



## Research Paper

# Life cycle assessment and cost analysis of an innovative automatic system for sorting municipal solid waste: A case study at Milan Malpensa airport

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## ABSTRACT

With the recent advancement in artificial intelligence, there are new opportunities to adopt smart technologies for the sorting of materials at the beginning of the recycling value chain. An automatic bin capable of sorting the waste among paper, plastic, glass & aluminium, and residual waste was installed in public areas of Milan Malpensa airport, a context where the separate collection is challenging. First, the airport waste composition was assessed, together with the efficiency of the manual sorting performed by passengers among the conventional bins: paper, plastic, glass & aluminium, and residual waste. Then, the environmental (via the life cycle assessment - LCA) and the economic performances of the current system were compared to those of a system in which the sorting is performed by the automatic bin. Three scenarios were evaluated: i) all waste from public areas, despite being separately collected, is sent to incineration with energy recovery, due to the inadequate separation quality (S0); ii) recyclable fractions are sent to recycling according to the actual level of impurities in the bags (SOR); iii) fractions are sorted by the automatic bin and sent to recycling (S1). According to the results, the current separate collection shows a 62 % classification accuracy. Focusing on LCA, S0 causes an additional burden of 12.4 mPt (milli points) per tonne of waste. By contrast, SOR shows a benefit (−26.4 mPt/t) and S1 allows for a further 33 % increase of benefits. Moreover, the cost analysis indicates potential savings of 24.3 €/t in S1, when compared to S0.

## 1. Introduction

Even though the major municipal solid waste (MSW) stream comes from households and commercial activities, waste is also generated in public places such as train stations, malls, airports, parks and streets. Unfortunately, separately collected waste streams from public places are usually characterised by high levels of contamination (Tjahjono et al., 2023). The reasons are various, such as people's haste, negligence or uncertainty or the fact that they have to make themselves familiar with a new context every time: bins in public areas are located in different spots and configurations and they are often made of different colours and shapes, making the correct separation more challenging (Cooley, 2013; Sebastian and Louis, 2021). Moreover, due to the lack of a true control, sometimes the different waste streams are mixed together by the collection operators, ending up in the residual waste (Hershkowitz and Darby, 2006; National Academies of Sciences, 2018; Sebastian and Louis, 2021).

Accordingly, public areas are the places where innovative systems are highly needed to improve the quality of the separate collection and

thus the quantity of materials actually sent to recycling. In recent years, many studies about artificial intelligence and waste sorting were carried out suggesting ways to automatically sort waste through different methods. They can be distinguished in two categories: the first includes devices which rely on physical sensors such as infrared sensors (to detect the presence of the waste) (Jayson et al., 2018; Sharanya et al., 2017), moisture sensors (Jayson et al., 2018; Sharanya et al., 2017), inductive proximity sensors (to detect metals) (Hassan et al., 2018; Jayson et al., 2018; Sharanya et al., 2017), or light dependent resistors (to distinguish plastic from paper) (Hassan et al., 2018; Sharanya et al., 2017). The second category relies on cameras collecting images of the waste items, which are then sorted in the correct bag by means of different types of machine learning algorithms (Jacobsen et al., 2020; Lin et al., 2022; Pamintuan et al., 2019; Xueming et al., 2022). As regards previous application of automatic sorting systems in public places, only Jacobsen et al. (2020) tested their prototype "Waste Wizard" in a zoo, in a retail store, and during a festival. The main aim was to explore people's knowledge and perception in sorting the waste in contexts where the waste segregation is more demanding for people. Similarly, the present

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study evaluates the effects of the implementation of an automatic system for sorting the MSW in a public place, and in particular in the public area of the Milan Malpensa international airport. In detail, the research is performed with the goal to explore the influence of the automatic sorting system on the whole waste management chain (i.e., waste collection, transportation, and recycling) from both the environmental and the economic points of view. First, the study aims at increasing the knowledge related to MSW composition and management in public places by collecting primary data since, to our knowledge, there is no such specific information in the literature. Then, a life cycle assessment (LCA) is carried out to evaluate the environmental impacts of the implementation of the automatic system in comparison with the current waste management. Moreover, a comparative simplified cost analysis between the two systems is performed.

A limited number of studies previously assessed the environmental and economic aspects of the management of waste at an airport with a life cycle perspective. Atkin (2006) highlighted the environmental benefits of applying recycling to airport waste, in terms of energy savings and greenhouse gases emissions reduction. Lam et al. (2018) established a cost benefit analysis framework to assess different food waste management alternatives (i.e., landfilling, incineration, and anaerobic digestion) at the Hong Kong airport. In this assessment, economic, environmental, and social costs were included. Environmental costs were obtained through the monetisation of the results of an LCA, while the social ones were based on opportunity costs of land and disamenity costs. The analysis demonstrated that co-incineration is the most suitable option for the treatment of food waste. Moreover, Sarbassov et al. (2020) evaluated the greenhouse gases emissions connected to the MSW management at the Astana airport, in Kazakhstan. The best scenario resulted the one with 29 % of waste recovered and 71 % incinerated with energy recovery, followed by the scenario in which 100 % is sent to incineration with energy recovery. In terms of costs, the scenario including both material and energy recovery resulted less expensive, even though landfilling most of the waste resulted the least expensive option.

In this framework, the novelty of this work is a specific focus on MSW generated in public places of an airport. Furthermore, a comprehensive analysis was performed, considering both environmental and economic aspects of current and hypothetically improved waste management scenarios. Finally, differently from the environmental analyses focused only on greenhouse gases emissions, a full LCA was performed including several impact categories, in order to include the widest range of issues potentially connected to the examined system.

## 2. Materials and methods

### 2.1. Analysed system

Milan Malpensa, an Italian intercontinental airport with more than 28 million passengers per year, was chosen as a case study. Its public areas are characterised by a waste generation of 752 tonnes per year, according to the analyses performed at the airport (described in Section 2.2), which correspond to about 11 % of the total MSW production at the airport (i.e., 6,946 tonnes; SEA, 2022). The current main type of bin used in the public areas to promote the separate collection of the waste is the quadripartite bin, capable of collecting residual waste, paper, plastic, and glass & aluminium.

Currently, the quality of the separate collection is variable, and materials often result mixed in each of the four bags (see Section 3.1). This is likely due to the little attention of passengers and to the absence of control and of monitoring activities. Consequently, the possibility to recycle the collected fractions is limited, and in most cases they are delivered to incineration.

To solve the issues of the current separate collection, a prototype of a smart bin, so called WiSort bin, designed and manufactured by the WiSort startup (WiSort, 2023), has been introduced (Figure S1 of the

Supplementary Material - SM). It is capable of automatically sorting the waste into the four different fractions of quadripartite bins: residual waste, paper, plastic, and glass & aluminium. Once the waste is introduced in the bin, a single board computer, connected to cameras and sensors, is able to extract features using a deep learning model to identify the type of waste, which is subsequently moved to the correct collection bag. The bin also has sensors which allow to determine the weight of the inserted items and to recognise when the collection bags are full. The characteristics of the bin are provided in Table S1 of SM.

### 2.2. Waste composition analysis

The average composition of the waste collected in the public areas was determined by randomly picking trash bags at the airport during different hours of the day and days of the week in order to consider changes in the generated waste, if any. Samplings were performed during a period of two months both in the airside and in the landside zones, including check-in areas (30 %), bar areas (48 %), food courts (15 %), gates (5 %), and shops areas (3 %). 21 independent waste composition analyses were performed, with a total weight of the analysed waste equal to 92 kg. The following methodology was applied for the analysis of the bags content: each of the four bags was emptied and each item inside the bag was classified in term of type (e.g., coffee cup, plastic bottle, and napkin), mass, and waste fraction. In detail, the following fractions were considered: i) plastic; ii) paper (and cardboard); iii) glass; iv) aluminium and steel; v) food waste; vi) residual waste and other (e.g., batteries and cloths); vii) liquid. Steel was associated to aluminium due to its small amount, while the “other” fraction was included in the residual waste fraction. The total weight for each fraction in each bag was then obtained. The rules for a good separate collection provided by the Italian packaging consortia were taken as reference model (Comieco, 2023; Corepla, 2023). In most cases the identification of the waste was performed following the mandatory specification (about the material and the end-of-life management) present on the products. For what concerns composite packaging (European list of waste code 150106), according to Comieco, the Italian paper packaging consortium, their disposal depends on their type. Composite material c/pap84 (e.g. juice and water boxes) were considered residual waste, while composite material c/pap81 were considered paper (e.g. coffee paper cup). Mixed packaging (European list of waste code 150105) was considered as residual waste. In the case of items containing other items (e.g. residual waste inside a plastic bag), each of them was considered as independent to define the actual composition of the bags. Further details and additional assumptions can be found in Sections S2 and S3 of SM.

#### 2.2.1. Current sorting

In addition to the definition of the average composition, the waste composition analysis was chosen as a method to understand the conditions necessary for an automatic system to be better at sorting than the actual passengers’ manual sorting. Two types of sorting accuracies metrics were applied to describe the current situation: the *classification accuracy* (Equation 1) and the *bag purity* (Equation 2). The *classification accuracy* indicates the dispersion of one material among the four bags, while the *bag purity* is representative of the dispersion of the impurities in each bag. As an example, if the *classification accuracy* for plastic is low and the plastic *bag purity* is high, most of the items inside the plastic bag are made of plastic, but a lot of plastic is also scattered among the other bags. For the evaluation of the *bag purity*, in accordance with the actual division of the quadripartite bin at the airport, the following couplings were considered: i) residual waste, other, and food waste in the residual waste bag; ii) paper in the paper bag; iii) plastic in the plastic bag; iv) glass, aluminium, and steel in the glass & aluminium bag.

$$\text{Classification accuracy}_x = \frac{\text{total weight of } x \text{ correctly sorted}}{\text{total weight of } x}$$

Equation 1: *classification accuracy* (by weight) which describes the precision of passengers in sorting each single fraction (x) in terms of weight correctly sorted (x: plastic; paper; glass; aluminium and steel; food waste; residual waste and other). The numerator expresses the mass of x present in the correct bag, while the denominator is the total mass of x introduced in all the four bags of the quadripartite bin.

$$Bag\ purity_y = \frac{total\ weight\ of\ y_f\ in\ the\ bag}{total\ weight\ of\ y\ bag}$$

Equation 2: *bag purity* (by weight) which describes the amount of a fraction (y<sub>f</sub>) in a bag (y) with respect to what is contained in the bag. (y<sub>f</sub>: RW, other, and food waste; paper; plastic; glass, aluminium, and steel. y: residual waste; paper; plastic; glass & aluminium). The total weight of the bag includes the fractions incorrectly collected inside.

Two similar sorting accuracies metrics expressed in term of number of items (instead of weight) were also considered (see Section S3 of SM).

### 2.2.2. Expected sorting

First, the waste composition (amount of each fraction) expected with the use of the WiSort bin was assumed to be the same found with the analysis of quadripartite bins (it does not depend on the type of container). A WiSort bin was installed in one of the public areas of the airport to test passengers' behaviour when using it and to gather opinions regarding the possibility of introducing an automatic system for MSW sorting in public places. Nevertheless, it was not possible to collect robust data for the WiSort bin due to the limited time of the experimentation and the need of training the machine learning algorithm for this specific case study. Accordingly, a 90 % *classification accuracy* of each fraction was assumed, based on a 75 % to 95 % range of values retrieved from the literature and other existing automatic bins available on the market (Bin-e, 2023; Cleanrobotics, 2023; Jacobsen et al., 2020; Pamintuan et al., 2019; see Table S3 of SM). In detail, 90 % by weight of recyclables (i.e., plastic; paper; glass, aluminium, and steel) was supposed to be correctly conferred in the corresponding bag, while the remaining 10 % was allocated to the residual waste bag. This hypothesis was made according to expected functioning principle of WiSort bin: items identified with a high degree of confidence will be sorted into the correct bag, while other items will be directed to the residual waste bin.

**Table 1**

Average waste composition of 1 t of waste contained in the bags of a quadripartite bin (S0 and SOR) obtained from the waste composition analysis; average waste composition of the bags of the WiSort bin (S1); *bag purity* and *classification accuracy*.

Bin (scenario)	Fraction/parameter	Residual waste bag	Paper bag	Plastic bag	Glass & aluminium bag	Total weight per fraction	Classification accuracy (average)
Quadripartite bin (S0 and SOR)	Plastic	20.4 kg	4.7 kg	107.0 kg	12.0 kg	144.1 kg	74.3 %
	Paper	55.2 kg	81.3 kg	13.6 kg	23.3 kg	173.5 kg	46.9 %
	Glass	2.8 kg	1.7 kg	3.1 kg	72.0 kg	79.5 kg	90.6 %
	Aluminium and steel	7.9 kg	0.4 kg	5.2 kg	14.9 kg	28.5 kg	52.3 %
	Food waste	166.8 kg	17.3 kg	32.7 kg	40.2 kg	256.9 kg	64.9 %
	Residual waste and other	37.9 kg	25.9 kg	16.8 kg	13.8 kg	94.3 kg	40.1 %
	Liquid	22.6 kg	4.6 kg	153.0 kg	43.0 kg	223.3 kg	–
	Total waste	313.5 kg	136.0 kg	331.3 kg	219.2 kg	1000.0 kg	61.8 %*
	<i>Bag purity</i> (average)	65.3 %	59.8 %	78.5 %	59.3 %	–	–
	<i>Bag purity</i> [min, max]	[32.6 %; 94.0 %]	[17.8 %; 88.2 %]	[34.1 %; 99.9 %]	[12.5 %; 99.0 %]	–	–
WiSort bin (S1)	Plastic	14.4 kg	–	129.6 kg	–	144.1 kg	90.0 %
	Paper	17.3 kg	156.1 kg	–	–	173.5 kg	90.0 %
	Glass	7.9 kg	–	–	71.5 kg	79.5 kg	90.0 %
	Aluminium and steel	2.8 kg	–	–	25.6 kg	28.5 kg	90.0 %
	Food waste	231.2 kg	8.6 kg	8.6 kg	8.6 kg	256.9 kg	90.0 %
	Residual waste and other	84.9 kg	3.1 kg	3.1 kg	3.1 kg	94.3 kg	90.0 %
	Liquid	22.3 kg	–	114.9 kg	86.1 kg	223.3 kg	–
	Total waste	381.0 kg	167.8 kg	256.2 kg	194.9 kg	1000.0 kg	90.0 %
	<i>Bag purity</i>	83.0 %	93.0 %	95.4 %	94.0 %	–	–

\* Weighted on fractions amounts.

Moreover, 90 % of residual waste, other, and food waste was supposed to be found in the residual waste bag, while the remaining 10 % was allocated to the other three bags evenly. Finally, 90 % of the liquids, mostly found inside bottles during observations, was allocated to the plastic (57 %) and glass & aluminium (43 %) bags, while the remaining 10 % was attributed to the residual waste bag.

### 2.3. Life cycle assessment

In order to compare the implications of passengers' manual sorting and automatic sorting in the waste value chain from an environmental perspective, an attributional waste management oriented LCA was performed.

#### 2.3.1. Definition of the functional unit

The comparison was made considering as the functional unit (FU) the management of one tonne of waste with the composition observed in the bags of the quadripartite bins given by the results of the waste composition analysis (see Table 1).

#### 2.3.2. Examined scenarios and system boundary

The LCA was applied to compare different management scenarios for the waste produced in the public areas of the airport. In the first scenario (S0) all the waste collected in public areas was assumed to be sent to incineration with energy recovery (Fig. 1A). This is the current situation for most of the waste collected in public areas of the airport, as a consequence of the bad sorting performed by the passengers and inaccuracies of the operators in the collection of the waste. Recyclable fractions should be intercepted by the Italian national consortium of packaging materials (CONAI) but this is not possible because the maximum allowed levels of impurity (15 %, 20 %, and 6.5 % respectively for paper, plastic, and glass & aluminium) are typically exceeded (CONAI, 2023a; CONAI, 2023b).

Nevertheless, in a second scenario (SOR) the material recovery was introduced according to the actual level of impurities in the bags and the current airport practices for MSW collected in areas other than public spaces: the paper and glass & aluminium bags are sent to sorting and material recycling, the plastic bag is sent to sorting for being recovered as solid recovered fuel (SRF), while the residual waste bag is sent to

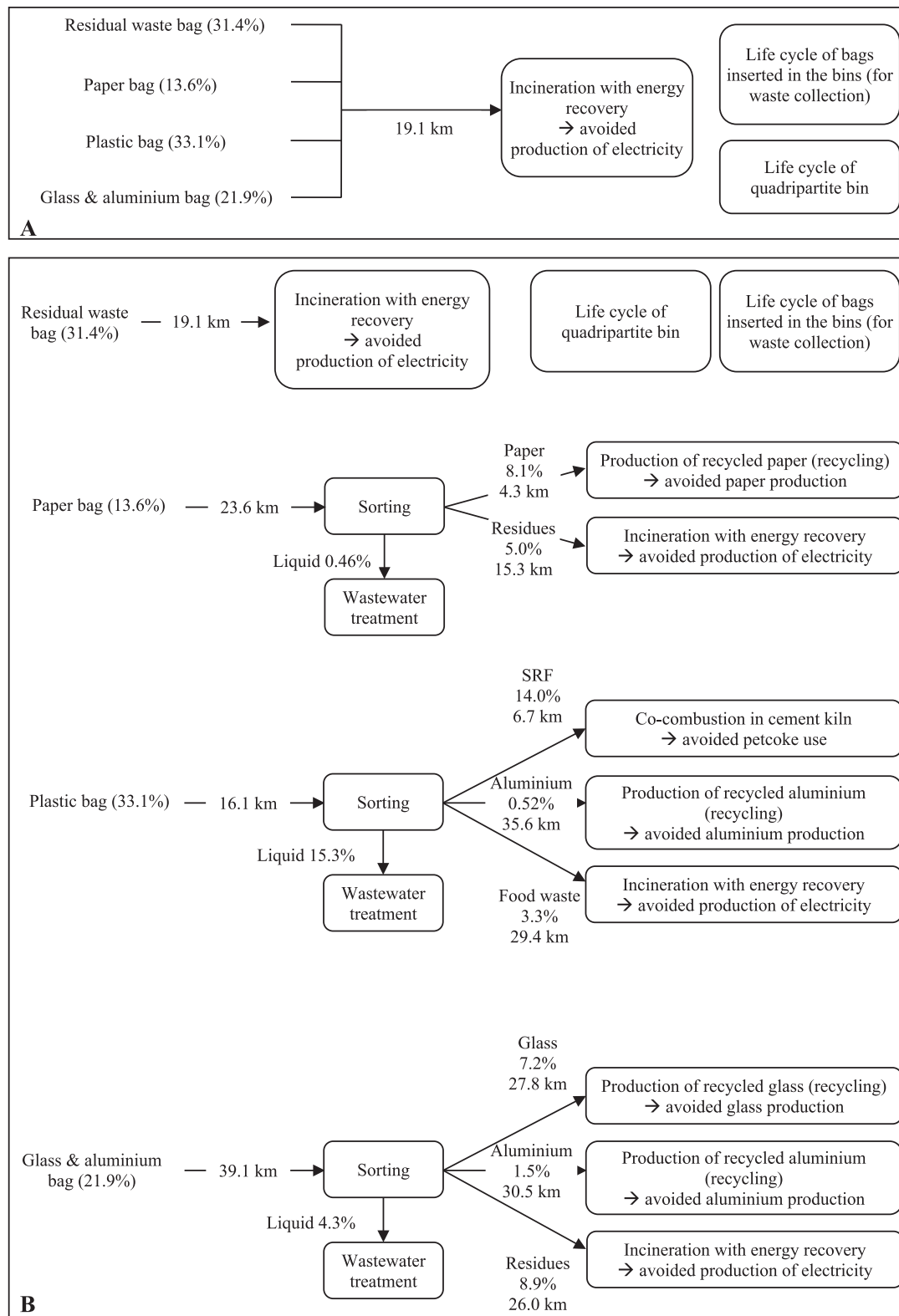


Fig. 1. S0 (A) and SOR (B) system boundary. Percentages are referred to the total amount of waste of public areas of the airport (100 %). They are calculated according to waste composition analyses (Table 1).

incineration with energy recovery (Fig. 1B).

In the alternative collection system (S1), the waste was supposed to be automatically sorted by the WiSort bin with a 90 % classification accuracy. Waste bags are managed in the same way of SOR except for the plastic bags which were assumed to be sent to a sorting plant for

polyethylene terephthalate (PET) sorting, due to the assumed higher sorting rate (Fig. 2). In S1 all the waste is supposed to be collected by many WiSort bins distributed around the public areas. According to data shown in Tables S6 and S12 of SM, one WiSort bin can substitute 2.6 quadripartite bins. The reduction of the total number of bins in S1 would

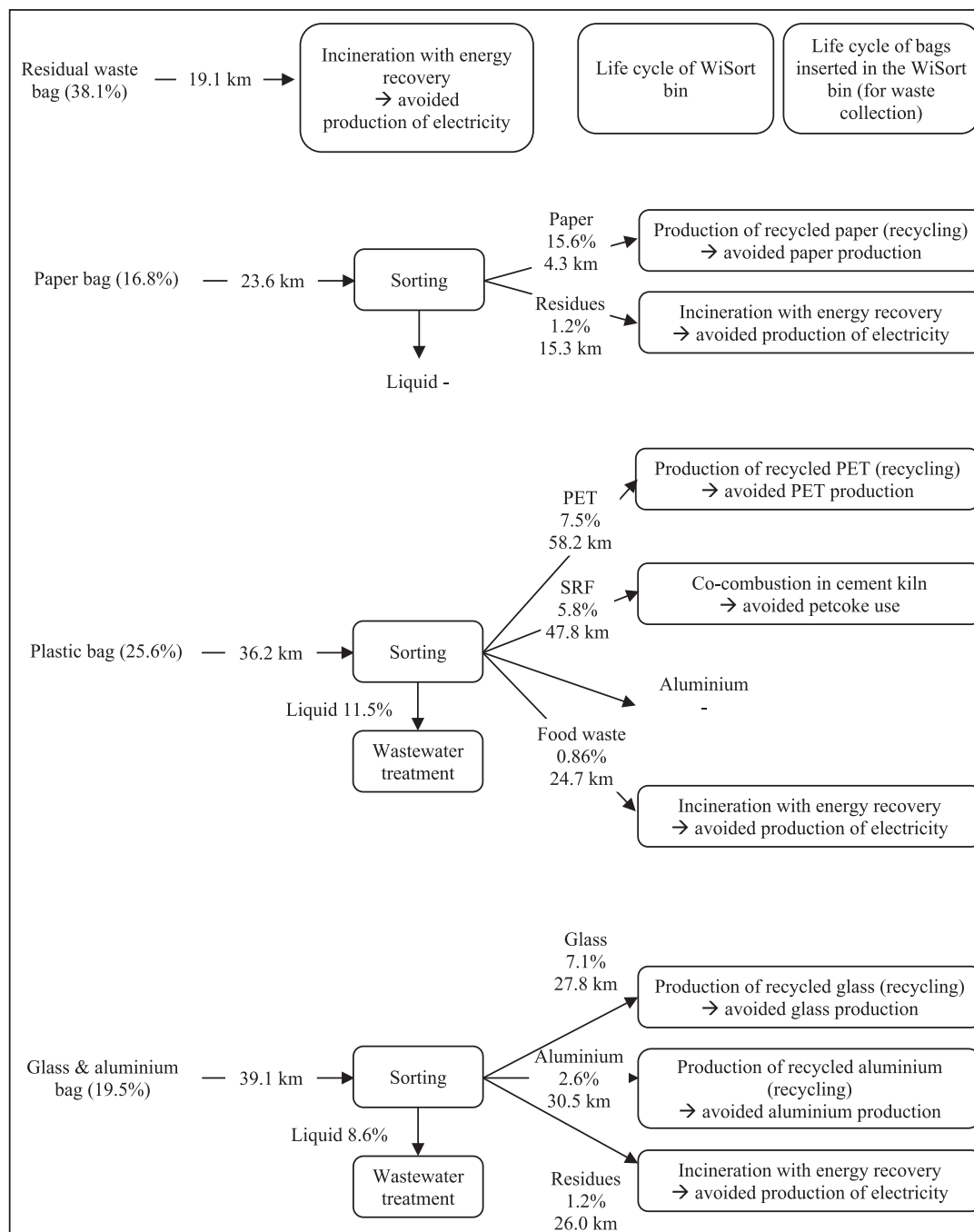


Fig. 2. S1 system boundary. Percentages are referred to the total amount of waste of public areas of the airport (100 %). They are calculated according to waste composition analyses (Table 1).

determine a change in their spatial configuration at the airport, which, however, was not analysed.

The system boundary of the compared scenarios starts from the waste generation corresponding to the discarding into the bin (*zero-burden approach*), including all the stages up to when the waste becomes a new resource or leaves the system as an emission or as inert material. The processes included in the system boundary are shown in Fig. 1 (S0 and S0R) and in Fig. 2 (S1). In case of waste sent to recycling, the secondary (recycled) material is indicated, together with the substituted material. Each secondary material was assumed to substitute a market mix between primary and secondary material (e.g. recycled paper avoids the production of both virgin and recycled paper according to their shares on the market). In case of waste sent to incineration, the produced

electricity was assumed to substitute electricity from the Italian mix. Finally, when waste is co-combusted in a cement kiln, it allows for the saving of petcoke.

### 2.3.3. Impact categories and characterisation method

This study was performed according to the Environmental Footprint 3.0 method (Fazio et al., 2018) by examining the following 16 midpoint impact categories: *Climate change; Ozone depletion; Ionising radiation, human health; Photochemical ozone formation; Particulate matter/respiratory inorganics (PM); Human toxicity, non-cancer effects; Human toxicity, cancer effects; Acidification; Eutrophication, aquatic freshwater; Eutrophication, aquatic marine; Eutrophication, terrestrial; Ecotoxicity freshwater; Land use; Water use; Resource use, energy carriers; Resource use, mineral*

and metals. The normalisation and weighting stages were then applied with the factors included in the Environmental Footprint 3.0 method (EC, 2018; Sala et al., 2018). The SimaPro software (v. 9.3) was used as LCA software to support data processing.

### 2.3.4. Inventory analysis and modelling of the system

LCI tables with detailed information regarding the three modelled scenarios are reported in Section S4 of SM. Regarding data quality, the foreground system was mainly described with primary data when available. In particular, data on bins and bags for the collection, information from the experimental tests performed at the airport, and transportation data were primary. Moreover, the waste treatments were modelled using Northern Italy plants primary data. Regarding the background system, data relative to the European context, and to the Italian one for electricity, were taken from the literature and the ecoinvent database, v.3.8 (ecoinvent centre, 2021).

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: i) the avoided production of electricity due to the incineration of the waste; ii) the avoided production of material due to recycling and of fuel thanks to the use of SRF.

Finally, the life cycle of the quadripartite bin and the WiSort bin was modelled with the Environmental product declaration (EPD) approach (EPD, 2021) due to the uncertainty in modelling their end-of-life. In fact, this approach includes the modelling of transportations and the sorting process, while the impacts and benefits of recycling are excluded.

### 2.3.5. Sensitivity analysis

Since the real value of accuracy of the WiSort bin could not be tested at the airport (see Section 2.2.2), a sensitivity analysis on the *classification accuracy* parameter was carried out to understand how the results would change with accuracy different from 90 % (assumed in S1): 70 %, 80 %, and 95 %. It should be highlighted that the current value of *classification accuracy* for manual passengers' sorting at the airport (i.e., S0 and S0R) is 61.8 %, which means that passengers of Malpensa airport are capable of classifying correctly on average 61.8 % of the waste they introduce in a quadripartite bin. This value was determined during the field experiment (see Table 1).

## 2.4. Cost analysis

In addition to the environmental assessment, a cost analysis from the perspective of the airport operator was performed to compare S0, S0R and S1. S0R was analysed despite exceeding the impurity thresholds required for accessing the CONAI sorting plants, which would make this recycling scenario not actually feasible. To be coherent with the LCA, the bags were assumed to be sent to those plants and the hypothetical cost of separation of impurities from the recyclable material and the cost of their transportation and incineration with energy recovery were considered. The same assumptions were made in the sensitivity analysis of S1 when impurity thresholds are not respected (S1 70 % and S1 80 %; see Section S5 of SM).

The analysis included the costs for the following operations: i) cleaning (i.e., personnel costs for emptying the bins in the public areas and moving the waste); ii) internal transportation and storage (i.e., costs of operators and fuel of trucks for carrying the waste to the airport waste storage area, including the management of the latter); iii) external transportations (i.e., the costs for transporting the waste to the final destination plants equal to 48 €/t). These cost items (the same for the different fractions) were assumed to be unchanged in all scenarios. Moreover, the analysis considered the airport waste treatment costs (i.e., the fees for processing the MSW at the final plants). They vary between 0 €/t and 150 €/t, according to the specific fraction. Residual waste sent to incineration and plastic to mechanical treatment for SRF production are the most expensive fractions, while for those sent to recycling the

cost is lower or null, since they are intercepted by the Italian national consortium of packaging materials (CONAI). This consortium, through the implementation of the extended producer responsibility (EPR) principle, provides an economic support for the recycling chain of each packaging material. This support is proportional to the quality of the collected material in order to encourage a better source separation: the lower the impurities, the higher the economic support (CONAI, 2023a; Rigamonti et al., 2015). Finally, the cost for the electricity consumption of the WiSort bin (20.3 €/t in S1) and for the purchase of the bins (15.4 €/t in S0 and confidential in S1) and of the bags inserted in the quadripartite bin or in the WiSort bin (46.6 €/t in S0 and 10.4 €/t in S1) were included. Primary data were provided by the airport operator and by the WiSort bin producer. More details on the modelling can be found in Section S5 of SM.

Furthermore, a possible reduction of cleaning operations costs in S1 was estimated. This can be possible thanks to the optimisation performed by the WiSort bin, which notify the operators when the bin is full and thus the route of the operators towards every bin of the airport can be reduced. This reduction was estimated through the travelling salesman problem, which was used to determine the optimal sequence for operators to get to the bins once they were notified of their full status, as explained in Section S5 of SM. Finally, as for the environmental analysis, a sensitivity analysis on the values of the *classification accuracy* of WiSort bin was performed.

## 3. Results and discussion

### 3.1. Waste composition analysis and sorting accuracy

Table 1 and Figures S2 to S5 provide the main findings of the waste composition analyses of the airport quadripartite bins (considered in S0 and S0R) with values referred to 1 t of waste. The potentially recoverable fractions (recyclables and food waste) amount to 87.9 % when the liquids are excluded. Currently, this amount is only 54.8 %, since food waste is collected as residual waste, and this is also the potential quantity recoverable by the WiSort bin. The two values are similar to the findings by Atkin (2006), which are 74 % and 54 % respectively (even though they refer to the overall MSW of airports).

On average, excluding liquids, 42.1 % of the total waste is packaging waste. Regarding glass waste, 46.3 % is green, 45.8 % white, and 7.9 % brown. Focusing on plastic waste, 65.3 % is PET, 2.4 % polypropylene (PP), 3.2 % polystyrene (PS), 14.5 % polyethylene (PE), and 4.6 % other.

Waste composition results for each of the investigated areas are reported in Figures S6 to S9 of SM. No great differences among the areas were observed, except for the glass & aluminium bag.

The average values of the *bag purity* and the *classification accuracy* parameters are presented in Table 1. Further details can be found in Section S6 of SM. The average *bag purity* (Table 1) confirms that the threshold for sending the separately collected waste to the CONAI plants, and thus to allow for recycling, are not met under the current management: the level of impurity (100 % minus the *bag purity*) is 40.2 % for paper, 21.5 % for plastic, and 40.7 % for glass & aluminium compared to requirements of maximum 15 %, 20 %, and 6.5 % respectively (CONAI, 2023b).

The potential of an automatic bin in this way can be double, increasing the level of accuracy and keeping it consistent. Table 1 also shows the waste data representative of the WiSort bin (considered in S1). As a consequence of the assumed 90 % *classification accuracy*, in S1 the recycling requirements are met for all the recyclable fractions (with levels of impurities equal to 7 %, 4.6 %, and 6 % respectively for paper, plastic, and glass & aluminium). Data for S1 70 %, S1 80 % and S1 95 % can be found in Table S20 of SM.

Finally, the results of waste composition analyses suggest another possible advantage of an automatic sorting: this process can be useful to detect PET bottle, whose amount in the plastic waste is relevant, in order to implement a deposit return systems that will be mandatory for single

use plastic bottles in the next future according to the new European regulation on packaging and packaging waste (EU, 2024).

### 3.2. LCA

Table 2 shows the potential environmental impacts of S0, S0R, and S1 with the comparison among all scenarios. Fig. 3 presents the comparison of the three scenarios, including the hotspot analysis.

S1 turns out to be better than the other two scenarios in all categories except the *Resource use, mineral and metals*. S0R is better than S0 for every category except the *Water use* where it shows a slightly higher impact. In S0R, only two impact categories have an overall positive impact (*Human toxicity, cancer effects* and *Water use*) differently from S0 which is burdensome for 10 out of 16 impact categories.

As shown in Fig. 3, for 9 categories out of 16 (*Ionising radiation, Photochemical ozone formation, Particulate matter, Acidification, Eutrophication, aquatic freshwater, Eutrophication, aquatic marine, Eutrophication, terrestrial, Ecotoxicity freshwater, and Resource use, energy carriers*) the main burden of S0 is the production of the bags for waste collection, while waste incineration provides a benefit in the same categories (except for *Eutrophication, aquatic freshwater*) mainly related to plastic and aluminium: plastic has a high lower heating value, which allows for an higher energy recovery compared to the other fractions, while incineration of aluminium allows for its subsequent recovery from the bottom ash. On the contrary, for *Climate change, Human toxicity, non-cancer effects, Human toxicity, cancer effects, and Eutrophication, aquatic freshwater*, incineration causes a positive burden in S0.

As regards S0R, material recovery resulted more advantageous than incineration performed in S0. In detail, the main contribution to the overall benefits is the glass & aluminium recovery except for the *Resource use, energy carriers* where the main contribution is plastic recovery (Fig. 3). Glass & aluminium recovery is beneficial especially because of the aluminium recycling (Figure S14 of SM reports the contribution analysis of glass & aluminium recovery in S0R).

The benefit of materials recovery increases in S1 because the amount of recyclable materials sent to recovery is higher than in S0R, due to the better sorting performed by the WiSort bin. Moreover, S1 allows for the reduction of burden for the production of the collection bags compared to S0 and S0R, where a higher amount is used (the WiSort bin allows to monitor the filling condition of the bag thus optimising the overall quantity of bags required to collect 1 tonne as shown in Tables S6 and S12 of SM).

**Table 2**

Potential impacts of S0 and S0R and potential impacts changes among scenarios. Results are referred to 1 t of waste with the composition shown in Table 1 (FU). Impact categories: *Climate change* (CC); *Ozone depletion* (OD); *Ionising radiation, human health* (IR); *Photochemical ozone formation* (POF); *Particulate matter/respiratory inorganics* (PM); *Human toxicity, non-cancer effects* (HTnc); *Human toxicity, cancer effects* (HTc); *Acidification* (A); *Eutrophication, aquatic freshwater* (EUf); *Eutrophication, aquatic marine* (EUm); *Eutrophication, terrestrial* (EUt); *Ecotoxicity freshwater* (ECf); *Land use* (LU); *Water use* (WU); *Resource use, energy carriers* (RUF); *Resource use, mineral and metals* (RUM).

Impact category		Impact			Impact change		
		S0	S0R	S1	(S0R-S0)/ S0	(S1-S0)/ S0	(S1-S0R)/ S0R
CC	kg CO <sub>2</sub> eq/FU	4.45 × 10 <sup>2</sup>	-9.16 × 10 <sup>1</sup>	-2.52 × 10 <sup>2</sup>	-121 %	-157 %	-175 %
OD	kg CFC11 eq/FU	-1.52 × 10 <sup>-5</sup>	-8.57 × 10 <sup>-5</sup>	-4.69 × 10 <sup>-4</sup>	-465 %	-2994 %	-447 %
IR	kBq U-235 eq/FU	-1.82 × 10 <sup>1</sup>	-3.74 × 10 <sup>1</sup>	-3.83 × 10 <sup>1</sup>	-105 %	-111 %	-3 %
POF	kg NMVOC eq/FU	1.33 × 10 <sup>-1</sup>	-9.72 × 10 <sup>-1</sup>	-1.47	-831 %	-1208 %	-52 %
PM	disease inc./FU	-3.63 × 10 <sup>-6</sup>	-3.29 × 10 <sup>-5</sup>	-3.92 × 10 <sup>-5</sup>	-806 %	-980 %	-19 %
HTnc	CTUh/FU	3.72 × 10 <sup>-6</sup>	-4.86 × 10 <sup>-6</sup>	-6.35 × 10 <sup>-6</sup>	-231 %	-271 %	-31 %
HTc	CTUh/FU	7.16 × 10 <sup>-7</sup>	8.82 × 10 <sup>-9</sup>	-1.87 × 10 <sup>-7</sup>	-99 %	-126 %	-2215 %
A	mol H <sup>+</sup> eq/FU	-6.78 × 10 <sup>-1</sup>	-2.80	-3.25	-313 %	-379 %	-16 %
EUf	kg P eq/FU	5.17 × 10 <sup>-2</sup>	-5.29 × 10 <sup>-2</sup>	-8.45 × 10 <sup>-2</sup>	-202 %	-263 %	-60 %
EUm	kg N eq/FU	8.93 × 10 <sup>-3</sup>	-3.31 × 10 <sup>-1</sup>	-4.43 × 10 <sup>-1</sup>	-3802 %	-5059 %	-34 %
EUt	mol N eq/FU	4.72 × 10 <sup>-1</sup>	-3.27	-4.47	-792 %	-1046 %	-37 %
ECf	CTUe/FU	-5.53 × 10 <sup>2</sup>	-8.20 × 10 <sup>3</sup>	-9.09 × 10 <sup>3</sup>	-1382 %	-1543 %	-11 %
LU	Pt/FU	7.81 × 10 <sup>1</sup>	-1.99 × 10 <sup>3</sup>	-2.71 × 10 <sup>3</sup>	-2649 %	-3574 %	-36 %
WU	m <sup>3</sup> depriv./FU	1.56 × 10 <sup>1</sup>	1.75 × 10 <sup>1</sup>	-6.34 × 10 <sup>1</sup>	+12 %	-507 %	-463 %
RUF	MJ/FU	4.03 × 10 <sup>2</sup>	-4.94 × 10 <sup>3</sup>	-7.03 × 10 <sup>3</sup>	-1324 %	-1842 %	-42 %
RUM	kg Sb eq/FU	-3.70 × 10 <sup>-4</sup>	-1.43 × 10 <sup>-3</sup>	1.10 × 10 <sup>-3</sup>	-287 %	+397 %	+177 %

Focusing on the different impact categories, incineration positive burdens in *Climate change, Human toxicity, non-cancer effects, and Human toxicity, cancer effects* are lowered in S0R and S1, since only residual waste bags are directly sent to this treatment. The highest contribution to the *Climate change* is the emissions of fossil CO<sub>2</sub> due to the combustion of plastic and residual waste, both with a higher carbon content than that of other fractions. Concerning *Human toxicity, non-cancer effects* and *Human toxicity, cancer effects*, the main contribution is the incineration of food waste present in the residual waste bag. Impacts in this case are associated to the landfilling of fly ash.

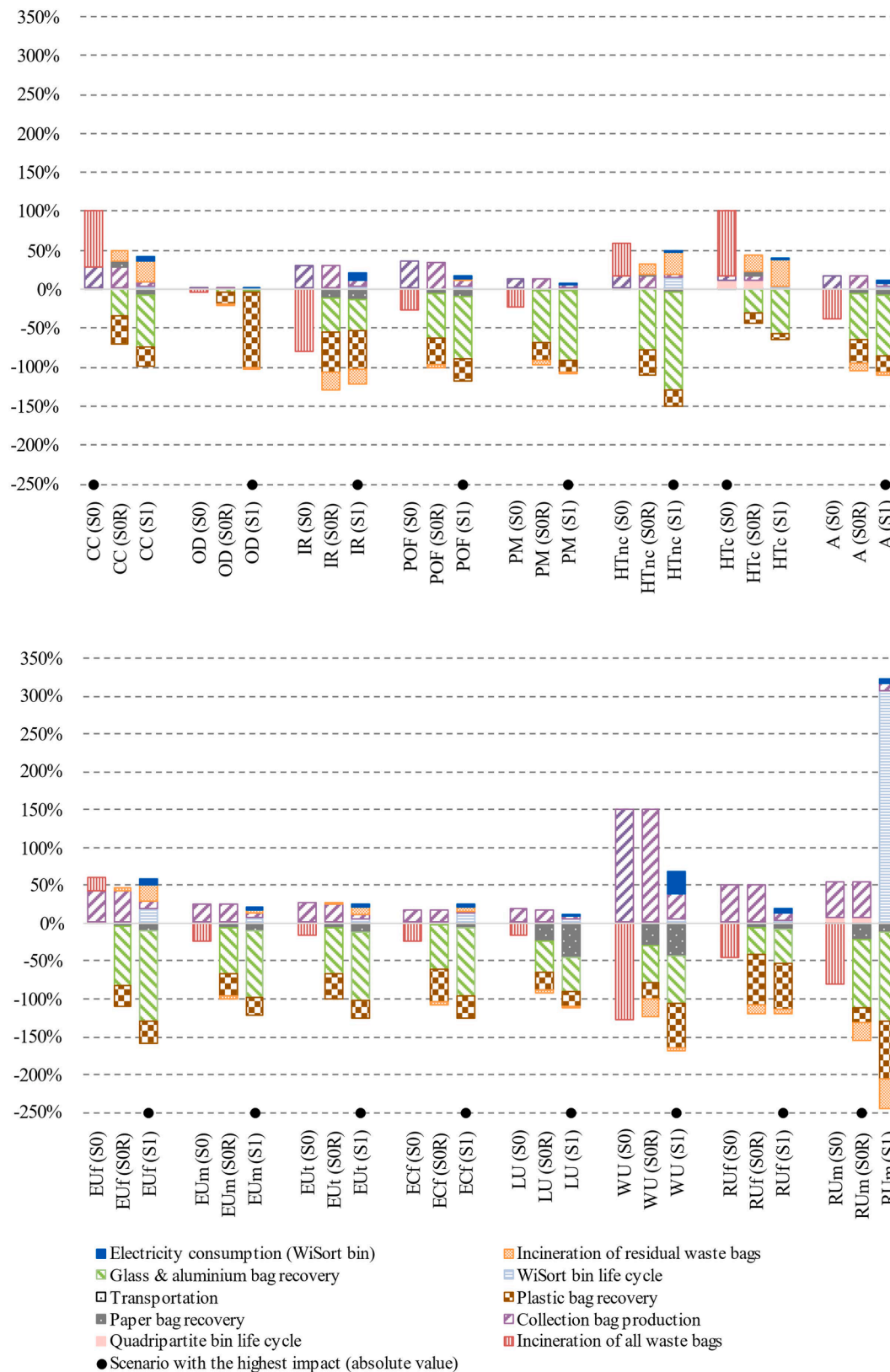
The *Ozone depletion* shows a strong improvement from S0 to S1 thanks to the recycling of PET (Figure S15 of SM reports the contribution analysis of plastic recovery in S1), which avoids the production of virgin PET and allows to have a SRF to be sent to cement kilns with an overall higher heating value, which in turn avoids the use of petcoke.

For what concerns the *Resource use, mineral and metals*, this is the only category in which S1 shows a positive impact, due to the production of the electronic components of the WiSort bin which contain rare metals. At this purpose, it must be highlighted that the life cycle of the WiSort bin was modelled according to the EPD approach (see Section 2.3.4). Accordingly, both the additional burdens for the WiSort bin and the benefits from the recycling of its components were not taken into account. Further investigations could be done to evaluate the potential benefits of recycling of these components, whose modelling is currently highly uncertain.

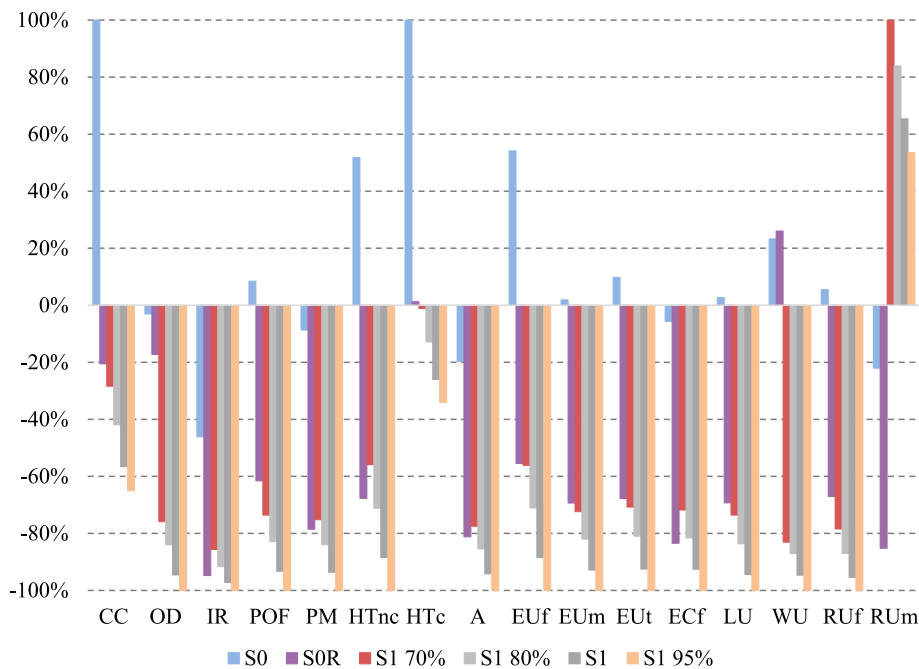
After the normalisation and the weighting stages, the examined scenarios are characterised by the following potential impacts: 12.4 mPt/FU (S0), -26.4 mPt/FU (S0R), and -35.2 mPt/FU (S1). Accordingly, it is possible to conclude that the current management (S0 - incineration of the overall waste) is not justified from an environmental point of view, showing a positive burden. On the contrary, S0R shows an overall environmental benefit. S1 allows for a further increase of the benefits compared to S0R (+33 %). The environmental benefits obtained by moving from incineration to recycling of airport MSW is in accordance with findings of Atkin (2006) and Sarbassov et al. (2020) (see Section 1).

#### 3.2.1. Sensitivity analysis

Fig. 4 shows the results of the sensitivity analysis performed on the *classification accuracy* parameter. Table S21 of SM reports the potential impacts for all the assessed categories. Irrespective of the level of the *classification accuracy* (i.e., 70 %, 80 %, and 95 %), S1 provides an



**Fig. 3.** S0, S0R, and S1 comparison and hotspot analysis. For each impact category, +100 % or -100 % (calculated as the sum of positive and negative contributions with their sign) is given to the scenario showing the highest impact (in absolute value). The impacts and contributions for the other two scenarios are rescaled with respect to the scenario with the highest impact (in absolute value), i.e. each contribution can be higher than 100 % but the sum of all positive and negative contributions with their sign is always lower than |100 %|. Impact categories: Climate change (CC); Ozone depletion (OD); Ionising radiation, human health (IR); Photochemical ozone formation (POF); Particulate matter/respiratory inorganics (PM); Human toxicity, non-cancer effects (HTnc); Human toxicity, cancer effects (HTc); Acidification (A); Eutrophication, aquatic freshwater (EUf); Eutrophication, aquatic marine (EUm); Eutrophication, terrestrial (EUt); Ecotoxicity freshwater (Ecf); Land use (LU); Water use (WU); Resource use, energy carriers (RUF); Resource use, mineral and metals (RUm).



**Fig. 4.** Sensitivity analysis results: comparison of S0, SOR, and S1 (with different values of *classification accuracy*) characterisation results. For each impact category, 100 % is given to the scenario showing the highest impact (in absolute value) and the impacts for the other scenarios are rescaled. Impact categories: *Climate change* (CC); *Ozone depletion* (OD); *Ionising radiation, human health* (IR); *Photochemical ozone formation* (POF); *Particulate matter/respiratory inorganics* (PM); *Human toxicity, non-cancer effects* (HTnc); *Human toxicity, cancer effects* (HTc); *Acidification* (A); *Eutrophication, aquatic freshwater* (Euf); *Eutrophication, aquatic marine* (EUm); *Eutrophication, terrestrial* (EUt); *Ecotoxicity freshwater* (Ecf); *Land use* (LU); *Water use* (WU); *Resource use, energy carriers* (RUf); *Resource use, mineral and metals* (RUm).

**Table 3**

Cost analysis results for S0, SOR, and S1 (with different values of *classification accuracy*) referred to 1 t of waste with the composition of Table 1. Results are shown both excluding and including the cleaning costs saving.

Scenario	Without cleaning costs saving		With cleaning costs saving	
	Overall cost (€/t of waste)	Cost change (Scenario-S0)/S0	Overall cost (€/t of waste)	Cost change (Scenario-S0)/S0
S0	449.6	–	449.6	–
SOR	424.8	–5.5 %	424.8	–5.5 %
S1 70 %	452.0	+0.5 %	441.3	–1.8 %
S1 80 %	435.4	–3.2 %	424.7	–5.5 %
S1	425.3	–5.4 %	414.6	–7.8 %
S1 95 %	423.4	–5.8 %	412.7	–8.2 %

environmental benefit for all categories except *Resource use, mineral and metals*. Although the average value of *classification accuracy* of SOR is 61.8 %, S1 with 70 % *classification accuracy* is worse than SOR for *Ionising radiation, Particulate matter, Human toxicity, non-cancer effects, Acidification, Ecotoxicity freshwater, and Resource use, mineral and metals* and only slightly better for the other impact categories. This is because in S1 with 70 % *classification accuracy* some fractions are sorted worse by the WiSort bin than in SOR which describes the current passengers’ separation. Even though the average value of *classification accuracy* of SOR is 61.8 %, the *classification accuracy* for plastic and glass is already higher than 70 % (i.e., 74.3 % and 90.6 %; Table 1). Moreover, the WiSort bin life cycle and its consumption of electricity cause higher burdens than the ones of the quadripartite bin life cycle. Increasing the *classification accuracy* to 80 %, S1 is slightly worse than SOR only for *Ionising radiation and Ecotoxicity freshwater* with differences lower than 10 %.

After the normalisation and the weighting stages, S1 with different *classification accuracy* levels is characterised by the following potential impacts: –24,9 mPt/FU (S1 70 %); –29,8 mPt/FU (S1 80 %); –38,4 mPt/FU (S1 95 %). Accordingly, to make a difference with respect to (SOR), the WiSort bin should have a minimum *classification accuracy* of 80 % (+13 % of environmental benefits), while 70 % causes a reduction of the benefits (–6 %).

### 3.3. Cost analysis

The results of the analysis, reported in Table 3, indicate a cost of 450 €/t, 425 €/t and 425 €/t respectively for S0, SOR and S1. In comparison with S0, cost savings of S1 in the waste treatment and in the purchase of the bags for the collection (5.4 %) more than compensate the additional costs for the purchase of the WiSort bin and for its electricity consumption. Similar savings would be allowed by SOR, although this scenario is not actually feasible.

Regarding waste treatment costs, in S0 all the waste is sent to incineration with energy recovery and the treatment cost of residual waste was applied to all waste fractions. On the contrary, SOR and S1 provide an economic benefit for this cost item due to the increased quantity of materials sent to recycling: this economic benefit is actually dependent on the amount of the fractions and can only increase the better the sorting and the lower the residual waste generated.

As for the bags for the collection, the benefits of S1 are associated to the fact that the amount of bags needed to collect 1 tonne of waste in the two scenarios differ. In S1, bags are removed only when almost full, thanks to the monitoring of the filling conditions performed by the WiSort bin, while in S0 and SOR they are often collected by the cleaning operators long before this condition during their daily route in all the

airport public areas. In this regard, in order to minimise this cost item in S0 and S0R, cleaning operators could optimise the emptying of the bins by doing so only when they are nearly full.

Concerning the potential savings connected to the cleaning operation, the overall cost of S1 becomes 415 €/t (Table 3), with an additional saving of more than 10 €/t under the assumptions of 5 emptying per day (see Section 5 of SM).

Finally, according to the sensitivity analysis on the *classification accuracy* parameter, S1 allows for an economic benefit (compared to S0) when the WiSort bin is able to sort the waste with an accuracy higher than 80 %. Table 3 provides the overall costs in S1 for the different values of *classification accuracy*.

### 3.4. Discussion

This research indicates the potential of an efficient management of airport waste. Indeed, 88 % of waste from public areas could potentially be recovered. These outcomes are confirmed by Atkin (2006). Accordingly, examining five major US airports handling 10 % of national passengers, between 66 % and 75 % of waste from terminal public areas could be recycled.

Nevertheless, the real waste management is less efficient. Similarly to what we found in this research, criticalities in the current airport waste management are highlighted by the existing literature (Pitt and Smith, 2003; Sarbassov et al., 2020; Sebastian and Louis, 2021). This research outlines a current classification accuracy of waste in Malpensa airport equal to 61.8 %, that is not high enough to allow for the recycling of the separately collected streams. Criticalities in waste recycling are also found in several international airports. Seven out of the European and Asian international airports examined by Sarbassov et al. (2020) are characterised by recycling rates lower than 60 % with four of them even lower than 30 %. The minimum value is observed for the Astana International Airport (11.5 % compared to a significantly higher amount of recyclable waste – 54 %; Sarbassov et al., 2020). The degree of contamination during manual separate collection is generally the issue affecting the actual recyclability of airport waste streams (Sebastian and Louis, 2021). As introduced in Section 1, the airport context is strictly related to the inadequate behaviour of people in the proper sorting of waste. Therefore, the benefits allowed by automatic systems in the improvement of the separate collection quality suggested by this research could be potentially extended to other international airports. Furthermore, the benefits of automatic sorting systems could be useful to improve the waste management of public areas such as shopping centres and train stations, where criticalities similar to those found in the examined airport are very likely to occur.

## 4. Conclusions

The potential improvement in municipal waste management in the public areas of Malpensa airport in Italy was assessed, observing that 88 % could potentially be recovered. Nevertheless, because of passengers' haste, negligence, or difficulties related to different habits, it is difficult to reach an adequate quality of the manually sorted fractions, with a current classification accuracy lower than 62 %. This is confirmed by the present study: due to the inadequate purity of the fractions conferred into the quadripartite bins, the impurity threshold required for recycling is not achieved and most of the waste is sent to energy recovery, as evaluated in S0. The material recovery (S0R) would allow for considerable environmental benefits. Examining the normalised and weighted results, S0 causes an additional burden on the environment (12.4 mPt per tonne of waste), while S0R shows an overall benefit (-26.4 mPt/t).

Furthermore, an automatic sorting system (S1) could guarantee higher and more constant accuracy of sorting. When a 90 % *classification accuracy* is assumed, S1 turns out to be better than S0 and S0R in all the impact categories excluding the *Resource use, mineral and metals*. At the same time, the automatic sorting could reduce waste management costs,

with S1 allowing for potential savings of 24.3 €/t when compared to S0. Although the use of such systems introduces additional burdens in its manufacturing and use, these are more than compensated by the benefits of a higher recycling rate, provided that the automatic sorting allows for at least 80 % of each fraction to be sorted in the right waste bag, according to the outcomes of the sensitivity analysis (S1 80 %). Future research should be focused on a detailed spatial analysis in order to optimise the distribution of the automatic sorting machines (e.g. minimising the number of machines without affecting the quality of the separate collection). This analysis could allow for a further improvement of the waste management at the airports and public areas in general, in terms of environmental impacts and costs.

### CRedit authorship contribution statement

**Alessandro Manea:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Giovanni Dolci:** Writing – review & editing, Writing – original draft, Methodology. **Mario Grosso:** Supervision, Conceptualization, Writing – review & editing.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

Data will be made available on request.

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### Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wasman.2024.04.049>.

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