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Transforming waste management methods: a Dutch Airport's journey toward a circular economy through baseline measurements and strategic priority setting

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Airports, the essential hubs of global travel, have to cater for the increasing demands for air travel, with growing passenger numbers and the associated growth in resource consumption. While the aviation sector prioritizes reducing environmental impact in the air, substantial waste is generated at airports. This necessitates a critical examination of waste management practices, especially since a Circular Economy (CE) approach is gaining momentum within the aviation sector. This article introduces the Baseline Circular Airports Method (BCAM), a methodology developed and rigorously tested at Schiphol Amsterdam airport. BCAM systematically analyzes resource streams, considering composition and relevant stakeholders, treatment processes, and environmental impact. By doing so, it establishes strategic prioritization of resource streams for airports to perform focused and effective interventions. BCAM analysis reveals that the highest impact of operational resource streams are Residual, Plastic, Swill, Paper, and International Catering Waste (CAT1), and that corresponding waste management efficiencies can be determined. These outcomes serve as a baseline for ongoing monitoring, offering airports a starting point for strategic planning and assessing progress towards sustainable waste management and CE transitions.

KEYWORDS

circular economy, zero waste airports, resource management, baseline measurements, environmental impact assessment

1 Introduction

Airports play a key role in global transportation and are experiencing a growing demand for air travel [International Civil Aviation Organization, 2022 (ICAO); International Air Transport Association (IATA), 2023]. The growing number of passengers hosted by airports has resulted in a corresponding increase in resource consumption. Whilst the aviation sector is typically focused on reducing environmental impact and emissions in the air, a by-product of these air transport operations is the substantial volumes of waste generated at airports (Baxter et al., 2018). As airports are considered key for international connectivity, creating zero-emission airports is one of the objectives set out in the European Green Deal (European Commission, 2021). The legislative objectives necessitate a critical examination of waste management practices, especially given the growing consensus that a Circular Economy (CE) is also relevant to the aviation industry (NLR, 2019). The Circular Economy Action Plan (European Commission, 2015) supports the transition towards the 2050 climate neutrality target, setting aviation targets of a 90% cut in emissions by 2050. This should be delivered by a smart, competitive, safe, accessible and affordable transport system. By developing circular ambitions and initiatives, airports can demonstrate their commitment to a greener future while reducing their carbon footprint (International Civil Aviation Organization (ICAO), 2019). This will enhance their appeal to passengers, airlines, and other stakeholders, and support the Green Deal legislative requirements for long-term sustainability.

To date, CE concepts have been relatively limited in the overall aviation sector (Saavedra-Rubio et al., 2023). Applying CE principles in an airport environment is considered a complex activity, thanks to the diversity of stakeholders pressuring sustainable management of waste streams (Dimitriou and Karagkouni, 2022) and the numerous activities and operations contributing to waste generation. The lack of stakeholder collaboration, coupled with a limited awareness of their roles and responsibilities, has been identified as a significant challenge, exerting a negative impact on waste management targets (Tjahjono et al., 2023). Secondly, despite the emphasis on prevention and reuse as outlined in the EU Waste Management Directive (European Commission, 2008), current waste management practices still focus on recycling, incineration, and landfill (Eurostat, 2020). This is in stark contrast to one of the key principles of a CE identified by Eurostat (2023) and PBL-Netherlands Environmental Assessment Agency (2023): "A model that maintains the highest possible value of raw materials, components and products by lengthening their lifetime or by looping them back in the system to be reused." Furthermore, with numerous interpretations of CE definitions and principles (Kirchherr et al., 2023), the absence of a universally recognized framework or set of indicators to assess circularity adds another layer of complexity (Smol, 2023). Assessing circularity is still not a common practice in organizations today (Sassanelli et al., 2019). Without a clear understanding of what is meant by circularity and how to assess the environmental impact of specific waste streams, performing and evaluating targeted interventions is challenging.

Although many studies have focused on researching airport waste volumes (Baxter et al., 2018), end-of-life treatment of waste (National Academies of Sciences, Engineering and Medicine, 2018; Özbay and Gokceviz, 2022), or actioning waste reduction (Tjahjono et al., 2023), no studies have identified and/or established a comprehensive connection between waste volumes, treatment methods and environmental impact for the purpose of determining priority waste streams. Dimitriou and Karagkouni (2022) identified the need for research focusing on a quantitative analysis of airports' environmental sustainability performance. In addition to mentioned gaps above, bringing relevant stakeholders in the mix in order to effectively manage and monitor resources is not performed before (Morrissey and Browne, 2004). To bridge this gap, our research objective is therefore to establish a method to systematically analyze the operational waste streams within airports, accounting for the key factors of waste composition, stakeholders, treatment, and its environmental impact. To achieve this, we developed a strategic prioritization setting, scalable across airports, enabling focused interventions instead of randomly targeted actions. By combining quantitative and qualitative waste stream analyses into a single method, airports can effectively monitor their performance towards the 2050 targets set for climate neutrality and circularity. We call this the Baseline Circular Airports Method (BCAM).

To avoid the differences in CE interpretation and implementation (Kirchherr et al., 2023), our group assessed and applied the following definition as a guiding principle for research and analysis: "The circular economy is a system solution framework (Ellen Macarthur Foundation, 2020). A circular economy decouples economic activity from the consumption of finite resources (Bocken and Short, 2020) to stay within planetary boundaries (Metabolic, 2020). It's a model that maintains the highest possible value of raw materials, components and products (Eurostat, 2023) either by lengthening their lifetime or by looping them back in the system to be reused (PBL-Netherlands Environmental Assessment Agency, 2023). Waste is eliminated or used as a resource (Ellen Macarthur Foundation, 2020), both by smart circular design and value retention processes (R strategies). Moreover, a circular economy aims to prioritize the regeneration of nature so that resources can restore, renew or revitalize their own sources of energy and materials (European Commission, 2015)."

Following up on existing research, we first explored current airport waste management practices, investigating stakeholders involved in waste generation and disposal, evaluating the types of waste streams that arise, as well as the underlying processes performed for collection and treatment. We then integrated these findings by developing a four-phased analysis method to identify the most impactful waste streams at airports. Consequently, we tested the method at Schiphol Amsterdam airport (Schiphol) and present the outcomes on prioritizing waste streams. The findings support Schiphol's strategic focus on four key themes: circular economy, energy positivity, sustainable aviation, and communities (Schiphol Group, 2019). Lastly, we align our BCAM findings with existing research, providing strategic longer-term managerial implications.

2 Background

This section explores the different aspects that contribute to waste generation at airports and examines stand-alone methods employed in previous research to assess airport waste management.

2.1 From waste to resource streams

Waste is typically defined as any material or substance no longer useful for its intended purpose (Basel Convention, 2011). The United Nations glossary (1997) defines waste as "materials that are not prime products for which the generator has no further use in terms of their own purposes of production, transformation or consumption, and of which they want to dispose."

At airports, there are many waste streams, including biodegradable and non-biodegradable waste, inert-composite waste, domestic hazardous and toxic waste (National Academies of Sciences, Engineering and Medicine, 2018). Mehta (2015) further specified

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municipal solid waste, construction and demolition waste, green waste, food waste, waste from aircraft flights, lavatory waste, as well as spill clean-up and remediation waste. However, in the CE context, the perspective of waste undergoes a transformative shift. Instead of viewing waste as something to dispose of, it is regarded as a resource that can be repurposed and reused to create new products. Embracing this perspective aligns with the core CE principles emphasizing the extension of resource use and quality (Ellen MacArthur Foundation, 2020). In line with our CE definition, we view waste as a resource; thus, airports can reduce it, while creating new economic opportunities and decreasing demand for virgin materials. Our focus is on the operational waste (or resource) streams that are monitored by the airport's waste management partner. In this study, we utilize both 'waste' and 'resources' to reframe the perception of waste, while ensuring clarity for our readers.

2.2 Engaging with stakeholders responsible for waste generation

To manage waste effectively, airports should acknowledge and engage with the diverse stakeholders contributing to these streams (Kanchanabhan et al., 2011; Raimundo et al., 2023). Understanding stakeholder perspectives is crucial, considering their diverse backgrounds and attitudes towards consumption and disposal (Tjahjono et al., 2023). Stakeholder theory denotes creating value for all partners involved (Mohd Isa, 2018) and collaborating with stakeholders can offer benefits such as shared insights, better service, reduced inefficiencies, and addressing environmental goals [International Air Transport Association (IATA), 2022]. Whilst the needed systemic change towards a CE requires collaboration and carefully managing resources (Sassanelli and Terzi, 2023), stakeholders often work in a divided and isolated manner, operating independent systems, and this can lead to widespread dysfunctions and inefficiencies (Planas Parra, 2023).

In the context of this article, a stakeholder is defined as any group or individual who can influence the generation and handling of resources at an airport building/terminal. In the airport resource management paradigm, stakeholders include passengers, tenants (restaurants and retail stores), employees, operators, maintenance and support, and local governments (Sebastian and Louis, 2021). These stakeholders are aware of the impact of airport operations on environmental sustainability and the need for an environmentally friendly approach (Bamidele et al., 2023). However, managing stakeholders can be complex as their objectives are not always aligned with those of airport management (Schaar, 2010) and challenges may arise from conflicting interests and goals.

2.3 Resource stream composition study at airports

In the pursuit of ambitious goals such as becoming a circular airport, understanding the generated resource streams is crucial. The predominant method for collecting data to identify the products and materials in each stream is through a resource stream composition study (National Academies of Sciences, Engineering and Medicine, 2018). This entails a systematic analysis of all available resources at a generating unit, revealing the types and quantities. The analysis also provides insights into the effectiveness of the current resource management system and highlights areas for improvement (National Academies of Sciences, Engineering and Medicine, 2018). A resource stream composition study is particularly valuable due to, for example, the widespread placement of bins typically found at airports, both before and after security. The diverse airport environment, with shops, restaurants, and a heterogeneous audience, requires a nuanced understanding of passenger behaviors. This necessitates inclusion of a qualitative resource stream composition study – a 'waste safari' to provide insights on passenger behavior and the "big five" (most common) resources.

2.4 Resource treatment

Although a stakeholder assessment and 'waste safari' can reveal which actors generate which resource streams and where these are disposed, it remains unclear what happens to the resource streams after collection. Gaining transparency in waste management treatment is increasingly important, especially in anticipation of upcoming legislation on transparency in the value chain such as the Corporate Sustainability Reporting Directive (CSRD) (European Commission, 2023) and the proposed Digital Product Passport (DPP) in the Eco-design for Sustainable Products Regulations (European Commission, 2023).

Waste handling practices at airports are guided by the EU Waste Management Directive (European Commission, 2008) and should ultimately aim at prevention (Figure 1). However, the evaluation of waste streams often relies on the narrow framework of cost–benefit analysis for treatment. Most waste management models are primarily focused on addressing waste once it is generated, often neglecting the aspect of waste minimization (Morrissey and Browne, 2004).

Despite the EU Waste Management Directive emphasis on prevention, current practices in the aviation sector primarily revolve around recycling, incineration, and landfill (International Civil Aviation Organization (ICAO), 2014). In the EU, 39.9% of all resources is recycled, with the remainder incinerated for energy or disposed otherwise (Eurostat, 2020). This reactive, linear approach contrasts with the proactive waste prevention focus as outlined in the EU Waste Management Directive (European Commission, 2008) and the ambitions set out in the Circular Economy Action Plan (European Commission, 2015).

2.5 Assessing the environmental impact of resource streams at airports

Airports typically use resource generation, diversion, disposal, recycling, and composting metrics to track performance and measure progress towards CE goals and targets (National Academies of Sciences, Engineering and Medicine, 2018). Embarking on the journey towards CE, there is a need to measure and understand the environmental impact of current resource streams. An Environmental Impact Assessment (EIA) can identify and assess the impact of resource streams. When performing an EIA, the Life Cycle Assessment (LCA) principles can be applied to offer a holistic perspective and evaluate the environmental impacts associated with all the stages of a material or product life. The LCA approach is based on ISO-14040 and

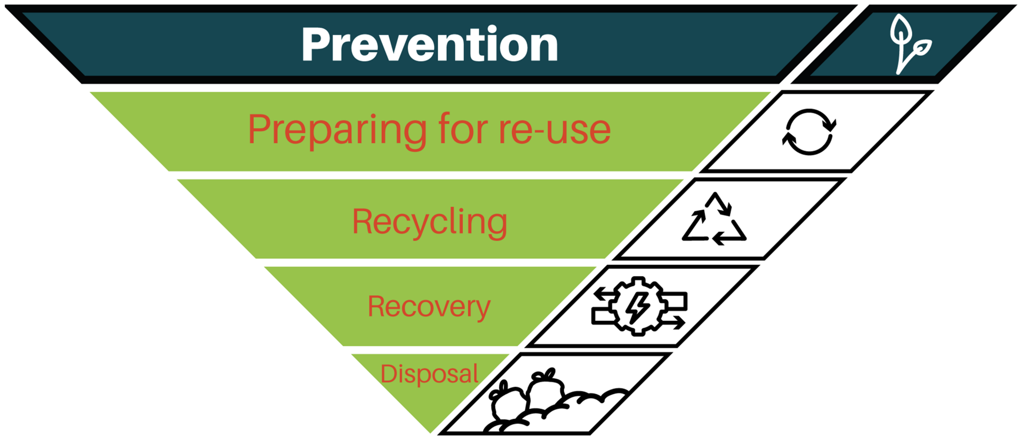

FIGURE 1
EU waste management directive.

ISO-14044 and considers all stages of a product or process, including raw material extraction, production, use, and disposal. As researched by Sassanelli et al. (2019), LCA is the most common assessment methodology in CE literature. The product or process data per stage is assessed against various environmental impact criteria. However, organizations often only work with one of these criteria, such as climate change (t CO2-eq). As a result, the European Commission has proposed the Product Environmental Footprint (PEF) method with 16 impact categories to measure a similar environmental performance across LCA stages (Table 1).

While EIA and LCA are distinct methodologies with different scopes, they complement each other. In this study, an EIA is applied with LCA thinking, focusing on resource treatment rather than the full lifecycle. However, the individual PEF environmental categories cannot be compared with each other as they measure different impacts. To solve this, Sustainability Impact Metrics (2023) developed the concept of eco-cost to quantify the environmental impact of products or services, based on the LCA modules chosen for analysis. The eco-cost represents the cost of the environmental burden of a product or process, for the scope of the LCA defined. This is expressed in monetary terms and is intended to reflect the cost necessary to reduce environmental pollution and resource depletion to a sustainable long-term level. By converting environmental impacts into monetary value, eco-cost makes these impacts tangible and comparable, allowing for more informed decision-making in terms of sustainability.

2.6 Baseline measurement and strategic priority setting

As defined by Lidow (2017), strategic priorities are determined by three interdependent variables: objectives, resources, and timing. While airports may already be working on creating zero-emission airports as reflected in EU objectives (European Commission, 2021), they may not be aware of when and where to invest resources and make most impact towards their goals. We advocate evaluating airport resource streams comprehensively (qualitatively and quantitatively) to establish a baseline for strategic intervention planning and assessing progress towards sustainable waste management and CE transitions.

3 Method development

As discussed in Sections 1 and 2, there is an urgent need for a robust and comprehensive methodology which assists airports in strategic prioritization aimed at waste reduction, emissions minimization, and the transition towards a CE. This section details the four parts of the BCAM and detailed steps of the data types collected. Through a mixed-methods approach, encompassing both quantitative and qualitative data, comprehensive data sets can be collected, rigorously analyzed, and thoughtfully interpreted. For a visual overview of the four methodology parts in the BCAM, leading up to the baseline measurement, please refer to Figure 2.

3.1 Part 1: waste safari

The 'waste safari,' entails a systematic analysis of airport waste, providing insights into the effectiveness of the current waste management system (National Academies of Sciences, Engineering and Medicine, 2018) and the key challenges and lessons learned around waste. Specifically it assesses how effectively passengers are able or willing to separate waste through three steps: preparation, sorting and evaluation.

Step 1 – Preparation.

Choices are made on the type of bins and location of bins to analyze. The predominance of a certain type of bin as well as the possibility to observe recycling behavior are important factors. Consideration should be made whether to include bins only available for passengers, or include those located in the employee-only areas. Preparatory meetings should be conducted with facilities (e.g., cleaning parties) and waste management partner(s) to establish a cohesive plan for sample selection, bag labeling (with time of collection and location), and process of picking up the bins to be stored and sorted.

TABLE 1 Sixteen impact categories of product environmental footprint.

Impact categories	Definition according to the European Commission's Product Environmental Footprint
Climate change (kg CO2 eq)	Increase in the average global temperature resulting from greenhouse gas emissions (GHG)
Ozone depletion (kg CFC11 eq)	Depletion of the stratospheric ozone layer protecting from hazardous ultraviolet radiation
Ionizing radiation (kBq U-235 eq)	Impact of exposure to ionizing radiations on human health
Photochemical ozone formation (kg NMVOC eq)	Potential of harmful tropospheric ozone formation ("summer smog") from air emissions
Particulate matter (disease Inc.)	Impact on human health caused by particulate matter emissions and its precursors (e.g., sulfur and nitrogen oxides)
Human toxicity, non-cancer (CTUh)	Impact on human health caused by absorbing substances through the air, water, and soil. Direct effects of products on humans are not measured
Human toxicity, cancer (CTUh)	
Acidification (mol H+ eq)	Acidification from air, water, and soil emissions (primarily sulfur compounds) mainly due to combustion processes in electricity generation, heating, and transport
Eutrophication, freshwater (kg P eq)	Eutrophication and potential impact on ecosystems caused by nitrogen and phosphorous emissions mainly due to fertilizers, combustion, sewage systems
Eutrophication, marine (kg N eq)	
Eutrophication, terrestrial (mol N eq)	
Ecotoxicity, freshwater (CTUe)	Impact of toxic substances on freshwater ecosystems
Land use (Pt)	Transformation and use of land for agriculture, roads, housing, mining or other purposes. The impact can include loss of species, organic matter, soil, filtration capacity, permeability
Water use (m3 depriv.)	Depletion of available water depending on local water scarcity and water needs for human activities and ecosystem integrity
Resource use, fossils (MJ)	Depletion of non-renewable resources and deprivation for future generations
Resource use, minerals and metals (kg Sb eq)	

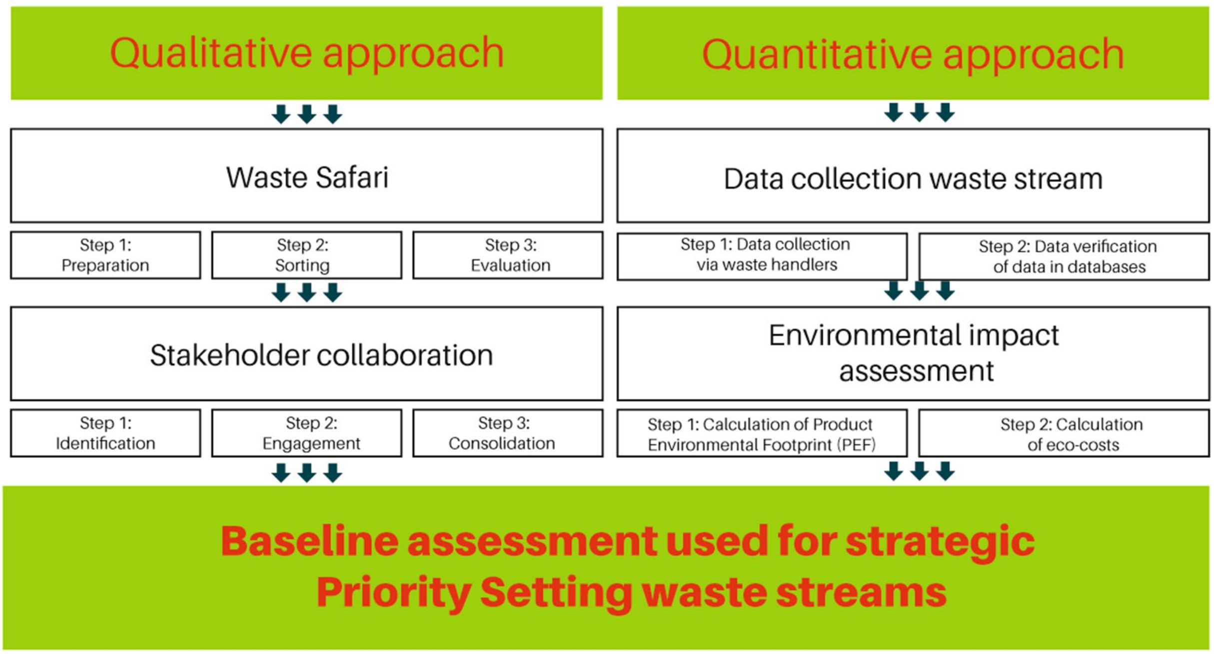

FIGURE 2
Four parts of the Baseline Circular Airport Method (BCAM).

Step 2 – Sorting.

Potentially supported by a waste management partner, the bags should be collected from the recycling bins, labeled, and weighed. On a sorting table, individual bags can be manually sorted into relevant streams, e.g. plastic, paper and residuals. All information per opened bag can be photographed and documented by the research team.

Step 3 – Evaluation.

After onsite observations and data analysis, conclusions can be drawn on the most common items and those that are commonly incorrectly disposed. Additional interviews with facilities and waste management partners are recommended, as elaborated in the following section.

3.2 Part 2: stakeholder collaboration

Stakeholder collaboration along the value chain is critical in a CE. The generation of waste at airports is frequently caused by the selection of products introduced into the airport ecosystem. Since each actor along the chain contributes to this, they play a role in preventing or minimizing the streams and related environmental impact. Three activities are needed for creating effective collaborations: stakeholder identification, engagement and consolidation.

Step 1 – Identification.

To identify stakeholders that directly contribute to the operational resource streams, representatives from different airport departments, such as Commercial, Passenger Insights, and Asset Management could be involved. Having a diverse group and hence a variety of perspectives results in more comprehensive decision-making that reflects the needs of all involved parties (Mohd Isa, 2018).

Step 2 – Engagement.

Per stakeholder group, the topics used for engagement can be determined to understand each stakeholder's vision and ambition, which CE initiatives are being undertaken, and the potential for future collaboration between the airport and the stakeholder. On site engagement strategies can include semi-structured interviews and observations which allow flexibility while maintaining a focused approach.

Step 3 – Consolidation.

The next step is to consolidate the input gathered and use this as a bridge to the strategic planning stage. This involves synthesizing the information obtained from steps 1 and 2, identifying recurring themes, and commonalities across stakeholder perspectives and understand areas for teaming up.

3.3 Part 3: operational resource streams

This third part of the BCAM is a quantitative assessment of operational resource streams at airports to validate insights from the qualitative approach. This involves collecting data on resource streams, including weight, volume, and treatment, and subsequently verifying the treatment methods.

Step 1 – Data collection.

Prior to collecting the data per resource stream, a baseline year needs to be chosen to provide a benchmark against which future data can be measured and to identify trends, changes, or deviations in airport performance and sustainability initiatives. Baseline year resource data (and corresponding weight in tonnes, volume, and treatments) could be provided from the waste management partner(s). This overview can consequently be aligned with the recognized resource streams at airports by National Academies of Sciences, Engineering and Medicine (2018) and Mehta (2015).

The total amount of disposed resources can be correlated with the total number of airport passengers, as shown by Baxter et al. (2018) and Sebastian and Louis (2021). Waste data per passenger is needed to identify trends in waste generation patterns; an increase in waste per passenger may indicate a need for improved recycling infrastructure or changes in passenger behavior, or allow airports to allocate resources more effectively. It helps in targeting specific areas where reduction efforts can have the most significant impact, whether through improved recycling programs or other sustainability initiatives. The calculation of the waste per passenger is defined as:

$$\text{Waste per passenger} = \frac{\text{total grams of waste}}{\text{number of annual passengers}} = \text{total gr / pax}$$

Step 2 – Data verification.

Historically, the Netherlands has faced issues with fraud and manipulation, loss of information, and a lack of control in the waste management sector (Ongena et al., 2018). To ensure waste treatment percentages shared by waste management partner(s) in the data collection process are correct and accurate, additional data could be collected and compared. There are two relevant databases for the context of waste treatment in the Netherlands:

- The Dutch Environmental Database: an independent organization that enables calculations of the environmental performance of structures in the Dutch context. The database also provides fixed values for end-of-life processing scenarios for various materials (Milieudatabase, 2022).
- Eurostat: provides high quality statistics and data at a European level and can validate waste treatment (Eurostat, 2020).

Should discrepancies emerge between the data provided by waste management partner(s) and those recorded in databases, further investigation is needed. If evidence from the waste management partner(s) is unavailable, the database information takes preference.

3.4 Part 4: environmental impact assessment

This part refers to the impact of waste streams on the environment, based on processing and disposal. It comprises two steps: the PEF calculation and the eco-cost calculation.

Step 1 – PEF calculation.

The environmental impact assessment is performed in line with established LCA standards as defined in ISO 14040:2006 and ISO 14044:2006. This selected impact assessment framework, supported by Raimundo et al. (2023), is instrumental in providing robust and detailed guidance for decision-makers and policy outcomes. The focus is deliberately narrowed to targeting the End-of-Life stage, with a specific emphasis on resources processing and disposal. This strategic decision is informed by the anticipation of limited information availability from earlier life stages such as raw material extraction or production. SimaPro is the applied software wherein the 16-category PEF impact assessment method (Table 1) is applied (European Commission, 2022). To assess the environmental impact of the airports' operational resource streams, the Ecoinvent v3.6 (Ecoinvent, 2021) database is used. This provides the required comprehensive and systematic data to evaluating the 16 environmental impacts of streams. As SimaPro datasets adhere to standardized LCA methodologies, consistency and comparability of results can be ensured.

Step 2 – Eco-cost calculation.

The LCA results in extensive lists of toxic substances, necessitating simplification into a single indicator (or number) that summarizes the total impact. Single indicators for LCA fall into three categories: single issue (such as carbon footprint), damage-based (such as focusing on raising awareness), and prevention-based (such as eco-costs). Eco-costs provide transparency, and ensure that results are expressed in both monetary terms and actionable measures. Eco-cost is the (marginal) costs needed to reduce environmental pollution and materials depletion to a level in line with the Earth's carrying capacity (Sustainability Impact Metrics, 2023). The total eco-costs are the sum of four types of eco-burdens, as presented in the formula below.

$$\text{Total eco-costs} = \text{Human Health} + \text{Ecosystems} + \text{Resource Depletion} + \text{Global Warming}$$

Eco-cost is calculated using Eco-costs 2022 V1 (Sustainability Impact Metrics, 2023) and measures the environmental burden of a resource stream based on the cost of preventing that burden. Eco-cost considers all 16 PEF indicators (European Commission, 2022) as presented in Table 1. Table 2 shows an overview of the calculations.

3.5 Informed strategic priority settings for resource streams

After applying a mixed-methods approach, the prioritized list of resource streams is the result of combining quantitative and qualitative data. Qualitatively, the 'waste safari' identifies top items in bins, while stakeholder interviews offer additional valuable insights. Quantitatively, waste management partner's data, cross-verified with databases, guides environmental impact and eco-cost assessments. The prioritization process leans towards quantitative results, ensuring a grounded, scientific ranking that aligns with sustainability goals.

4 Results

The research objective of this article was to establish a method to systematically analyze and evaluate airport operational resource streams considering key factors such as waste composition, stakeholders, treatment, and environmental impact. The aim was to develop strategic prioritization settings that facilitate a successful transition towards a CE. The BCAM was tested for validation at Schiphol.

Schiphol has set ambitious sustainability goals and aims to make its airports circular and energy-positive, achieve CO2 neutrality in the aviation sector, and create a pleasant living and working environment in the vicinity by 2050 (Schiphol Group, 2022). Schiphol, a major international hub, has a surface area of 27,870,000 square meters with its terminals spanning 650,000 square meters. In 2019, Schiphol facilitated a significant 496,826 aircraft movements, underscoring its importance as a key player in global aviation. At Schiphol, a centralized waste management system streamlines waste handling for both airport terminals and aircraft. However, flight catering operators typically manage their own waste. The airport employs FF3 bins (Figure 3) which include separate compartments for paper (50 liters), plastic, metal, and drink cartons (50 liters), and residual waste (70 liters).

To validate the BCAM, we set the baseline year for waste data to 2019 as this period represents the airport's normal performance before COVID significantly impacted air travel.

4.1 Waste safari

During the 'waste safari' conducted in December 2022, 46 bin bags from FF3 recycling bins (Figure 3) were sampled, collected, and weighed. They were then labeled for further assessment. The selected bags were gathered on multiple days in December (3, 4, 7, 9, 10, and 11). The collection took place in the morning between 07:06 and 09:45. Almost all bags were transparent and color-coded for Plastic Metal and Drinking cartons (PMD), paper, or general waste. However, some bags selected before the security area were blue, which restricted visual inspection. Figure 4 details the bag collection process.

The total weight of the selected bags during pick-up by cleaning companies were 32.19 kg, 25.1 kg, and 19.24 kg for residual, PMD and

TABLE 2 Calculation and details of the eco-cost.

Eco-costs	Calculation	Details	Values applied (2022)
Human Health	The sum of carcinogens, summer smog, fine dust	Eco-costs of fine dust	35.0 €/kg fine dust PM2.5 equivalent
		Eco-costs of human toxicity cancer	3,750 €/kg Benzo(a)pyrene equivalent =920,000 €/ CTUh
		Eco-costs of human toxicity non-cancer	25,500 €/kg Mercury equivalent =216,000 €/ CTUh
		Photochemical oxidant formation ('summer smog')	5.35 €/kg NOx equivalent (NMVOS equivalent)=9.625 euro/kg C2H4 eq
Ecosystems	The sum of acidification, eutrophication, ecotoxicity	Eco-costs of acidification	8.75 €/kg SO2 equivalent (=6.68 euro/mol H+ eq)
		Eco-costs of eutrophication	4.70 €/kg PO4 equivalent (=14.40 euro/kg P eq)
		Eco-costs of ecotoxicity	340 €/kg Cu equivalent
Resource depletion	The sum of abiotic depletion (scarcity of metals, REE, and energy carriers), land-use, water, and land-fill	Examples (based on 2023 eco-cost): - Aluminum: 1.02 €/kg - Nickel: 13.52 €/kg - Oil: 0.78 €/kg * Full details: https://www.ecocostsvalue.com/ecocosts/eco-costs-resource-scarcity/	
Global warming	The sum of CO2 and other greenhouse gases (the GWP 100 table)	Eco-costs of global warming	0.116 €/kg CO2 equivalent

FIGURE 3
FF3 bin employed at Schiphol Amsterdam airport.

FIGURE 4
The bin bag collection process prior assessment.

FIGURE 5
Visual representation of a randomly selected bin bag being manually sorted.

paper streams, respectively. The bags were opened and manually sorted into plastics, paper, food, and residual resource streams (Figure 5).

Examination showed that resource contamination occurred in all streams and bin bags, indicating that passengers and other users of the airport premises are not separating waste correctly. Paper bins were found to be frequently contaminated with other objects including glass, PET, coffee cups, and cans. Further, food waste was found in all waste streams, with a significant effect on the weight of the bag. Finally, PET, cans, and coffee cups were identified as common items present in all bags. This contamination not only increases the difficulty of recycling but also reduces the quality of the recycled material. The common five contaminating items found in all bags were cups, PET bottles, food bags, food boxes, and cans, all of which are related to food and beverage consumption (Figure 6). Other frequently found items included napkins, food leftovers, tickets/baggage labels, wooden cutlery, and random items such as belts, socks and party decorations.

4.2 Outcomes: advantages, limitations, possible pitfalls, and key takeaways

- Advantages: contamination issues highlight the need for improved post-separation methods to ensure accurate recycling percentages. Understanding passenger challenges with effective waste separation indicates a need for nudging initiatives, such as redesigning bin openings, icons, or color coding.
- Limitations: 'waste safari' observations were based on a small sample and could not be generalized without further investigation. The lack of interrelation studies between bin bag and bin location hindered a comprehensive overview of waste composition.
- Possible pitfalls: variability in data collection methods, including differences in timing, frequency, and personnel, may have caused inconsistencies and data reliability issues.
- Key takeaway: human behavior is a significant factor in airport waste separation issues (Tjahjono et al., 2023). Adequate preparation for the 'waste safari,' including thorough training for collectors and sorting teams, is essential for reliable and consistent data collection.

4.3 Stakeholder collaboration

Identified stakeholders are those who directly influence the operational resource streams of Schiphol (Figure 7). The stakeholder engagement strategies outlined in Table 3 resulted in the following insights per stakeholder group.

- Food & Beverage (F&B) partners manage the restaurants, cafes, and other food vendors operating at Schiphol. They contribute to the waste stream through food packaging, leftover food, and other disposables as observed during the observations on site. In the semi-structured interviews, the F&B partners noted shared CE-related ambitions for 2030 and 2050 and performing various initiatives in that regard. Examples include installing smart cameras to monitor food waste, piloting PET bottle deposit systems, exploring technology for better estimations of food consumption, and finding alternatives for the single-use coffee cups.
- Retail partners include shops and stores, and generate waste through packaging, shopping bags, and other disposable items. Based on the semi-structured interviews, it was clear that some retailers share similar CE objectives to those of Schiphol. Initiatives to reduce waste include the usage of external warehouses to decrease packaging waste, alternatives for plastic packaging and sealed bags, and exploring incentives for sustainable passenger behavior.
- Facilities partners include those responsible for maintaining the cleanliness of the airport, including the collection of waste. In the semi-structured interviews, they mentioned contributing to the waste stream through the use of cleaning products, disposable items such as paper towels, and other materials used in their operations. This stakeholder group also noted similar CE goals

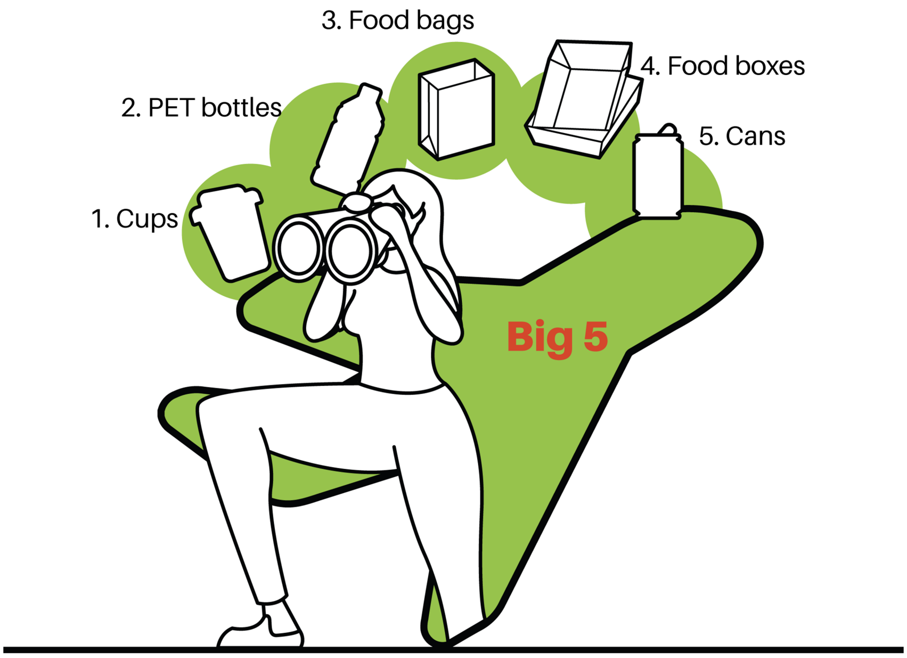

FIGURE 6
The big five spotted items during the Waste Safari.

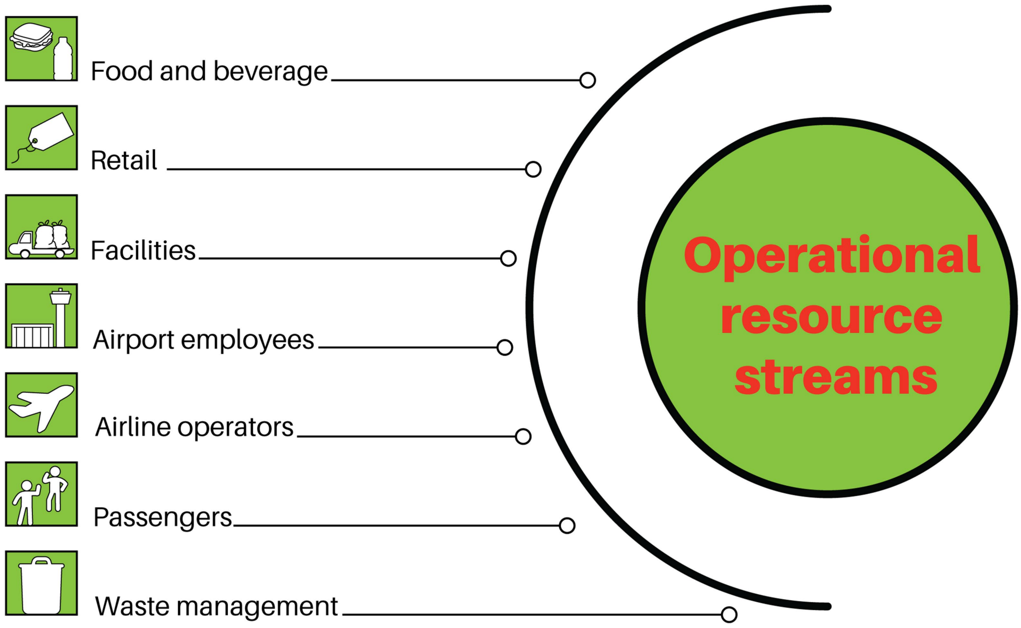

FIGURE 7
Stakeholders influencing operational resource streams at Schiphol Amsterdam airport.

TABLE 3 Stakeholder engagement strategies performed at Schiphol Amsterdam airport.

Stakeholder group	# Stake-holders	Engagement strategy	Participant information	# of sessions in 2022 and 2023	Average session duration
Food & Beverage (F&B)	2	Semi-structured interview Observation	• Two main F&B providers • 7 people per session (3 per stakeholder and 4 of the research team)	6	60 min
Retail	1	Semi-structured interview	• Schiphol department overseeing all Retail partners • 4 people per session (1 per stakeholder and 3 of the research team)	6	60 min
Facilities	3	Semi-structured interview	• Three main providers • 7 people per session (3 per stakeholder and 4 of the research team)	6	60 min
Airport employees	1	Observation	• Various observations during site visits	3	60 min
Airport operators	1	Observation	• Various observations during site visits	2	120 min
Passengers	1	Semi-structured interview Observation	• Various observations during site visits • Schiphol department overseeing passenger trends • 6 people per session (2 per stakeholder and 4 of the research team)	2	120 min
Waste management partners	2	Semi-structured interview	• Two main waste management partners (former and current one) • 8 people per session (4 per stakeholder and 4 of the research team)	8	60 min

for 2030 and 2050 and are performing various initiatives in that regard. Examples of waste reduction initiatives include bin sensor monitoring, optimizing the waste collection routing, shifting to alternative cleaning products or reusable packaging materials, finding alternatives for paper tissues, and switching to recycled bin bags due to the large amount of plastic lining used in bins since as they are often replaced without being completely full, among others.

- Airport employees include security personnel, maintenance staff, and administrative personnel, and generate waste through their daily operations in the terminal or offices. In various exchanges with airport employees, we noted that they are willing to contribute to transforming the airport's waste management methods, but that they are unsure of which steps to take.

- Airline operators generate waste through in-flight services, such as F&B, handing out products to passengers during flights (e.g., headphones or blankets), as well as through ground operations, such as baggage handling. Limited information is available to them regarding sustainable practices, incentives or related performance indicators to motivate these practices, as they operate from many different airlines. The involvement of this group of stakeholders adds further complexity to the objectives of on-site resource management. Various facilities and waste management partners are tasked with managing their respective streams. Additionally, one of these streams, CAT1, is categorized as a high risk material and hence need to be treated in compliance with related EU legislation (Lex, 2011).
- Passengers are the primary users of airport terminals and have a direct influence on streams related to paper, PMD, residual waste (as FF3 bins are used in the terminals, see Figure 3) and the Liquids, Aerosols, and Gels (LAG) disposed of at security. We observed passenger behavior to understand the "passenger journey" and Schiphol had obtained insights via Passenger Insights by interviewing 24 randomly selected passengers (20 min interview each). These interviewees were from a wide range of age groups, nationalities, genders and passenger types (e.g., private or business). We were informed that passengers want to play a role in the transition to sustainable aviation, but apart from waste separation practices, they are unaware of most practices provided by the airport.
- Waste management partners oversee the final collection and treatment of resource streams. During the course of this study, Schiphol changes their waste management partner. From the semi-structured interviews and site visits, we noted that they are responsible for the management of primary waste collection areas and that they collaborate closely with facilities to influence downstream treatment choices. Additionally, they aim to collaborate to implement initiatives that encourage passengers, foster innovation, and prevent waste (upstream).

The stakeholder insights were applied to bridge the baseline results to the strategic planning phase.

4.3.1 Outcomes: advantages, limitations, possible pitfalls, and key takeaways

- Advantages: stakeholders share similar CE objectives as shown from the methods, increasing opportunities to collaborate on initiatives like the 'waste safari.' This allows stakeholders to align their visions and ambitions for effective teamwork.
- Limitations: despite the collaboration potential, challenges may arise from existing large master agreements amongst F&D, retail, facilities or waste management partners or from the lack of incentives or performance indicators amongst passengers, employees, and operators.
- Possible pitfalls: key stakeholders, as observed in the meetings, acknowledged their role in the airport value chain. While they had information and control over some parts, there were gaps in others. For instance, one option is to include more bins of various types in kitchens to separate most resource streams. However, this is not always feasible due to limited space. In addition, despite passengers' choices regarding disposal methods and materials, cleaning personnel play a role in determining which press container the bin bags are ultimately placed into. If a paper bin bag is heavily contaminated, the cleaning parties might dispose of it in the residual bin.
- Key takeaways: initial meetings with key stakeholders revealed a varying level of expertise in CE topics, indicating the need for targeted engagement and education. In addition, stakeholders often operate in silos, while they acknowledge opportunities to work together.

4.4 Operational resource streams

The third part of the BCAM focuses on the operational resource streams at airports. The year 2019 was selected as it represents a pre-COVID period. This provides a baseline measurement that reflects typical operational conditions and passenger volumes, providing a more accurate representation of the airport's standard performance. Schiphol's waste management partner provided an overview of all operational resources streams generated in 2019, including the weight (tonnes) and volume (Table 4). Additional information regarding the actual treatment of streams was requested. If not provided, we utilized the Dutch Environmental Database and Eurostat databases.

In 2019, Schiphol's total waste was 15,183 kg tonnes; Figure 8 shows the division into Residual, CAT1, Swill, Paper/Cardboard, Plastic, and others (all remaining streams from Table 4).

Nearly half the waste generated at Schiphol falls under residual streams. The presence of residuals in the recycling stream refers to either a problem with source separation, for instance, of commercial waste and waste generated by passengers, or the presence of non-recyclable plastics, food waste, or mixed packaging materials. CAT1 waste is regulated by EU law (Regulation 1069/2009) and is classified as a risk for infection, requiring appropriate handling and disposal to prevent the spread of disease. The swill waste stream refers to food-related discards from airport establishments, including food scraps, leftover meals, and packaged food items. This waste can be further classified into edible and non-edible categories. The paper waste at airports comprises a distinct stream of paper-based products used by both staff and passengers. This includes items such as tissues, office archive material, cardboard, and newspapers. Plastic waste, a ubiquitous concern, is a dedicated waste stream. Notably, Schiphol adopts a comprehensive approach by collecting PMD with a separate PET collection and donation system, as is common practice in the Netherlands (Nederland Statiegeld, 2023), showcasing a commitment to sustainable waste practices.

The waste per passenger was calculated based on the total volume generated in 2019 (15,183 tonnes). In 2019, 71.7 million passengers flowed through the airport (Schiphol Group, 2019), resulting in a waste per passenger of 212 grams. There is a strong relationship between the operational waste produced and the number of passengers, with a Pearson correlation coefficient of 0,991.

$$\text{Waste per passenger} = \frac{15{,}183{,}000{,}000 \text{ grams waste}}{71{,}700{,}000 \text{ passengers}} = 212 \text{ gr / pax}$$

TABLE 4 2019 overview resource streams and treatment of Schiphol Amsterdam airport.

Operational resource streams	Weight (tonnes)	Volume (m³)	Calculated % for waste scenarios		
			% Landfill	% Incineration	% Recycling
Archive material	44	272	10%	85%	5%
CAT1	3,372	26,920	0%	100%	0%
Cans	4	69	3%	3%	94%
Coffee grounds	109	106	15%	85%	0%
Debris	21	56	90%	10%	0%
Electronics	18	114	0%	22%	78%
Glass	385	3,321	30%	0%	70%
Hazardous waste	27		7%	93%	0%
Hazardous waste (small)	2		7%	93%	0%
Insulation materials	2	60	85%	5%	10%
Metal	233	1,637	5%	5%	90%
Paper and cardboard	1,505	9,083	10%	85%	5%
Plaster	6	40	95%	0%	5%
Plastic	123	2,181	0%	90%	10%
Plastic packaging material	167	7,009	0%	90%	10%
Porcelain	10	57	100%	0%	0%
Residual waste	6,743	50,062	2%	98%	0%
Sand/minerals	363	492	1%	0%	99%
Swill	1,578	2,135	2%	9%	89%
Tissue	101	400	10%	85%	5%
Wood A	16	400	11%	89%	0%
Wood B	352	5,242	10%	90%	0%
Total	15,183				

4.4.1 Outcomes: advantages, limitations, possible pitfalls, and key takeaways

- Advantages: insights were gained into the volume of different resource streams and waste per passenger, providing the basis for setting a baseline for further monitoring.
- Limitations: energy and water are excluded from the total operational resource streams at Schiphol and hence not included in this study.
- Possible pitfalls: discrepancies between database assumptions and actual data from waste management partners can occur. In the case of wood, the waste management partner initially asserted a high recycling percentage (>90%), but practical evidence supporting this claim was lacking. Upon investigation, it became apparent that in the Netherlands, incineration of wood was financially more viable than recycling. Following our methodology, we relied on the defined data verification databases which reported a 0% recycling rate.
- Key takeaways: an understanding of total waste and treatments supports the exploration of alternative waste management strategies. For instance, for paper waste, a low recycle rate suggests the need for initiatives to reduce paper usage (e.g. replacing tissues with hand dryers) or implementing nudges for cleaner disposal. Additionally, waste per passenger data serves as a valuable aviation KPI for monitoring progress toward circularity and achieving CO2 neutrality by 2050.

4.5 Environmental impact assessment

The fourth part of the BCAM is the Environmental Impact Assessment. For each resource stream as identified in part three, the treatment process (landfill, incineration, and recycling) was determined based on the Dutch Environmental Database and Eurostat database. We calculated the environmental impact of 1 tonne of waste using the Ecoinvent database. All impact scores are included in Supplementary Table S1.

The different waste processing methods result in different environmental impacts. In the case of incineration, the main environmental burden lies in direct emissions to the air from burning waste, such as toxic chemicals and pollutants, as well as the energy required to run the incineration facility. For landfill, the negative impact on the environment comes from the release of greenhouse gasses such as carbon dioxide and methane, and the contamination of surrounding soil and water. Recycling is the most sustainable waste processing method, although it still involves energy for operating the recycling facility, resulting in indirect emissions. Note that in a CE, as highlighted by our definition, value retention processes (R strategies) are to be applied to ensure the highest possible value of raw materials, components and products (Eurostat, 2023) either by lengthening their lifetime or by looping them back in the system to be reused (PBL-Netherlands Environmental Assessment Agency, 2023). Hence,

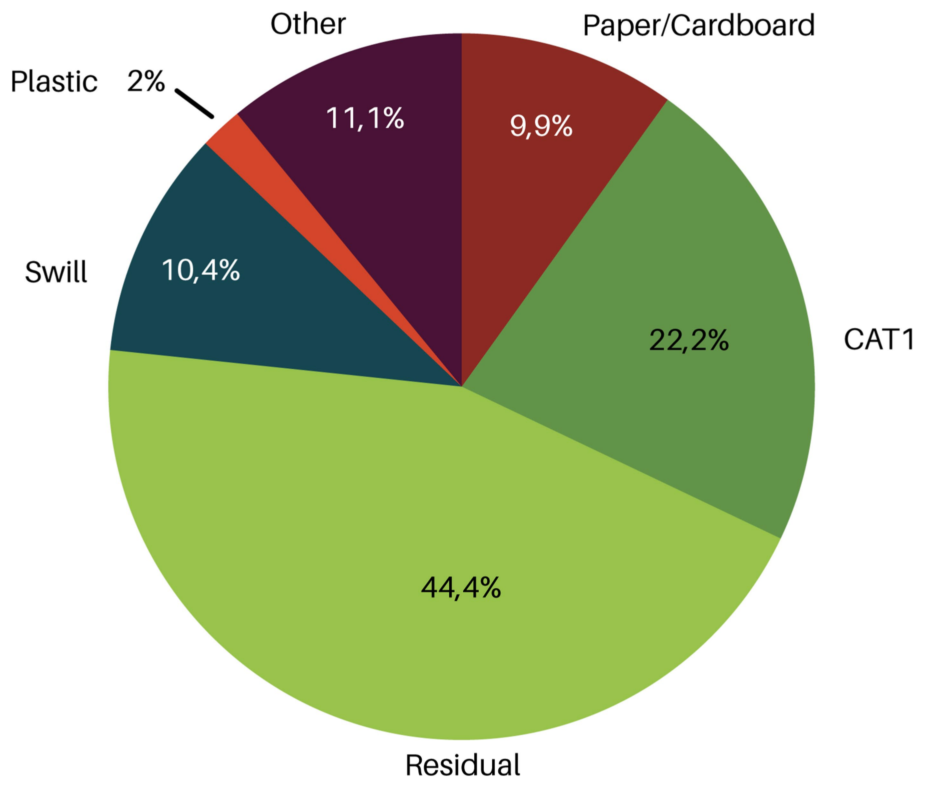

FIGURE 8
Resource stream division based on weight at Schiphol Amsterdam airport (2019).

while prevention strategies are preferred over waste treatment strategies, there is no maintained information to substantiate this preference.

The total eco-costs are calculated by the sum of eco-costs of human health, ecosystems, resource depletion and global warming (Table 2). Note that the eco-costs of resource depletion consist of multiple topics. The original eco-costs of materials depletion were based on a combination of recycling and "deeper digging" in combination with mining of ores with a lower concentration (which is more expensive), as prevention measures for depletion. Additionally, this category includes the eco-costs of energy carriers, water use, land use and landfill.

The eco-costs shown in Figure 9 allow a comparison of the different waste streams.

4.5.1 Outcomes: advantages, limitations, possible pitfalls, and key takeaways

- Advantages: the environmental impact assessment, emphasizes eco-costs related to climate change, reinforces Schiphol's 2050 objectives to be circular and energy-positive and achieve CO2 neutrality, and offers new perspectives by comparing impact versus weight/volume. In this way, airports can better understand the environmental impact savings of waste reduction.
- Limitations: the scope of impact assessment based on LCA methodology is limited to waste collection and treatment, and excludes resource extraction, production, and transportation.
- Possible pitfalls: risk of getting lost in data without proper categorization.
- Key takeaways: relying solely on weight for resource streams may overlook environmental harm, hence we combined these elements. Impact assessments that include criteria beyond weight and volume offer valuable insights. Eco-costs provide a useful means to compare the sixteen impact categories.

4.6 Baseline measurement and strategic priority setting

The BCAM tested at Schiphol highlights insights related to the operational resource streams generated by various stakeholders. The qualitative and quantitative information obtained via the mixed-methods research approach is the foundation of the baseline measurement for the year 2019. The consolidated results from the BCAM are shown in Table 5.

Table 5 prioritizes the streams in future efforts towards the airport's ambitions towards zero waste (2030) and circularity (2050):

- Residuals: this stream constitutes the largest and environmentally most impactful stream at Schiphol (57% of total eco-costs) and involves contributions from all mentioned stakeholders. It could be challenging to decide what stakeholders to target. For instance, bin bags containing paper disposed of by passengers may still end up in the residual stream. Facilities (cleaning parties) have the discretion to determine the appropriate action for each transparent bin bag, particularly if it is highly contaminated.

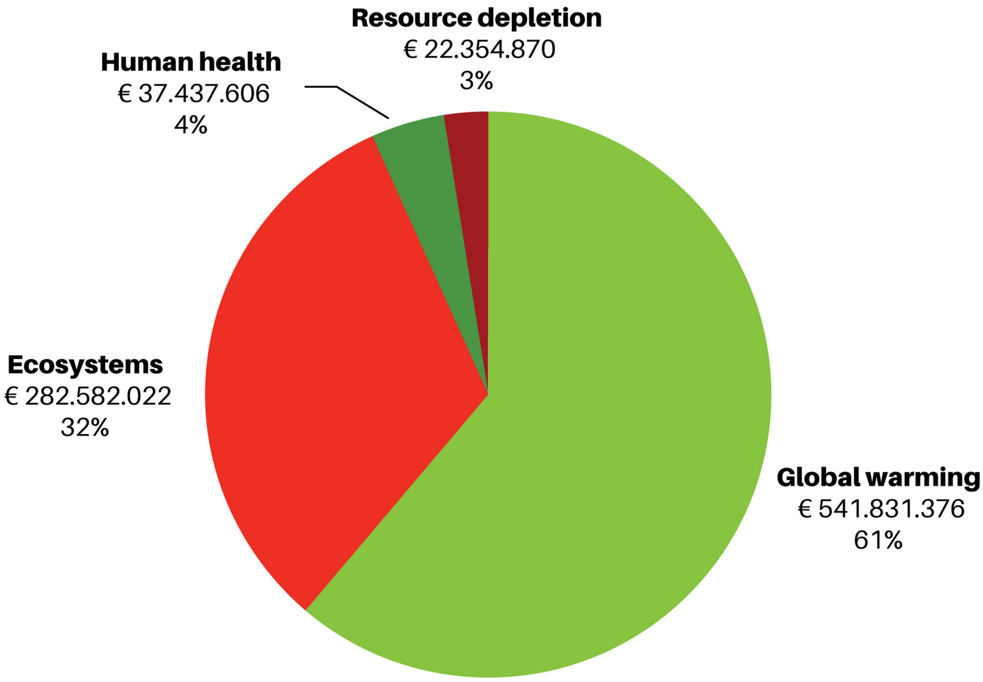

FIGURE 9
Eco-Cost Comparison of Resource Streams at Schiphol Amsterdam airport (2019).

TABLE 5 Summary of four parts of BCAM applied at Schiphol Amsterdam airport.

Recurring operational resource streams	Qualitative approach		Quantitative approach	
	Waste Safari	Stakeholder collaboration	Operational resource streams	Environmental impact assessment
	Spotted in BIG 5:	Stakeholder groups contribute mostly to resource stream:	Largest streams include:	Eco-costs are:
Residual	Many items that could be recycled, but are currently wrongly separated	All stakeholder groups	44.4%	€ 500,854,081
CAT1	Out of scope (no bin selected as this comes from airplanes and is highly regulated)	Airline operators	22.2%	€162,893,351
Plastic	Highly contaminated	Facilities and Retail	2%	€80,782,640
Swill	Out of scope (no bin available for passengers, only kitchens have swill bins)	F&B and Passengers	10.4%	€ 76,169,462
Paper	Highly contaminated with F&B waste plus other disposables	Airport employees and Retail	9.9%	€23,611,44
Other	Out of scope (no bin)	All stakeholder groups	11.1%	€39,894,896

Subsequently, the waste management partner decides on the actual treatment.

- CAT1: this stream accounts for nearly a quarter of total airport waste, and presents challenges due to airline operations often managing both generation and collection plus the legal requirements for this stream.
- Swill: approximately 10% of Schiphol's waste is food waste. While F&B partners can separate food waste, passengers currently cannot, which is one of the challenges observed leading to contamination in other on-site bin bags.
- Plastic (including PMD/PET): despite its low weight (2%), plastics ranks high in the environmental impact assessment. Found in most airport bins, plastics, like residuals and food, significantly contaminate bags.
- Paper/Cardboard: comprising 10% of airport waste, paper, like residuals and plastics, contaminates bins during disposal. As

noted in the 'waste safari' and on-site observations, passenger confusion in separating items like coffee cups (which may contain plastic) contributes to this. Clean cardboard mainly originates from F&B and retailers.

The main five resource streams – Residual, CAT1, Plastic, Swill and Paper – together with the eco-cost calculations are shown in Figure 10.

5 Discussion

This article has presented the BCAM key findings, as well as the testing of the method at Schiphol airport. Schiphol's sustainability roadmap sets out their aims to be zero waste by 2030 and circular in 2050. In order to achieve this they can now, following BCAM, strategically plan and assess progress towards sustainable waste management and CE transitions. In the following sections, we reflect on BCAM's contribution to the literature, the learnings drawn from its application at Schiphol, managerial implications, as well as its applicability to other airports and contexts.

5.1 Contribution to the literature

This study presents a significant contribution to the existing literature on waste management practices in airport environments, particularly in the context of the evolving concept of CE within the aviation industry. We addressed the limited application of CE concepts in aviation as highlighted by Saavedra-Rubio et al. (2023), by developing and testing BCAM in practice.

Our introduction of BCAM is a major step forward when applying CE principles within the airport environment. This task has been acknowledged as complex in the literature on waste composition (National Academies of Sciences, Engineering and Medicine, 2018), on stakeholder engagement (Bamidele et al., 2023) and multicriteria methods such as EIA, and on LCA principles (Morrissey and Browne, 2004). BCAM fills a gap identified by Dimitriou and Karagkouni (2022), who called for a quantitative analysis of airports' environmental sustainability performance. In addition, BCAM provides momentum and an actionable way of aligning stakeholder groups when working together to achieve CE (Morrissey and Browne, 2004; Bamidele et al., 2023; Sassanelli and Terzi, 2023).

5.2 Learnings from the application of BCAM at Schiphol

BCAM was applied with Schiphol as a case study to provide a systematic analysis of resource streams, their composition, treatment, and environmental impact. Conducting the two qualitative and two quantitative parts of BCAM identified current resource management efficiencies to be obtained, stakeholder collaboration opportunities, and pinpointed high-impact resource streams. For the qualitative approach, examples pertain to insights obtained via stakeholders, such

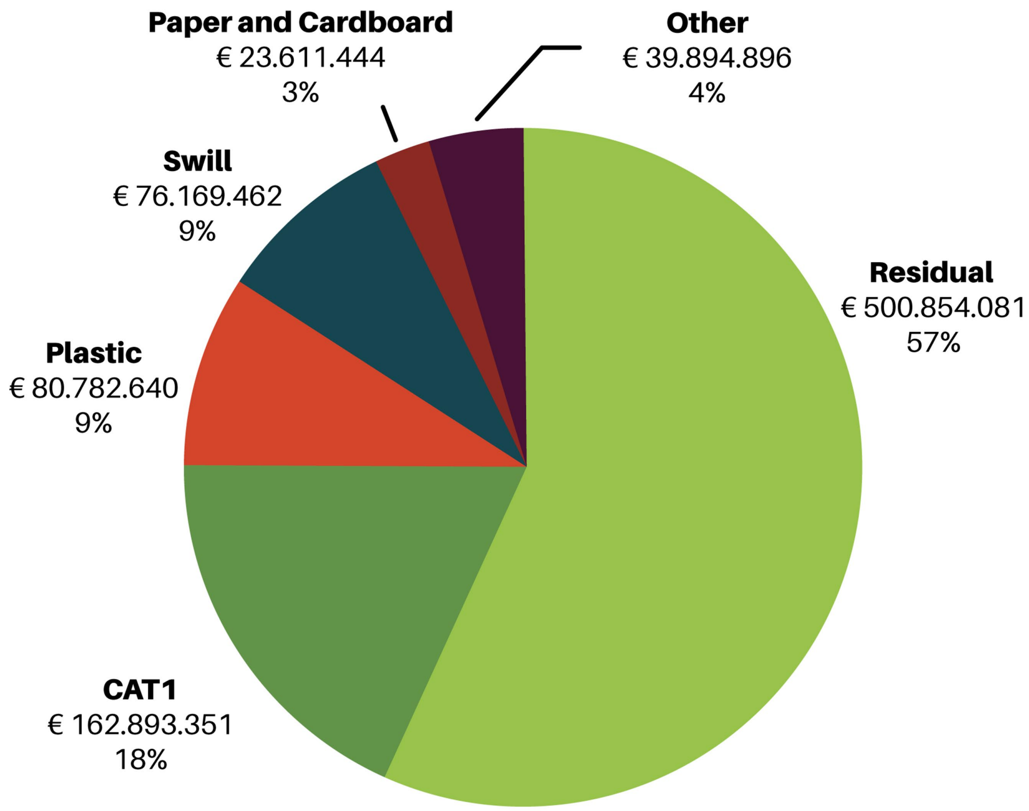

FIGURE 10
Breakdown of total waste, eco-costs, and waste streams at Schiphol Amsterdam airport (2019).

as the current amount of virgin plastic lining used in bins. This occurs because bin bags are often replaced without being completely full and need to be see-through for passing through airport security. Additionally, there is often mention of willingness to team up and collaborate on shared objectives, aiming to make more impact together, but in practice, this collaboration is less visible and performed. Utilizing information from the qualitative approach can support in setting specific targets to accelerate the transition to a CE. Regarding the quantitative approach, a lack of transparent data on treatment processes of waste partners for resource streams was observed, even though it is deemed crucial for CE monitoring. This is considered a challenge, as transparency should be at the forefront of (new) collaborations, in line with legislation such as the CSRD or DPPs.

The detailed insights obtained with BCAM offer airports a starting point for strategic planning and assessing progress toward sustainable waste management and CE transitions. The BCAM can help airports to identify the most impactful operational resource streams and hence define focused interventions in those areas instead of introducing randomly targeted interventions. The BCAM results can hence serve as a baseline for further monitoring and improvement.

5.3 Managerial implications

Performing the BCAM provides airports with a solid and comprehensive baseline measurement and prioritization of resource streams. This can support airports in understanding their current performance and defining focused and specific pathways to achieve CE related objectives. Additionally, CE practitioners can be supported by the BCAM to apply in other sectors. By doing so, the method could be useful in paving the way to find opportunities for collaboration and accelerating the transition to a CE.

Some detailed implications for airports became visible while performing each part of the BCAM. For example the recurring five products spotted during the 'waste safari' – PET, cans, food wrapping, food boxes, coffee cups – indicate the need for targeted interventions to offer a range of more sustainable products in restaurants, support passengers better in disposing their waste with bin signage, and involve facilities and waste management partners to efficiently pick up and recycle waste. This indicates the need for a close collaboration between stakeholders to efficiently organize resource management as confirmed by Sassanelli and Terzi (2023). Airports can play a key role to ensure that all stakeholders are willing to play their role in a system solution framework, as highlighted by Ellen Macarthur Foundation (2020). In summary, a holistic approach that involves collaboration with stakeholders, prioritization of resource streams, and continuous monitoring will contribute significantly to achieving CE goals in airport waste management.

5.4 Applicability to other airports and contexts

The BCAM was not adjusted after assessing the results as it provided the required level of detail for strategic planning purposes for Schiphol. In addition, the BCAM results are shown to be generalizable as the research steps described in this article were also performed at Cyprus Larnaca airport and Avinor Oslo airport. These airports are partners of the EU TULIPS consortium (Tulips, 2020). Similar insights were obtained as well as similar priority streams – Residual, CAT1, Paper, Swill and Plastics – despite differences in local airport infrastructure and culture.

6 Conclusion

The BCAM supports airports in offering a starting point for strategic planning and assessing progress towards sustainable waste management and CE transitions. The results assisted in identifying the most impactful operational resource streams (Residual, CAT1, Paper, Swill and Plastics) and formed the basis for defining strategies to reduce or prevent such streams. The BCAM can be applied by organizations wishing to focus on optimizing and reducing high-impact waste streams by exploring ways to reduce the overall volume of high-impact waste categories. They can track progress over time by regularly assessing waste from different angles, both qualitatively and quantitatively. This continuous monitoring allows for adaptive strategies, ensuring that reduction initiatives are effective and aligned with sustainability goals.

The mixed methods research design provides a comprehensive understanding of Schiphol's environment, however, it is important to note possible limitations. The qualitative research could be improved by conducting a more detailed analysis of the waste collected, for example by performing more 'waste safaris' and engaging more stakeholders through structured meetings to ensure consistent input. In the case of quantitative research, the assessment of resource stream treatment relied on databases. In instances where data from the waste partner was not available, assumptions had to be made as the Ecoinvent database does not contain references for every single waste stream. We adopted worst-case datasets to prevent underestimation of the total environmental impact. To deepen our understanding, future research could explore the actual waste pathways of waste management partner(s). Obtaining primary data will contribute to a more accurate and nuanced picture of the situation.

Some aspects merit further investigation. The BCAM showed comprehensive connections between waste volumes, stakeholders, treatment methods, and environmental impact. However, airports still lack clarity on how to intervene effectively. Exploring how to translate the understanding of prioritized resource streams into actionable steps on the circularity roadmap, including the use of metrics, is a significant area for exploration, especially in scenarios involving prevention and reuse. In addition, prioritizing prevention strategies over recycling strategies underscores the importance of airports maintaining the data used and applied in the BCAM method themselves. Further research might indicate what data to collect and how to ensure the management with a monitoring framework. Third, in addition to testing the method in two other airports with generalizable results, a larger sample is needed to better understand true effectiveness and potential deviations. Next, from the results obtained, we note that uncertainties persist about the fate of materials post-departure from airports, necessitating detailed tracking to understand potential resource loss. Lastly, integrating the assessment of social impact as part of LCA methods into future studies can enhance the overall understanding of airport operations. These aspects collectively represent avenues for research and development in this sector.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary material.

Author contributions

AT-R: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. ET: Investigation, Methodology, Visualization, Writing – review & editing, Conceptualization, Writing – original draft. CM: Project administration, Resources, Writing – review & editing, Data curation, Supervision. SS: Project administration, Resources, Writing – review & editing, Funding acquisition, Validation. SC: Methodology, Software, Writing – review & editing. SD: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2024.1356041/full#supplementary-material

References

Bamidele, R. O., Ozturen, A., Haktanir, M., and Ogunmokun, O. A. (2023). Realizing green airport performance through green management intransigence, airport reputation, biospheric value, and eco-design. *Sustain. For.* 15:2475. doi: 10.3390/su15032475

Basel Convention. (2011). National definition of waste. [Online] Available at: https://www.basel.int/Portals/4/Basel%20Convention/docs/natreporting/2009/compI/2009-question-2a.pdf

Baxter, G., Srisaeng, P., and Wild, G. (2018). Sustainable airport waste management: the case of Kansai international airport Graham Wild (0000-0003-1223-4675) – ORCID. *Int. J. Traffic Transport. Eng.* 8, 334–358. doi: 10.7708/ijtte.2018.8(3).07

Bocken, N. M., and Short, S. W. (2020). Chapter 19 transforming business models: towards a sufficiency-based circular economy. *Handbook of the circular economy*. Cheltenham, UK: Edward Elgar Publishing. [Online] Available at: https://doi.org/10.4337/9781788972727.00028

Dimitriou, D., and Karagkouni, A. (2022). Assortment of airports' sustainability strategy: A comprehensiveness analysis framework. Sustainability 2022, 14, 4217. [Online] Available at: https://www.mdpi.com/2071-1050/14/7/4217

Ecoinvent. (2021). Ecoinvent 3.6. [Online] Available at: https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-6/

Ellen MacArthur Foundation. (2020). The circular economy in detail-deep dive. [Online] Available at: https://www.ellenmacarthurfoundation.org/the-circular-economy-in-detail-deep-dive

European Commission. (2008). EU waste framework directive. [Online] Available at: https://environment.ec.europa.eu/topics/waste-and-recycling/implementation-waste-framework-directive_en

European Commission. (2015). Circular economy action plan. [Online] Available at: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en#timeline

European Commission. (2021). Mobility strategy and action plan. [Online] Available at: https://transport.ec.europa.eu/document/download/be22d311-4a07-4c29-8b72-d6d255846069_en?filename=2021-mobility-strategy-and-action-plan.pdf

European Commission. (2022). Circular economy strategy. [Online] Available at: https://research-and-innovation.ec.europa.eu/research-area/environment/circular-economy/circular-economy-strategy_en

European Commission. (2023). Commission welcomes provisional agreement for more sustainable, repairable and circular products. [Online] Available at: https://ec.europa.eu/commission/presscorner/detail/en/ip_23_6257

European Commission. (2023). Corporate sustainability reporting. [Online] Available at: https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en

Eurostat. (2020). Waste statistics. [Online] Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics#Total_waste_generation

Eurostat. (2023). Circular economy overview. [Online] Available at: https://ec.europa.eu/eurostat/web/circular-economy/overview

International Civil Aviation Organization (ICAO). (2014). Waste management at Airports [Online] Available at: https://www.icao.int/environmental-protection/Documents/ecoairports/Final%20Waste_Management_Case_Studies.pdf

International Civil Aviation Organization (ICAO). (2019). Circular Economy. [Online] Available at: https://www.icao.int/environmental-protection/Pages/CircularEconomy.aspx

International Civil Aviation Organization (ICAO). (2022). ICAO forecasts complete and sustainable recovery and growth of air passenger demand in 2023 [press release]. [Online] Available at: https://www.icao.int/Newsroom/Pages/ICAO-forecasts-complete-and-sustainable-recovery-and-growth-of-air-passenger-demand-in-2023.aspx#:~:text=Air%20passenger%20demand%20in%202024,over%20the%202019%2D202420period

International Air Transport Association (IATA). (2022). Understanding the Pandemic's impact on the aviation value chain. [Online] Available at: https://www.iata.org/en/iata-repository/publications/economic-reports/understanding-the-pandemics-impact-on-the-aviation-value-chain/

International Air Transport Association (IATA). (2023). Global outlook for air transport. [Online] Available at: https://www.iata.org/en/iata-repository/publications/economic-reports/global-outlook-for-air-transport---december-2023---report/#:~:text=passenger%2Dkilometers%20(RPKs)%2C,set%20to%20double%20by%202040

Kanchanabhan, T. E., Mohaideen, J. A., Srinivasan, S., and Sundaram, V. L. K. (2011). Optimum municipal solid waste collection using geographical information system (GIS) and vehicle tracking for Pallavapuram municipality. *Waste Manag. Res.* 29, 323–339. doi: 10.1177/0734242X10366272

Kirchherr, J., Yang, N.-H. N., Schulze-Spüntrup, F., Heerink, M. J., and Hartley, K. (2023). Conceptualizing the circular economy (revisited): an analysis of 221 definitions. *Resour. Conserv. Recycl.* 194:107001. doi: 10.1016/j.resconrec.2023.107001

Lex, EUR. (2011), Regulation (EC) no 1069/2009. [Online] Available at: https://eur-lex.europa.eu/eli/reg/2011/142/oj

Lidow, D. (2017). A better way to set strategic priorities. Harv. Bus. Rev. [Online] Available at: https://hbr.org/2017/02/a-better-way-to-set-strategic-priorities

Mehta, P. (2015). Aviation waste management: an insight. *Int. J. Environ. Sci.* 5, 179–186. doi: 10.6088/ijes.6020

Metabolic. (2020). Circular Economy. [Online] Available at: https://www.metabolic.nl/what-we-do/circular-economy/

Milieudatabase. (2022). Forfaitaire waarden voor verwerking-scenario's einde leven behorende bij: Bepalingsmethode Milieuprestatie Bouwwerken. [Online] Available at: https://milieudatabase.nl/media/filer_public/05/54/05542700-02b3-439b-91c9-7824353da2c2/forfaitaire_waarden_november_2020.pdf

Mohd Isa, N. A. (2018). A stakeholder analysis of the KLIA2 airport terminal project. *Asian J. Behav. Stud.* 3:1. doi: 10.21834/ajbes.v3i13.138

Morrissey, A. J., and Browne, J. (2004). Waste management models and their application to sustainable waste management. *Waste Manag.* 24, 297–308. doi: 10.1016/j.wasman.2003.09.005

National Academies of Sciences, Engineering and Medicine. (2018). Airport waste management and recycling practices. Washington, DC: The National Academies Press. [Online] Available at: https://nap.nationalacademies.org/catalog/25254/airport-waste-management-and-recycling-practices

NLR. (2019). Circular economy gradually finding its way in the aviation sector [press release]. [Online] Available at: https://www.nlr.org/news/circular-economy-gradually-finding-its-way-in-the-aviation-sector/

Nederland Statiegeld. (2023). Statiegeld in Nederland. [Online] Available at: https://www.statiegeldnederland.nl/

Ongena, G., Smit, K., Boksebeld, J., and Adams, G. (2018). Blockchain-based smart contracts in waste management: A silver bullet? [Online] Available at: https://www.researchgate.net/publication/325773842_Blockchain-based_Smart_Contracts_in_Waste_Management_A_Silver_Bullet

Özbay, İ., and Gokceviz, N. A. (2022). Towards zero-waste airports: a case study of Istanbul airport. *J. Mater. Cycles Waste Manag.* 24, 134–142. doi: 10.1007/s10163-021-01308-2

PBL-Netherlands Environmental Assessment Agency. (2023). Circular economy topics [Online]Available at: https://www.pbl.nl/en/topics/circular-economy

Planas Parra, M. (2023). Assessing the status of airport collaborative decision making (A-CDM) concept at European airports. [Online] Available at: https://upcommons.upc.edu/bitstream/handle/2117/383721/memoria.pdf?sequence=2

Raimundo, R. J., Baltazar, M. E., and Cruz, S. P. (2023). Sustainability in the airports ecosystem: a literature review. *Sustain. For.* 15:12325. doi: 10.3390/su151612325

Saavedra-Rubio, K., Stoikou, N., Pierrat, E., Rupcic, L., Thonemann, N., Moloney, P., et al. (2023). *Assessment of environmental performances and circular economy potentials in airports*. [Online] Available at: http://dx.doi.org/10.2139/ssrn.4443182

Sassanelli, C., Rosa, P., Rocca, R., and Terzi, S. (2019). Circular economy performance assessment methods: a systematic literature review. *J. Clean. Prod.* 229, 440–453. doi: 10.1016/j.jclepro.2019.05.019

Sassanelli, C., and Terzi, S. (2023). Circular economy and sustainable business performance management. *Sustain. For.* 15:8619. doi: 10.3390/su15118619

Schaar, D. (2010). Analysis of airport stakeholders. [Online] Available at: https://catsr.vse.gmu.edu/pubs/ICNS_Schaar_AirportStakeholders.pdf

Schiphol Group. (2019). Sustainability Roadmap 2030. [Online] Available at: https://www.schiphol.nl/nl/download/b2b/1576260712/5L8gEqMHuWuh0MWoN1tLZK.pdf

Schiphol Group. (2022). Road to the most sustainable airports. Schiphol.Nl. [Online] Available at: https://www.schiphol.nl/en/schiphol-group/page/road-to-the-most-sustainable-airports/

Sebastian, R. M., and Louis, J. (2021). Understanding waste management at airports: a study on current practices and challenges based on literature review. *Renew. Sust. Energ. Rev.* 147:111229. doi: 10.1016/j.rser.2021.111229

Smol, M. (2023). Inventory and comparison of performance indicators in circular economy roadmaps of the European countries. [Online] Available at: 10.1007/s43615-021-00127-9, 3, 557–584

Sustainability Impact Metrics. (2023). *The concept, structure, and midpoint tables of the eco-costs for LCA*. [Online] Available at: https://www.ecocostsvalue.com/ecocosts/eco-costs-concept/

The United Nations glossary. (1997). Glossary of environment statistics. [Online] Available at: https://unstats.un.org/unsd/envstats/Glossary/SeriesF/SeriesF_67E.pdf

Tjahjono, M., Ünal, E., and Tran, T. H. (2023). *The circular economy transformation of airports: An alternative model for retail waste management*. [Online] Available at: https://doi.org/10.3390/su15043860

Tulips. (2020). EU consortium focused on - DemonsTrating lower pollUting soLutions for sustaInable airPorts acrosS Europe. [Online] Available at: https://tulips-greenairports.eu/