2.444.00
Unsorted MSW	4.121.15	380.85	4.502.00
TOT MSW (sorted+unsorted)	5.828.65	1.117.35	6.946.00
Public places			153.50

In paragraph 6.1. and 6.2 the results of the two costs analysis are shown. Here a discussion about some of the cost item is given.

Average unitary cost for external transport and disposal are usually decided by the collection & transport company according to market conditions (e.g. change in the price of fuel or change in the prices for processing the waste at the plants) and agreements made with its clients. These companies are usually private so the aim is to maximize their profit too. External transport cost are usually dependent on cost of the fuel, number of journeys and maintenance rather than distance from the plant. Disposal costs on the contrary present great variations depending on the fraction. It can be observed that the highest values refer to those fractions which are not sent to recycling but to other kind of treatments (such as incineration and anaerobic digestion), i.e.

residual waste, food waste, plastic waste, bulky and sweeping waste. These latter cost are in line with the average gates fees of Lombardy's plants (PRG, 2022).

For the other fractions the cost is either low, null or even negative. This is due to the fact that these materials are usually intercepted by the CONAI system, which handles the packaging waste in Italy[20]. The CONAI, the Italian national consortium of packaging materials, has the role of connecting and interacting with all the stakeholders (i.e. the suppliers of the packaging materials, the producers, the users and the retailers) involved from the production to the final disposal of this kind of waste, which is addressed by the new circular economy package directive of 2018. The CONAI is responsible for charging all these stakeholders an environmental fee called "Contributo ambientale CONAI (CAC)" for the subsequent separate collection, recovery and recycling of the packaging waste. Through the ANCI-CONAI agreement, CONAI redistributes the collected capital to the municipalities or the other companies involved in the management of the packaging waste through the so called "corrispettivi per la raccolta" or collection fees. These fees are a contribution to the expenses that the municipality has to bear in order to collect and send to recycling this type of waste. The CONAI consortium coordinates the activities of the 7 consortia which are directly involved in the recovery of the packaging waste and interact with various municipalities and plants located on the Italian territory. Each consortium targets a specific packaging material: Comieco for paper, Ricrea for steel, CiAl for aluminium, CoReVe for glass, Corepla for plastic, Rilegno for wood and Biorepack for biodegradable and compostable plastic. The collection fees are set by each of the consortia and depends on the quality of the collected materials: the lower the impurities, the higher the collection fee in order to encourage a better source separation (CONAI, n.d.; Rigamonti et al., 2015). At the moment more than 75% of the total packaging waste is handled by the CONAI's consortia (Grillo et al., 2018).

Because of the CONAI systems, the collection & transport company thus collects these fractions free of charge or pays the airport for disposing them (excluding the transport) and receives the collection fees from the plants. The plants reported in table 3.3 of paragraph 3.3 are in fact plants selected by the respective consortia (paper, glass and aluminium and plastic with option 2).

Even though plastic packaging is addressed by the CONAI too, in this case it has a cost almost equal to the one of RW and this is due to the fact that it is sent to energy recovery as explained in paragraph 3.3. When recycling is not applied, the collection fees are not given.

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[20] Paper, plastic, glass, metals and wood fractions from the airport are not made of packaging waste only but can still be managed by the CONAI according to different agreements and limits (see "Allegati tecnici" on https://www.conai.org/regioni-ed-enti-locali/accordo-quadro-anci-conai/)

To sum up, it is possible to conclude that for the airport is much more convenient to implement source separation as much as possible in order to reduce the disposal costs in those areas of the airport where the TARI is not implemented.

For what concerns cleaning costs, their annual value is lower considering the fact that it is a cost connected only to the public areas of the airport but their cost per ton is the highest cost item since these costs refer only to the collection of 153.5 ton per year. Internal operation cost per ton are higher than the ones for external transport also because the transport of the waste from the ground floor of the airport to the WSA occurs every day despite the amounts produced per day while the external transport cost (48 €/ton) is more optimised as the trucks leaves the WSA when full.

6.1 The total cost of MSW

The overall costs of managing the MSW generated in the airport are given by the sum of the four cost categories described above. More specifically, they are given by the sum of the cost of the two main areas of competence of the airport: T1+airside T2 and landside T2. The former is obtained by identifying the single cost of managing each fraction and then by summing up all these single costs. The single cost of each fraction is given by the aggregation of the four cost categories, which are partially dependent on the amounts generated. The latter (landside T2) is the sum of the cost of the TARI tax and the cleaning costs. Final results only are presented in table 6.2 and they are relative to the two areas of the airport. The total cost amount to 1,969,898.6 €/year[21] and it is equivalent to 6.86 cent/passenger. A similar value (6 cent/passenger) was described also by Hershkowitz et al. in 2006 when studying the cost of seven U.S. airports. This cost, in charge of SEA, is then re-distributed among all the activities and operators of the airport.

Table 6.2 Overall MSW costs of the Malpensa airport.

OVERALL MSW COSTS	€/year	€/ton
T1+T2 airside	1,480,839.8	254.1
T2 landside	489,058.8	437.7
TOT	1,969,898.6	

Even though it is not possible to see this information from the above table, the total cost of RW is the main component of the cost of T1+T2 airside (78.6%) for two reasons: a higher disposal fee and an higher amount generated with respect to other fractions. In fact, also all the waste coming from airplanes is not sorted and thus contribute to the RW fraction.

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[21] Value subjected to some approximations

The table also displays the cost in €/ton of the two area of competence of the airport. It's possible to notice how this price for T2 landside is almost double (1.7 times) the price for the other areas of the airport. The fixed cost of the TARI doesn't allow to pay depending on the amount of waste produced according to the PAYT principle. Even though from an economic point of view this might be seen as a disincentive to carry on a good source separation in landside T2 (as the costs to pay is fixed), it is for sure beneficial from an environmental one. This is proved by the results of the LCA in paragraph 5.3.

6.2 *Cost comparison for public areas*

The same scenarios described in paragraph 5.1 (S0, S0-r and S1) are used here to assess the economic costs and benefits in addition to their environmental performance. This cost analysis only refers to the MSW coming from the public areas (153.5 ton). During the experimentation, only one prototype was tested and thus only a small percentage of all the potential MSW from public areas was intercepted by the bin. The cost analysis that will follow assumes that all the waste is collected by many WiSort bins scattered around the public areas in order to intercept all the waste generated there. The idea is to compare the actual situation with the one in which WiSort bin replaces the use of the normal quadripartite bins[22]. Nevertheless, comparison is also made in terms of cost per ton (and not only total costs) so that the cost-benefit referred to a lower amount managed by one automatic bin can still be computed.

When moving from the actual scenario (S0) to a new hypothetical one (S0-r, S1), not all costs change in the same way (US EPA, 1997). Variable costs can instantly change: an example is the costs for external transport and disposal, which are costs per ton, so if the amount of a certain fraction is increased or reduced then there is an immediate variation of the price the airport has to pay. Some other costs are fixed and can change only after a transitory period. Maybe the new way the waste is sorted allows to make the internal collection and the emptying of the bags more efficient (since for example WiSort bin is capable of notifying the operator when the bin is full and allows a more optimised process) or some modification can be applied in the way the waste is transported to the waste storage area (different trucks depending on the amounts collected). This kind of latter considerations are not taken into account in this cost analysis. Furthermore, the comparison of the scenarios underlines the following hypothesis: only small changes would be observed in the way the waste is managed. For example, no structural changes (e.g. new plants) are required: even if waste fractions are diverted from incineration, they are sent to plants which are already selected by the collection & transport company, and so indirectly by the airport, so

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[22] From the environmental analysis performed in chapter 5 and relative assumptions it was obtained that one WiSort bin equals 2.6 quadripartite bins (see tables 5.2 ad 5.10)

no new plants have to be found (except for the plastic alternative). It is also assumed that variable costs (transport and disposal costs) do not change as a consequence of the economy of scales. This hypothesis can be considered more than acceptable especially in this situation as the amounts coming from the public areas are only a small portion of the total MSW handled at the airport. For the same reasons no changes regarding the internal and external collection were accounted for (e.g. same trucks, same journeys, same number of operators).

Table 6.3 shows the amounts relative to the four bags of a quadripartite bin used for the cost analysis based on experiment 1. These values are the same of table 5.1 and 5.9 (average weight of the four bags) of paragraph 5.2.1 and 5.2.3 respectively but rescaled to the 153.5 tons (and not 1 ton anymore).

Table 6.3 Waste amount per bag in the three scenarios used for the cost analysis.

Amount (ton/year)	S0/S0-r	S1
Paper bag	20.9	25.8
Plastic bag	50.9	39.3
Glass/Aluminium bag	33.6	29.9
Residual waste bag	48.1	58.5
TOT	153.5	153.5

The values in the table represent the average amount of tons collected by each of the four bags of a quadripartite bin in a year. Note that this is not the effective amount of the four fractions because the bags are never 100% w/w accurate but contains impurities (average level of impurities can still be seen in table 5.1 and 5.9). To give an example, 20.9 ton is the amount of material (paper + impurities) that is collected in the paper bags over a year in the public areas of the airport under scenario S0-r.

Table 6.4 and 6.5 shows the total cost for scenario S0, S0-r and S1 calculated from the four cost categories, whose details are not given due to confidentiality. Under scenario S0, as for the LCA, all the waste (153.5 ton) was considered as residual waste sent to incineration thus the total cost of S0 was determined by summing the four cost categories, using as disposal cost the price of residual waste for all the waste. For scenario S0-r, even though recycling is put into place, the total cost is equivalent to the one of scenario S0. This is due to the fact that, as mentioned before, in order to have the chance of sending the material to the CONAI consortia certain threshold of impurities have to be met. Under scenario S0-r (and S0) the actual average level of impurity is 40.2% for paper, 21.5% for plastic and 40.7% for glass/aluminium[23] while the consortia requires

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[23] They can be deduced from table 5.1 and 5.9 by doing 100% minus the bag accuracy by weight

no more than 15%, 20% and 6.5% respectively[24]. Consistency is required to allow the access of these fractions to the CONAI plants. In some cases it is still possible to bring the material to the consortia but the management of the impurities is at the expense of the municipality[24]. So for scenario S0-r the disposal price for residual waste has been used for the all fractions again. This scenario doesn't indeed provide any advantage from an economic point of view. For Scenario S1 the total cost was obtained by summing up the management cost of each fraction, in turn given by the sum of the four cost categories. Therefore, the prices of each fraction were used as disposal cost. The disposal costs for plastic was assumed equivalent to the disposal prices for the other packaging materials (i.e. glass, aluminium and paper). It can be noticed that with respect to scenario S0/S0-r, the amount of residual waste is higher (58.5 kg vs 48.1 kg) but this is due to the assumption made for the building of scenario S1. This might be seen as a drawback as a higher amount would mean a higher price for disposal. Nevertheless, in this scenario recycling to the consortia is possible as the level of impurities are 7% for paper, 4.6% for plastic and 6% for glass/aluminium[24]. This would be beneficial for the collection and transport company as well as they would receive the corresponding CONAI fees.

Table 6.4 Cost analysis results for S0 and S0-r.

S0/S0-r	**TOT (€/year)**	**TOT (€/ton)**
TOT	135,253.5	881.1

Table 6.5 Cost analysis results for scenario S1.

S1	**TOT (€/year)**	**TOT (€/ton)**
Paper	19,527.4	-
Plastic	29,826.4	-
Glass/Aluminium	22,681.1	-
Residual waste	51,531.6	-
TOT	123,566.5	804.9

Under scenario S0/S0-r, the total cost for managing 1 ton of MSW of the public areas of the airport is 881.1 €/ton and it decreases to 804.9 €/ton in scenario S1 (the latter value represents an average value of managing the different fraction of the waste, RW included). Nevertheless, the use of WiSort bin in scenario S1 introduces an additional cost, i.e. the cost of electricity use.

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[24] See "Allegati tecnici" on https://www.conai.org/regioni-ed-enti-locali/accordo-quadro-anci-conai/)

Knowing that the energy consumption of the bin is 67.1 kWh/ton (see table 5.11) and by using the average price of electricity in 2022 (0.303 €/kWh), it is possible to determine that this additional cost is 20.3 €/ton. Thus the total cost of scenario S1 becomes 825.3 €/ton and it grants a saving of 6.3% over the total cost of MSW management, which corresponds to 55.8 €/ton. This saving goes up to 45.4% if only disposal costs are considered over the four cost categories as after all WiSort bin is able to cause a change only on this cost item, leaving unvaried the other ones (at least in the short term). This economic benefit is actually dependent on the amount of the fractions and can only increase the better is the sorting and the lower is the residual waste generated. A visual representation of the saving is given in figure 6.1.

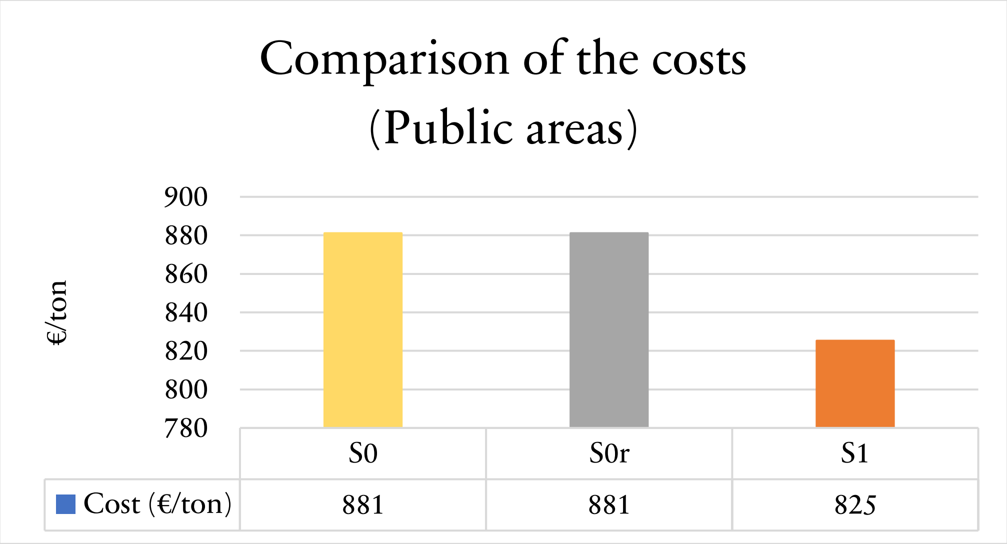

Figure 6.1 Results of the cost analysis under scenario S0, S0-r and S1.

In this figure it is possible to observe that the average costs per ton for treating the MSW of the public areas is much higher than the average cost for treating the MSW of the rest of the airport (i.e. 254.1 €/ton). This is due to the costs for cleaning operations which involve the direct payment of operators for emptying the bins and moving the waste to ground floor. The movement of the other MSW of the airport, as said before, is a cost which directly weigh on the activities of the airport and thus allow the airport to have an average lower value for the total MSW.

As for the environmental analysis, a sensitivity analysis on the accuracy level of WiSort bin (classification accuracy by weight) was performed in order to study how the economic savings would change. The same additional values of accuracy were tested: 70%, 80% and 95%. Table 6.6 shows the results. The total cost of S0 (881.1 €/ton) was attributed to the actual average level of accuracy (61.5%) and this is the only case in which the additional cost of energy use is not added.

Table 6.6 Sensitivity analysis results for different values of classification accuracy by weight.

Classification accuracy by weight	**Total cost (€/ton)**	**Saving (€/ton)**
61.5% (**S0/S0-r**)	881.1	0.0
70.0% (**S1**)	873.7	7.4
80.0% (**S1**)	851.9	29.3
90.0% (**S1**)	825.3	55.8
95.0% (**S1**)	823.5	57.7

All values provide an economic benefit even though in the case of classification accuracy by weight of 70% and 80% it is quite reduced and in the case of classification accuracy by weight of 95% is slightly increased thus suggesting that from an economic point of view the optimal range of WiSort classification accuracy by weight would be around 90%.

It must be also highlighted that since the experimentation was performed on T1 the total costs of the MSW coming from the public areas are dependent on the amount of each fraction. The presence of WiSort bin in T2 landside wouldn't have changed the costs as they only depend on the TARI tax. Nevertheless, in that case, a better source separation would be advantageous for the collection & transport company, which would benefit from higher revenues do to higher CONAI fees. Every time a TARI model is implemented, the first customer for WiSort could be the collection & transportation company, as an economical benefit would be given to them. The airport would still benefit from increasing its sustainability scores.

The above analysis doesn't include the cost of purchase of the quadripartite bins o WiSort bins that would be needed in the airport to collect the 153.5 tons. The purchase of an automatic bin would be more expensive than normal bins because of the more complex architecture and the use of electricity. In order to keep the overall cost of managing the MSW from the public areas with WiSort bin lower or equal to the actual one, the purchase price of the bin should be done in a way that doesn't call off completely the savings of 55.8 €/ton achieved in scenario S1, taking into account the price of normal bin as well. Furthermore, an additional benefit (but difficult to evaluate) could come from the reduction of cleaning operations due to the optimization performed by WiSort bin. This type of benefit might be achieved in the long term because at the beginning the maintenance of an automatic bin (due to jams or other related problems) might require more effort (and so higher costs) than simpler cleaning operations with normal bins.

7 CONCLUSIONS

The public area of the airport of Malpensa currently generates 153.5 tons/year of waste, which is collected inside quadripartite bins with the following separate collection: residual waste, paper, plastic and glass/aluminium.

The present study allowed to investigate the consequences of the implementation of an automatic waste sorting bin (the WiSort bin) in a public area of the airport of Milano Malpensa. Different field experiments and analyses were performed in order to verify the effectiveness of this instrument from an environmental, social and economic point of view.

In the first part of the thesis, a field test allowed to obtain the waste composition of the airport's public areas showing that 87.9% by weight of the waste generated can be classified as recoverable materials (recyclables + food waste). Since food waste is at the moment collected together with the residual waste, the actual potential recoverable fraction is 54.8%. Nevertheless, food waste accounts for 33.1% of the waste composition (excluding liquids), so dedicated bins for its collection should be put in place to make sure that this fraction joins the same path of the other food waste produced by the activities of the airport (i.e. anaerobic digestion). The waste composition analysis also showed that the level of accuracy of the materials in the bags is very variable both in terms of items and weight suggesting a bad manual sorting performed by the passengers due to either negligence or difficulties related to different behaviours or sorting uncertainty. The use of an automatic sorting system such as WiSort bin could thus guarantee a more constant and higher value of accuracy in all the bags and increase the level of source separation from 37.9% to 49.3% when a classification accuracy by weight of 90% is assumed. As a final remark, the analyses showed a high presence of liquids (mainly inside glass and PET bottles), therefore the installation of a liquid collector in the public area is suggested.

Another field test focused on the social part with the aim of collecting opinions of passengers about the Wisort bin. Observations and interviews to passengers in the public area showed that some design modifications should be done in order to make the function of the automatic prototype more intuitive since many passengers in need of throwing a waste didn't notice it or thought the machine was something else other than a waste bin. The main limitations in the use of the prototype identified by the passengers were the slowness in processing the waste and the fact that the bin could process only one waste item at a time. The signage on the bin was also not initially clear to all users. In spite of those, users gave general positive feedback regarding the bin and they were curious to know the operating principle and if the automatic sorting was performed correctly or not.

In the second part of the work, an environmental assessment and a cost analysis were carried out.

The environmental analysis showed that the scenario with the highest environmental benefits is S1, in which the WiSort bin is implemented, provided that the usage of the bin is high (to balance the effects of the use of electricity to sort the waste) and the sorting allows 90% w/w of each fraction to be sorted in the correct trash bag. A sensitivity analysis on this value of accuracy (classification accuracy by weight) shows that scenario S1 remains advantageous with respect to the other scenarios for values higher than 80%. The real value of accuracy of the WiSort bin couldn't be tested at the airport so it is still unknown how far the actual performance of the bin is from these assumptions. Only in the category of RUm scenario S1 performs worse than the other scenarios and this is related to the electronic components of the WiSort bin. A further investigation should be done to study and include the potential benefits of recycling of those components. Scenario S0-r is also beneficial with only two categories that provide a burden to the environment (HTc and WU). Scenario S0 is harmful for 10 out 16 impact categories, leaving it as the last alternative scenario among the studied ones from an environmental point of view. A sensitivity analysis that studies the effects of alternative treatment plants (e.g. WTE or selection plants) with different efficiencies and type of processes should be done in order to extend the research and evaluate the conditions needed for an automatic sorting system to make a difference with respect to actual practices.

The results of the cost analysis on the management of the MSW generated in the public areas of the airport show that the only scenario which guarantees an economic benefit with respect to the actual situation is scenario S1, where there is a saving of 55.8 €/ton. A sensitivity analysis on the value of classification accuracy by weight showed that the optimal level for economic savings should be around 90%. Actual savings should include the price of purchase of the WiSort bin and the relative price of purchase of the quadripartite bins. Even though in S0-r the recycling of the fractions is assumed and the LCA shows mainly environmental benefits, the actual average levels of impurities in the bags don't allow the acceptance of those at the corresponding plants, excluding recycling as possible solutions and the possibility of receiving the CONAI fees for the collection and transport company.

In addition to the economic and environmental benefits of the WiSort bin in scenario S1, it must be highlighted a social drawback which Jacobsen et al. (2020) have already pointed out: this kind of technology has a non-educational effect on people as they are not directly involved anymore in sorting the waste with a subsequent reduction of the awareness connected to this action. The screen present on WiSort bin might on the other hand contribute to give same environmental awareness even if in a different way.

The WiSort bin is still a prototype, so many improvements can be made before it becomes a product available on the market. Since it is capable of separating the waste by simply taking pictures of waste items, its structure can be easily modified in a way that allows it to sort more or less fractions. This flexibility allows to meet the different municipality collection requirements or other desirable alternatives. Further research could be carried out to study the level of accuracy of an image classification system like this to differentiate among glass colours or plastic polymers as these type of differentiation are always made at the corresponding plants.

This automatic sorting system has also the opportunity of solving the doubts of the people when throwing a waste (due to different habits or uncertainty on the type of material or the correct sorting according to the regulations of the municipality) or their negligence (people caring less or being in a rush). Despite this, at the moment the bin is not capable of improving the situation when mixed packages or items inside other items are discarded in the bin and this has the consequences of introducing unavoidable impurities in the bags. The limit of processing one item at a time could be also faced in order to find a solution that would made the sorting process easier for the passenger.

To sum up, a type of technology like this has a high potential in improving the levels of source separation in public places, provided that it will reach a high level of sorting accuracy. Even though the amount of waste generated from the public areas at Malpensa airport is low with respect to the total of the airport's MSW (2.21%), the positive effects of such system could be applied to other public areas such as shopping centres and train stations, producing a ripple effect that could make this waste stream more and more circular. This study could be used as reference case for these other contexts.

8 FUTURE RESEARCH

This chapter reports the two experiment that couldn't be tested at the airport.

8.1 Experiment 3: rewarding experiment

This was one of the experiment that couldn't be carried out at the airport due to limited time and because of the issues with experiment 2. This paragraph reports anyway the methodology as it might be a useful starting point for a follow up campaign or similar future tests in the field.
The purpose of this experiment is to test the "rewarding effect" i.e. whether people are more willing to use the automatic bin if they know they can win a reward. The intent is to understand if rewarding is an important feature for customer experience and if it makes sense in a place such as the airport. Since the WiSort bin is still a prototype, this information can be useful for shaping the features that the future product must have in order to be the most effective and convince more people to use it.

The experiment could be performed during a period of two weeks (week 1 and week 2) and it makes use of online surveys as method of testing the rewarding. A QR code can be used to give access to the online survey and it can either be located close to the opening of the bin or on the screen when images connected to waste and its environmental consequences are not shown. The QR code allows interested passengers to access the online survey by simply scanning it with a smartphone. The survey has to be made available at least in the Italian and English language. Two online surveys were prepared: one to test the customer experience on the use of the bin while the other for rewarding. The English version of them is shown in table 8.1 and 8.2. A process of selection of the questionnaires can be made in order to leave out the incomplete or unreliable ones.

Table 8.1 User experience survey.

USER EXPERIENCE SURVEY			
1	What’s your age group? 1. <25 2. 25-39 3. 40-60 4. >60	**2**	It was easy to use Wisort bin 1. Strongly disagree 2. Disagree 3. Neither agree or disagree 4. Agree 5. Strongly agree
3	How likely will you use it again? 1. Very likely 2. Somewhat Likely 3. Neither likely or unlikely 4. Somewhat unlikely 5. Very unlikely	**4**	Do you think it is useful? 1. Yes 2. No 3. Maybe
5	In your opinion, is it necessary to have an automatic bin if we want to improve recycling in public places? 1. Yes 2. No 3. Maybe	**6**	Would you also prefer to find it in other public places instead of normal bins? 1. Yes 2. No
7	How satisfied are you with the prototype? 1. 😍 2. 🙂 3. 😐 4. 🙁 5. 😠	**8**	How can we improve it for you? (suggestions, feature to add or drawbacks) (OPTIONAL)
9	Share your e-mail with us if you want to stay in touch :)		

Table 8.2 Rewarding survey.

<table>
<tr><th colspan="4">REWARDING SURVEY</th></tr>
<tr><td>1</td><td>What’s your age group?
1. <25
2. 25-39
3. 40-60
4. >60</td><td>2</td><td>How satisfied are you with our prototype?
1. 😍
2. 🙂
3. 😐
4. 🙁
5. 😠</td></tr>
<tr><td>3</td><td>Did the reward encouraged you to use the automatic bin?
1. Yes, but I would have used it anyway
2. Yes, otherwise I wouldn’t have used it
3. No, I would use it even without a reward
4. Other</td><td>4</td><td>Would you use it again knowing that you could win a reward?
1. Yes. I would!
2. No. I would use it even without a reward
3. Depends on the reward
4. Other</td></tr>
<tr><td>5</td><td>Do you think a reward could work to make people use the bin?
1. Yes
2. No
3. Maybe</td><td>6</td><td>Do you have any comments that you would like to share with us? (OPTIONAL)</td></tr>
<tr><td>7</td><td>Share your e-mail with us if you want to stay in touch and for being contacted in case of winning :)</td><td></td><td></td></tr>
</table>

The following procedure could be then applied: during week 1 passengers scanning the QR code would be asked to fill in the customer experience questionnaire while during week 2 they would be redirected to the rewarding questionnaire. While in week 2 the QR code simply appears on the screen or on the bin, in week 3 every time the QR code is shown a sentence saying “Throw one item and scan the QR code to try to win a reward” can be added in order to stimulate people’s participation. Week 2 is thus considered a baseline to see if something changes in week 3 as a consequence of the chance of winning a gift. The reward could be a discount ticket for one of the shops of the airport.

To compare the two weeks, first of all the number of passengers in the area in those weeks has to be taken into account; then it must be counted how many times the bin has been used in the two weeks (the proxy to use is the number of items collected by the bin) and the number of questionnaire filled out in both weeks. Table 8.3 can then be completed.

Table 8.3 Starting table for assessing the rewarding experiment.

	People not using the bin (or people not answering the survey)	People using the bin (or people answering the survey)	Total
Week 1	a	b	
Week 2	c	d	
Total			n

In this way it is possible to determine two metrics: the usage rate and the response rate. They are defined as:

$$Usage\ rate = \frac{number\ of\ people\ using\ the\ bin}{number\ of\ people\ in\ the\ area}$$

$$Response\ rate = \frac{number\ of\ people\ answering\ the\ online\ survey}{number\ of\ people\ using\ the\ bin}$$

For what concerns the response rate, a priori limit value has been identified in order to decide whether to consider reliable or not the results from the experiment. As a matter of fact, a minimum number of people, which uses the bin, has to complete the survey otherwise the answers given cannot be taken as representative of all the passengers in the airport. Similar tests which were based on online and/or hybrid format surveys delivered in public places showed a response rate varying from 9% up to 22% (Agrawal et al., 2017; Monzon et al., 2020). Websites specialized in online surveys also show response rates in the range of 5%-30% (table 10.3 in appendix). Thus a value of 10-15% can be assumed to be the minimum value of response rate to proceed with the comparison of the two weeks and the analysis of the results.

The chi-squared test with one degree of freedom and significance level of 5% can be used to statistically compare the two rates defined above and affirm if something changes in the two weeks. In particular, the chi-squared can be used to:

- Compare the percentages of people using the bin in the two weeks (to make sure the two weeks are comparable and no great differences in the number of people can affect the conclusions)

- Compare the percentages of people answering the questionnaire in the two weeks (to see for example if the presence of a reward encourages more people to join the online survey in the second week)

Formulas of the chi-squared ($\chi^2(1)$ and $\chi^2(2)$) for this case were chosen following the guided example of Bottarelli (Bottarelli. n.d.) :

$$\chi^2(1) = \frac{(a \times d - b \times c)^2 \times n}{(a + b) \times (a + c) \times (b + d) \times (c + d)}$$

Where:

a: number of people not using the bin in week 1
b: number of people using the bin in week 1
c: number of people not using the bin in week 2
d: number of people using the bin in week 2
n: total number of people in week 1 and week 2 (a+b+c+d)
i.e. the values introduced in table 8.3

$$\chi^2(2) = \frac{(a \times d - b \times c)^2 \times n}{(a + b) \times (a + c) \times (b + d) \times (c + d)}$$

Where:

a: number of people not answering the survey in week 2
b: number of people answering the survey in week 2
c: number of people not answering the survey in week 3
d: number of people answering the survey in week 3
n: total number of people in week 2 and week 3 (a+b+c+d)
i.e. the values introduced in table 8.3

Depending on the values of a, b, c, d and n some modifications might be applied to the formulas (Bottarelli, n.d.).

The direct comparison of the number of people using the bin or answering the survey couldn't be done without knowing the pool of people who potentially could do it (i.e. respectively the number of people present in the area and the number of people using the bin in those weeks). The chi-squared test with one degree of freedom is able to determine the probability for which two values (two percentages) are statistically different. The initial hypothesis of this test is that the difference in the two values is due to chance. When this hypothesis is not met then it is possible to affirm that the two values are statistically different with a certain probability. If for example the percentage of people answering the questionnaire in week 2 is higher than the one in week 1 and according to the test it turns out to be statistically different, then it is possible to conclude that the rewarding effect has occurred. In order to come to a conclusion, the resulting value from the formula has to be compared with the tabled value of the chi-squared (for one degree of freedom and 5% significance level is 3.841) and if it is higher than it is possible to conclude that the two percentages are statistically different with a probability of 95% and considerations on the causes of that can be made.

In all the experiments it has always been preferred a format that would limit direct conversation with the passengers: that's the reason why QR code were mostly used to give access to surveys instead of direct interviews with people. Lots of people tend to be reluctant in answering questions in such way and tend to stay away from people who might intercept them for their opinions, especially if they are in a rush. Moreover, it was thought that answers given by people filling in an online survey would be more genuine and unbiased with respect to a possible positive connection with the undersigned when asking for their opinion which might have led to more positive comments than reality.

8.2 *Experiment 4: awareness experiment*

The other experiment that was not performed aimed at exploring people's awareness connected to waste management and its environmental effects. The focus was to see if people are more encouraged to throw a waste in the WiSort bin if the environmental benefits of the bin are shown to them. The idea was to show a sentence illustrating the amount of CO_2-eq saved thanks to the use of the bin by displaying it on the screen in order to convince more people passing nearby to use the bin knowing the positive action they would produce by doing that. A preliminary value of the CO_2-eq savings due to the use of the WiSort bin (as an alternative to the normal bin) could also be obtained by using the SWM-GHG calculator mentioned in paragraph 2.5. This tool is based on an excel file which allows to compare different waste management alternatives. The savings shown on the screen of the bin can be calculated assuming that all the 153.5 tons generated in the public areas are collected by the WiSort bin in place of quadripartite bin. Thus the CO_2-equivalent refers to the potential amount that can be saved each year.

Furthermore, another online survey was prepared to understand if people were aware or cared about receiving information about the environmental benefit of such a bin and if this aspect had to be included in the next version of bin's prototype/product. The survey is shown in table 8.4.

Table 8.4 Awareness survey.

AWARENESS SURVEY			
1	What's your age group? 1. <25 2. 25-39 3. 40-60 4. >60	**2**	How satisfied are you with our prototype? 1. 😍 2. 🙂 3. 😐 4. 🙁 5. 😠
3	Did the information you saw on the screen ("….") made you more aware about the recycling benefits of the bin? 1. Yes. I didn't know that before 2. No. because I didn't notice it 3. No. I'm already aware of the importance of recycling 4. Other	**4**	I don't think it is useful to provide this kind of information to people when using the bin 1. Agree 2. Disagree
5	In your opinion, is it necessary to show information like this if we want to increase recycling in public places? 1. Yes 2. No 3. Maybe	**6**	Select what is true for yourself: a I would use the bin anyway even if it doesn't tell me its environmental benefits b I would feel more encouraged to use the bin if it tells me its environmental benefits c Other
7	Select what is true for yourself: a Waste is anything without value b I am aware of the benefits of recycling c In my opinion information and awareness campaigns change behaviour d Incentives (e.g. a reward for those who use the bin) to encourage recycling are important e I would recycle more if I was aware of the benefit f Sorting the waste is time consuming	**8**	Do you have any comments that you would like to share with us? (OPTIONAL)
9	Share your e-mail with us if you want to stay in touch :)		

In this case a QR code can be made available on the screen but no rewarding system is put in place so only willing passenger might reply.

The experiment can be performed with the same structure of the previous one during a period of two weeks, choosing one as reference case. In the reference week no information of the environmental impacts of the bin has to be shown on the bin. The same statistical method (chi-squared) and assumptions can be used to analyse and compare the results of those weeks with the calculation of the $\chi^2(1)$ and $\chi^2(2)$ in addition to the answers provided by the people in the questionnaires. In the case of low usage of QR codes, direct interviews to passengers could be chosen as an alternative.

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10 APPENDIX

Table 10.1 Waste emission contributions in the total CO2-eq emissions of some worldwide airports. CO2-eq emissions from waste generated in the airport only include transport emissions to the final plant when waste is sent to incineration or recycling while they consider collection, transportation and landfill emissions when landfill is the chosen disposal method (BEIS, 2022).

Airport	Ton of CO2 eq from waste (scope 3)	Total CO2 eq (scope 1+2+3)	% CO2 eq/ tot CO2 eq	Year	Reference
Edinburgh Airport	3,328.00	117,074.00	2.840%	2019	(Edinburgh Airport, 2020)
Auckland Airport	262.50	21,202.03	1.230%	2021	(Auckland Airport, 2021)
Sydney Airport	8,968.00	957,636.00	0.930%	2018-2019	(Sydney Airport, 2022)
Heathrow Airport	588.00	20,804,708.00	0.003%	2019	(Heathrow Airport, 2021)
Aberdeen International. Glasgow and Southampton International Airports	344.00	80,936.00	0.425%	2020	(AGS, 2021)
Milano Malpensa Airport	75.00	558,078.00	0.013%	2021	(SEA, 2022) and direct interview with SEA

Table 10.2 Passenger' number and waste generation for various airport worldwide[25].

Country	Airport	Waste (ton/day)	Passengers (mln/yr)	Year	Reference
Lithuania	Vilnius Airport	0.98	5.00	2019	(Lithuanian Airports, 2020 & 2021)
Kazakhstan	Astana International Airport	7.70	5.10	2019	(Air Astana, 2021)
US	Cincinnati-Kentucky International Airport	21.10	7.80	2017	(CVG, 2018)
Australia	Adelaide International Airport	2.70	8.52	2019	(ALL, 2019)
Italy	Naples International Airport	10.70	9.90	2018	(GESAC, 2019)

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[25] All data come from airports' sustainability/annual reports. Small, medium and large airports were selected all around the world and the choice was based mostly on Sebastian & Louis (2021) with updated data. Year 2019 was chosen as last unaffected year by Covid-19 pandemic as reference year. Whenever 2019 data were not available, data from earlier reports were taken.

UK	Edinburgh Airport	5.70	14.30	2019	(Edinburgh Airport, 2020)
US	Portland International Airport	11.70	19.80	2019	(Port of Portland, 2021)
New Zealand	Auckland International Airport	7.90	20.60	2018	(Auckland Airport, 2019)
Canada	Vancouver International Airport	13.10	26.40	2019	(Vancouver Airport Authority, 2020)
Italy	Milano Malpensa Airport	19.90	28.70	2019	(SEA, 2022)
Qatar	Hamad International Airport	134.80	32.40	2019	(Qatar Airways Group, 2021)
Italy	Leonardo da Vinci International Airport	35.10	43.50	2019	(ADR, 2020)
Australia	Sydney International Airport	17.40	44.40	2019	(Sydney Airport, 2020)
UK	Gatwick Airport	37.00	46.60	2019	(Gatwick Airport, 2020)
Germany	Munich Airport	42.90	47.90	2019	(Munich Airport, 2022)
India	Mumbai international Airport	14.90	48.80	2019	(MIAL, 2020)
China	Hong Kong International Airport	71.82	60.90	2019	(AAHK, 2020)
Singapore	Singapore Changi Airport	44.40	62.90	2019	(Changi Airport Group, 2020)
Thailand	Suvarnabhumi Airport	41.20	64.70	2019	(AOT, 2020)
France	Charles du Gaulle Airport	109.62	72.20	2018	(ADP, 2019)
UK	Heathrow Airport	65.60	80.90	2019	(Heathrow Airport, 2020)
China	Beijing Airport	104.20	95.79	2017	(BCIA, 2018)

Table 10.3 Average response rates for online surveys (values found in different online website which make use of online surveys).

Response rate	**Source**
Avg 5-30% (10-15% for external surveys)	(Cleave. P., 2020) (PeoplePulse, n.d.)
Avg 20-30% Low <10% Good> 50%	(Qualtrics, n.d.)

Avg 29%	(Lindemann. N., 2021)
Avg 16%	(Chung. L., 2022)
Avg 13-16% (B2C surveys)	(QuestionPro, n.d.)

Incineration in a WTE plant

Incineration was modelled taking into account the main burdens (resources and chemicals consumption, air emissions and solid residues disposal) associated to the WTE plants of Neutalia Srl (fig. 10.1) according to the composition of the different fraction of waste (see table 10.4). Furthermore, it was included the electricity recovery from combustion, considering the lower heating value of the input waste and the net conversion efficiency of the plants (ηEL=19.3% (Neutalia, 2023)). The avoided electricity was modelled with the ecoinvent dataset *Electricity, medium voltage (IT) market for*. Table 10.5 shows the inventory data and assumptions adopted for the incineration of the RW (reference unit of 1 ton). Equivalent inventories have been created for the other fractions.

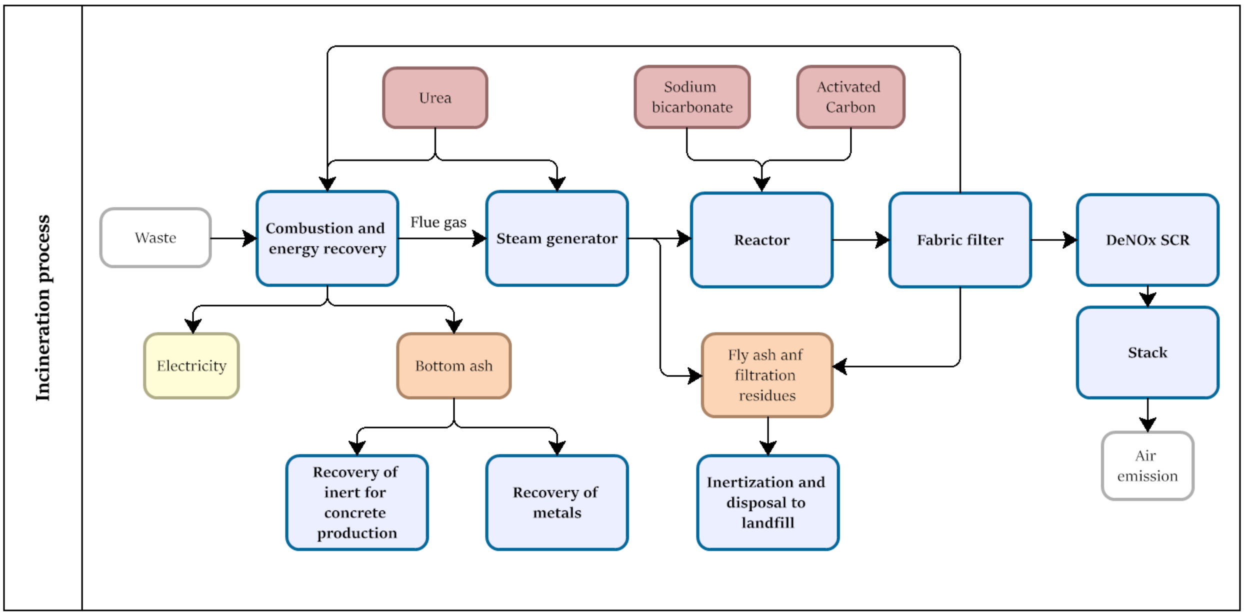

Figure 10.1 Scheme of the main processes of the Neutalia WTE plant. Bizagi Modeler (version 4.0.0.014) was used to create the figure, which was based on Neutalia 2021 report (Neutalia, 2021).

Table 10.4 Information relative to the different MSW fractions useful in the modelling of the incineration process. First six columns contain data from ecoinvent dataset while the last two are calculated from the quantities of bottom ash and by considering the relative proportion between bottom ash and fly ash provided by Neutalia for research work of AWARE group.

Ecoinvent process	**LHV (MJ/kg)**	**S (ppm)**	**Cl (ppm)**	**N (ppm)**	**C (ppm)**	**Bottom ash (EWC 190112) (kg/ton)**	**Ferrous material recovered from bottom ash (EWC 190102)* (kg/ton)**	**Fly ash and filtration residues (EWC 190115. 190105))* (kg/ton)**
Treatment of biowaste, municipal incineration {GLO} (used for food waste)	4.289	1,307.7	3,488.9	3,488.9	141,650	135.7	0	36.93
treatment of waste glass, municipal incineration {CH}	0.04602	0	195.89	0	0	977.7	0	266.08
treatment of municipal solid waste, incineration {IT} (used for residual waste as fraction)	11.7	1,532.3	6,670	3,206.1	338,960	222.1	9.84	60.44
treatment of waste packaging paper, municipal incineration {CH}	14.12	1,381.8	1892	4,098.6	403,520	80	0	21.77
treatment of waste aluminium, municipal incineration {CH}	31[26]	0	4,825	0	0	932[27]	0	253.65
treatment of waste polyethylene terephthalate, municipal incineration {CH}	22.95	147.87	788.62	6,456.8	553,640	10.6	0	2.88

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[26] 1 kg of aluminium undergoes oxidation with an energy release of 31 MJ. In aluminium can 90.8% is metallic aluminium, while the remaining 9,2% undergoes oxidation (Biganzoli e Grosso (2013))

[27] Specific value for aluminium cans (Biganzoli e Grosso (2013))

treatment of waste polyethylene, municipal incineration {CH}	42.47	426.9	1,461.5	1,297.2	822,050	19.17	0	5.22
treatment of waste polypropylene, municipal incineration {CH}	32.78	360.46	1,234.1	1,095.3	694,120	16.18	0	4.40
treatment of waste polystyrene, municipal incineration {CH}	38.67	678.75	1,132.1	1,942.6	868,490	16.49	0	4.49
treatment of waste plastic, mixture, municipal incineration {CH} (used for P7)	30.79	1,406.7	18,131	6112	633,590	16.93	0	4.61

Table 10.5 Inventory table for the incineration of RW. Values referred to 1 ton (functional unit).

PROCESS		**VALUE (for ton)**	**ECOINVENT DATASET AND ASSUMPTIONS**
Consumption of chemicals and resources	Tap water	16.81 kg	Specific consumption of the reference WTE plant (Neutalia, 2023)
	Auxiliary fuel (natural gas)	15.27 Nm^3	
	Sodium bicarbonate	28.62 kg	Calculation according to the neutralization reactions of HCl and SO_2 starting from the elemental composition of RW: $2NaHCO_3 \rightarrow Na_2CO_3 + H_2O + CO_2$ $Na_2CO_3 + SO_2 + 1/2O_2 \rightarrow Na_2SO_4 + CO_2$ $Na_2CO_3 + 2HCl \rightarrow 2NaCl + H_2O + CO_2$ 1) S content in the RW waste: 1.5 kg/ton (table 10.4) 2) Cl content in the RW waste: 6.67 kg/ton (table 10.4) 3) 20% excess of the reagent (Bazzoni. 2014)
		380 km	Transport of Sodium bicarbonate from producer (Solvay plant in Rosignano) to Neutalia WTE Plant. It has been assumed performed with a small lorry (3.5-7.5 ton).
	Activated carbon	1.35 kg	Specific consumption of the reference WTE plant (Neutalia, 2023)

	Urea solution (45% by weight of pure urea and 55% water)	13.75 kg	Calculation according to the selective non catalytic reduction reaction: $2NO + CO(NH_2)_2 + \frac{1}{2}O_2 \rightarrow 2N_2 + 2H_2O + CO_2$ 1) N content in the RW waste: 3.2 kg/ton (table 10.4) 2) double stoichiometric amount of the reagent
Recovery of energy	Electricity → avoided production of the same amount of electricity from Italian market mix	627 kWh	Calculation based on: 1) the lower heating value of the RW waste (11,700.0 MJ/t table 10.4) 2) the net efficiency of the Neutalia WTE plant (19.3% (Neutalia, 2023))
Air emissions	NH_3	37.47 g	Specific emission of the reference WTE plant (Neutalia, 2023). The total emissions of Cd and Tl was evenly allocated to the two metals; the total emission of the other 10 metals was evenly allocated to Sb/As/Pb/Cr/Co/Cu/Mn/Ni/V/ Sn.
	NO_X	338 g	
	CO	32.6 g	
	TOC	4.48 g	
	HF	0.82 g	
	HCl	25.3 g	
	Total particulate (< 10 µm)	2.53 g	
	Dioxins and furans	90.6 ng	
	Polycyclic aromatic	60.1 µg	
	SO_2	9.85 g	
	Hg	24 mg	
	Zn	285 mg	
	Cd/Tl	1.93 mg for each metal	
	Sb/As/Pb/Cr/Co/Cu/Mn/Ni/V/ Sn	87.98 mg for each metal	
	Fossil CO_2 from waste	1243 kg	Calculated from the C content of the RW waste (55.36% table 10.4)
	Fossil CO_2 from methane	30 kg	Derived from the combustion of the auxiliary fuel
	Steam	610 kg	Specific emission of the reference plant (Neutalia, 2023)
Solid and liquid residues to final treatment	Bottom ash (ferrous materials excluded) → sent to the recovery of the inert fraction, used in the production of concrete (inventory data from Cernuschi et al. (2017))	211.0 kg	Specific value of the reference plant (Neutalia, 2023)
		117.2 km	Transport of bottom ash to dedicated treatment plants

	Ferrous material recovery (Cernuschi et al., 2017)	9.84 kg	Specific value of the reference plant
		124.5 km	Transport of ferrous material to recovery plants
	Fly ash → inertization process and subsequent disposal in a landfill (Ambienthesis SpA, 2017)	60.44 kg	See assumption indicated in caption of table 10.4
		148 km + 250 km	Transport of fly ash to treatment plants for inertization and subsequent transport to landfill
	Water discharged into a river	610 kg	Specific emission of the reference plant (Neutalia, 2023)

CO-COMBUSTION of SRF in a cement kiln

The SRF sent to the cement kiln (see tables 5.6 and 5.12 in the text) can be used as alternative of petroleum coke (traditional fuel). In the modelling it is assumed that the type of fuel (SRF or coke) does not influence the cement characteristics and its production process in terms of input and output except for CO_2 emissions. So, a specific dataset (see table 10.6) was built considering the avoided production of pet coke (according to its LHV) and considering the difference in CO_2 emissions of the two fuels.

Table 10.6 Inventory table for the co-combustion in a cement kiln. Values referred to 1 ton (functional unit).

<table>
<tr><th>PROCESS</th><th>VALUE (for ton)</th><th>ECOINVENT DATASET AND ASSUMPTIONS</th></tr>
<tr><td>CO-COMBUSTION (CEMENT KILN)</td><td></td><td></td></tr>
<tr><td>INPUT</td><td></td><td></td></tr>
<tr><td>SRF</td><td>1 ton of SRF with composition in table:
<table>
<tr><th>%</th><th>S0-r</th><th>S1</th></tr>
<tr><td>PET</td><td>49.6%</td><td>17.0%</td></tr>
<tr><td>PP</td><td>9.4%</td><td>28.1%</td></tr>
<tr><td>PS</td><td>2.4%</td><td>7.0%</td></tr>
<tr><td>PE</td><td>11.0%</td><td>32.8%</td></tr>
<tr><td>P7 (mix of plastic)</td><td>3.5%</td><td>10.1%</td></tr>
<tr><td>Paper</td><td>10.0%</td><td>-</td></tr>
<tr><td>Glass</td><td>2.0%</td><td>-</td></tr>
<tr><td>RW</td><td>12.0%</td><td>4.0 %</td></tr>
</table></td><td>LHV and Carbon content of each fraction in the SRF are reported in table 10.4.</td></tr>
<tr><td>OUTPUT</td><td></td><td></td></tr>
<tr><td>CO2 emissions
(ton CO_2/ton of plastic)</td><td>
<table>
<tr><th></th><th>S0-r</th><th>S1</th></tr>
<tr><td>Fossil</td><td>1.89</td><td>2.57</td></tr>
<tr><td>biogenic</td><td>0.15</td><td>-</td></tr>
</table></td><td>The average C content of SRF in S0-r is 55.5% while it is 70.2% in S1.</td></tr>
<tr><td>AVOIDED PRODUCTS</td><td></td><td></td></tr>
<tr><td>Avoided fossil C02 emissions (ton CO_2/ton of pet coke)</td><td>
<table>
<tr><th>S0-r</th><th>S1</th></tr>
<tr><td>2.12</td><td>3.14</td></tr>
</table></td><td>The CO2 emissions of petroleum coke are 3.122 ton CO_2/ton of pet coke (Assolombarda, 2021)</td></tr>
<tr><td>Avoided petroleum coke production and transportation (kg of pet coke/ kg of plastic</td><td>
<table>
<tr><th>S0-r</th><th>S1</th></tr>
<tr><td>680</td><td>1005.2</td></tr>
</table></td><td>The lower heating value (LHV) of petroleum coke is 33385 kJ/kg (Assolombarda, 2021) while the one of SRF is 22695 kJ/kg in S0-r and 33559 kJ/kg. Substitution coefficient based on LHVs.</td></tr>
</table>