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A Multi-Criteria AHP-Based Framework for Sustainable Municipal Waste Collection

Mattia Cottes * and Patrizia Simeoni

Polytechnic Department of Engineering and Architecture, University of Udine, Via delle Scienze 206, 33100 Udine, Italy; patrizia.simeoni@uniud.it

* Correspondence: mattia.cottes@uniud.it

Abstract

The management of waste has become increasingly complex due to the growing volume and diversity of waste generated by modern societies. Effective collection systems are essential for mitigating environmental impacts and promoting sustainability. However, the increasing complexity of waste management requires a comprehensive approach that considers multiple criteria in order to evaluate the performance of these systems. This study evaluates the environmental performance of waste collection systems by comparing various methods using the Analytic Hierarchy Process (AHP). The research involves identifying key performance indicators (KPIs) that could be relevant for all the stakeholders involved and important for environmental sustainability. These KPIs are then used as criteria for the AHP model, allowing for a detailed comparison of each collection method. Data is collected from a case study in the Friuli-Venezia Giulia region in Italy. The preliminary results indicate significant variations in environmental performance and user fruitfulness across different collection methods. Door-to-door collection was found to be the preferred methodology with an absolute weight of 0.527. The AHP framework proves to be a robust tool for integrating diverse criteria and stakeholder preferences, facilitating informed decision-making in waste management. Moreover, it underscores the importance of adopting a holistic approach to evaluate and improve recycling systems. By leveraging AHP, policymakers and waste management professionals can identify optimal strategies that align with environmental sustainability goals.

Keywords: waste collection; sustainability; multi-criteria decision making; analytic hierarchy process

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1. Introduction

In recent decades, social awareness of the importance of environmental protection has grown [1]. This has given a push toward the initiation of a regulatory process which has led to increasing attention towards environmental protection, which is understood as a complex system in which different elements interact with each other [2]. In this context, the EU has set 2030 climate targets, including a reduction of at least 55% in greenhouse gas emissions [3]. Among the various sectors responsible for emissions, the ever-increasing production of waste must undoubtedly be included. Waste refers to substances, products, mixtures, and objects that, having exhausted their "useful" phase, must be managed. Waste management is therefore an activity that can generate various impacts in all its phases: production, collection, transport, recovery, disposal, the post-closure operational management of landfills, and the decommissioning of end-of-life technological plants [4,5].

Given the impact that waste management can generate, one of the methods implemented to reduce it is separate waste collection (SWC).

Possibilities to reduce the environmental impact of waste management through several efforts have been put forward in the literature. Zitouni-Petrogianni et al. investigated the energy sustainability and cost-effectiveness of plasma gasification for the treatment of MSW combined with energy recovery, highlighting good economic feasibility [6]. Chen et al. developed a multi-objective optimization model to identify the optimal technological configuration and provide recommendations for applicable solutions [7]. Xu et al. developed a multi-objective optimization model for MSW gasification, taking into account economic and environmental benefits. This allows decision-makers to control the allocation of resources and GHG emissions by selecting different technological configurations [8]. Demichelis et al. compared different pre-treatments prior to anaerobic digestion (AD), evaluating the biogas production and energetic sustainability of the entire process. They concluded that thermal pre-treatment at 120 °C was the most effective configuration [9].

Regarding the research focused on waste collection impacts, Benitex-Bravo et al. proposed a strategy for the design of MSW collection routes that minimize the environmental and economic impacts, based on an LCA approach, leading to a reduction in collection distance up to 20% [10]. A similar approach has been adopted by Bala et al., highlighting however that real fuel consumption data should be used [11]. Salazar-Adams compared the efficiency of waste collection services managed by private companies with those managed by municipal governments, concluding that private providers perform better [12]. Another study introduced a novel strategy for collecting and transporting MSW that increases recycling rates, albeit at the cost of higher fuel consumption [13]. Singh et al. compared different collection techniques and ICT-based technologies worldwide. They concluded that existing management schemes must be aligned with future collection technologies [14].

The application of the circular economy principle to MSW has also been widely investigated. Hoang et al. analyzed MSW valorization from a circular economy perspective, concluding that waste-to-energy technologies are hindered by low utilization rates and high costs [15]. Another study focused on technological developments for MSW valorization into valuable chemicals and energy discussing the economic, environmental, and health impacts [16]. Similarly, Sondh et al. proposed key facets for designing a solid waste management system driven by circular economy principles [17]. Sieradzka et al. identified strategies for managing refuse-derived fuels in line with the circular economy, demonstrating their significant potential as an alternative energy source in gasification processes [18].

The Analytic Hierarchy Process (AHP) is a method that has been widely adopted in similar investigations. Thangarasu et al. applied the AHP to identify suitable locations for wastewater treatment plants [19]. Another study used AHP to determine the most effective PET collection methods, evaluating various strategies based on efficiency and sustainability while taking stakeholders' preferences into account [20]. Liu et al. integrated AHP with value proposition design to optimize waste management business models [21]. Similarly, Madonsela et al. assessed the environmental, social, and economic sustainability of indigenous waste management practices using the AHP approach [22]. Harfadli et al. developed a tool to help governments formulate waste management policies by quantifying emissions and identifying reduction pathways [23]. With a similar aim, Nguyen et al. provided a novel framework for closed and unsanitary landfills in developing countries to help authorities manage environmental risks [24].

Despite the extensive research conducted on SWC strategies, there is still a lack of integrated decision support frameworks that: (i) compare operational configurations across different waste collection modes; (ii) explicitly quantify environmental trade-offs under

realistic, managerially actionable criteria; and (iii) translate these insights into concrete recommendations for urban hygiene service managers taking into account varying policy and logistical constraints.

In this context, the present study aims to develop an AHP model to evaluate the impact of the separate collection of urban waste, building on the work presented in [25]. Three management scenarios based on different collection models are analyzed: (i) street-only mode; (ii) mixed street/door-to-door mode; (iii) enhanced door-to-door mode. The objective is to identify the most effective model, while also highlighting possible corrective or integrative actions to maximize strengths and minimize weaknesses. The analysis is conducted from the perspective of urban hygiene service managers, with the ultimate goal of supporting decision-making processes that consider environmental impacts.

The developed model would then be applied to the case study of the Gorizia province, in the Friuli-Venezia Giulia region in Italy, to unveil its practicality and utility. The remainder of this paper is organized as follows: In Section 2 the considered waste collection modes are described and the developed AHP model for decision support is exposed, while the case study of application is depicted in Section 3. Section 4 discusses the obtained results and the conclusions are drawn in Section 5.

2. Materials and Methods

2.1. Operational Collection Modes

Three collection systems were analysed: street collection, door-to-door collection and a mixed system.

The street collection model was used in Italy until the late 1990s, before the regulatory push given by the so-called "Ronchi Decree" (the first real act of transposing European directives with a clear "green" shift) introduced significantly ambitious separate collection targets for that period. The containers are placed, according to precise rules that respect both the Highway Code and the necessary urban decorum, along the streets or in designated public spaces (e.g., at the sides of roadways) or accessible to public service (e.g., common areas of condominiums or mixed residential/commercial private areas). Waste not managed through roadside collection is collected through the system of Collection Centers [26], areas set up where users can dispose of bulky waste, waste electrical and electronic equipment (WEEE), hazardous waste (paints, used mineral oils, batteries, etc.), inert waste from construction and demolition from small DIY jobs, etc. Since this system is the same in all three methods, this part of the urban hygiene service will not be considered for the purposes of this work. This system provides users with maximum freedom in disposal, which is not tied to a collection schedule and eliminates the logistical inconveniences that arise in the door-to-door system from the need to keep waste at home until the specific commodity fraction collection day.

The door -to-door collection model, which has now become the reference model in Italy to ensure the achievement of the legal separate collection targets (65%), involves a series of specific rules and tools. Users are required to adhere to a precise collection schedule, which usually includes the following:

- Bi-weekly collection of organic/wet waste;
- Weekly collection of residual dry waste;
- Weekly or bi-weekly collection of paper and cardboard waste;
- Weekly or bi-weekly collection of plastic packaging and cans;
- Weekly or every two weeks collection of glass.

For logistical reasons and related to collection yields, sometimes glass is collected in roadside containers. Waste not managed through roadside/door-to-door collection is collected through the system of Collection Centers also used in this strategy.

The mixed street–door-to-door collection model is an intermediate method between collection carried out only with roadside containers and intensive door-to-door collection. The most impactful fractions from a management perspective, "residual dry waste" and organic waste (so-called "wet waste"), are collected through roadside disposal; this allows users to make free disposals, which are not tied to a collection schedule, of these fractions that are "inconvenient" to keep at home due to potential odor and insect nuisances. The containers are placed, according to precise rules that respect both the Highway Code and the necessary urban decorum as in the "only roadside containers" strategy. For logistical reasons and related to collection yields, glass is collected in roadside containers. All other fractions (paper, plastic, cans) are collected door-to-door, according to a predetermined collection schedule. Transparent bags are provided for plastic and cans to avoid improper disposals and to encourage citizens to correctly differentiate these wastes. Waste not managed through roadside/door-to-door collection is collected through the system of Collection Centers, as explained previously.

2.2. Adopted AHP Model

The functioning of the AHP method involves having the members of each stakeholder group compare a pair of alternatives at a time for each defined criterion. This pairwise analysis allows decision-makers to systematically classify performance characteristics. From a purely scientific perspective, the method involves two fundamental steps:

- The first step involves breaking down the problem to be addressed into hierarchically connected sub-problems.
- The second step involves addressing the various specific sub-problems through a series of pairwise comparisons among different choice opportunities, assigning each comparison a relative importance score. This process concludes with the assignment of a unitary or percentage weight. The sum of all percentage weights will be equal to 1 or 100%, depending on the absolute or percentage scale used.

The scores used for each pairwise comparison are chosen from a rating scale called the Saaty scale, which uses a numerical or linguistic scale composed of 5 fundamental judgments and 4 intermediate ones, as shown in Table 1.

Table 1. Fundamental Saaty judgment scale.

Numerical Judgments	Verbal Judgments
1	Equally important
3	Moderately more important
5	Strongly more important
7	Very strongly more important
9	Extremely important
2, 4, 6, 8	Intermediate judgments

The scale introduced by Saaty is based on the proven assumption that people classify elements or factors better based on a range.

To apply the AHP method, a pairwise comparison matrix $A = [a_{ij}]$ of order n is constructed, where a_{ij} expresses the relative importance of the element i with respect to element j. By definition, $a_{ii} = 1$ for all i, and reciprocity holds, such that

$$a_{ij} = \frac{1}{a_{ji}}, \text{ with } a_{ij} > 0$$

The priority vector $w = (w_1, w_2, \ldots, w_n)^T$, representing the weights of the elements, is derived as the principal eigenvector of the comparison matrix as follows:

$$Aw = \lambda_{\max} w, \text{ with } \sum_{i=1}^{n} w_i = 1$$

where $\lambda_{\max}$ is the maximum eigenvalue of the matrix A.

The consistency of the judgements is then assessed by computing the *Consistency Index* (CI) and the *Consistency Ratio* (CR):

$$CI = \frac{\lambda_{\max} - n}{n-1}, CR = \frac{CI}{RI_n},$$

where RI_n is the *random index* depending on the order n of the matrix. A CR value below 0.10 is generally considered acceptable, ensuring that the judgements are logically consistent.

Through this formalized procedure, the AHP provides a quantitative framework that transforms subjective pairwise comparisons into consistent priority weights usable for decision-making.

2.2.1. First Phase: Problem Decomposition

The first phase of the AHP methodology aims to create a hierarchical structure of the problem under analysis. The steps that led to the establishment of a hierarchical model are as follows:

- The first step involves defining the highest level of the hierarchy, consisting of the overall objective, which, in this case, has been identified as: "Identification of the best solution";
- The next step involves breaking down the main objective into the most important elements of the decision-making problem, following a top-down approach.

Since the objective of the work is to identify the collection system that best suits waste management, a set of indicators was defined by a team constituted by university professors, representatives from the management of the service-providing company, field operators, and citizen representatives. This set allows a manager of urban hygiene services to directly and autonomously evaluate the "environmental performance" of SWC services using data already available within the company. There is thus no need to collect additional external data, which are often difficult to obtain and would require significant time for reprocessing as well as specific professional figures, which are often absent in the stable internal staff of the aforementioned companies.

A complex system such as a widespread SWC service over a fairly large area would indeed have required a large amount of specific data that would not have been easy to obtain nor subsequently easy to verify in terms of reliability and accuracy. The set of indicators identified to evaluate the "environmental performance" consists of the following:

- Carbon Footprint (CFP), a component of the so-called "ecological footprint," as defined by international standards [27].
- Four indicators based on consolidated data from SWC services carried out in the area and on the relevant technical standards:
    1. % of separate waste collection (%SWC) achieved by different collection models.
    2. The extent of the use of roadside bins.
    3. The extent of the use of disposable containers.
    4. The average number of operators used in the service.

- Three indicators established to evaluate the impact of different types of collection on users:
  (a) The usability of the service by users.
  (b) Urban décor.
  (c) The environmental awareness of users (EAU).

The criteria defined and described earlier have been grouped into three sets: environmental, technical, and social. Each set of parameters has been given a weight in the overall final evaluation by the team through a collaborative discussion and mutual agreement, ensuring that all perspectives were considered in the final decision. Figure 1 depicts the hierarchical schematization of the analyzed system, which was subsequently implemented with the software.

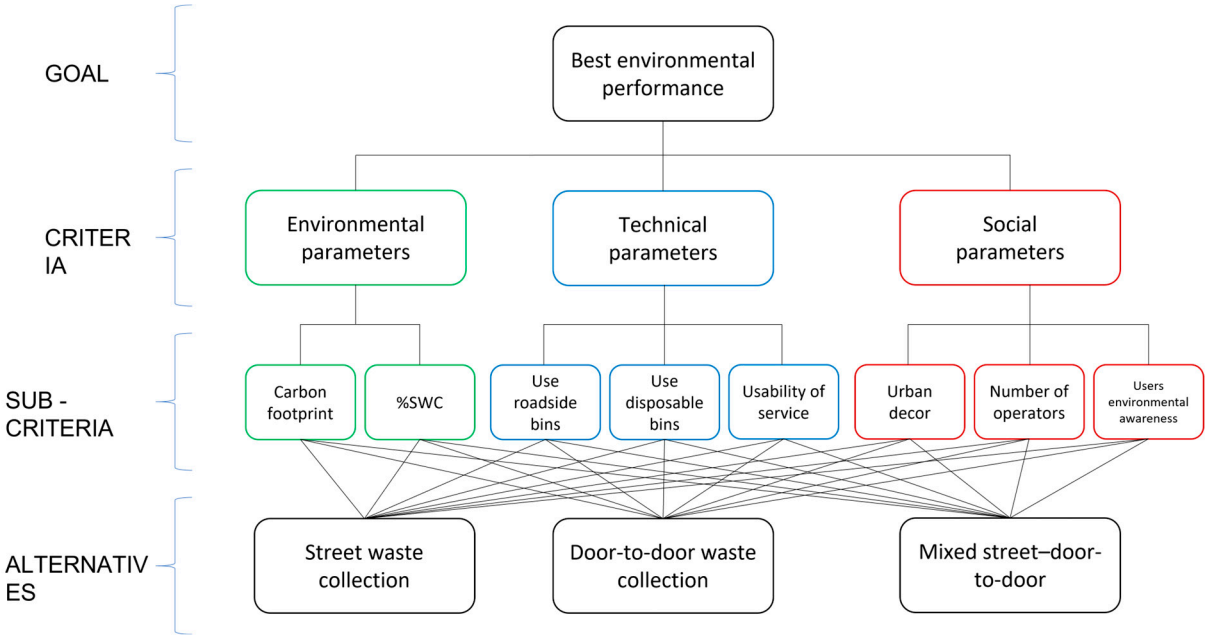


Figure 1. Model hierarchical framework.

2.2.2. Second Phase: Pairwise Comparison

The second phase is based on pairwise comparisons, which make it possible to derive weights and priorities from structured judgements. A square comparison matrix is constructed for a set of elements (criteria, sub-criteria, or alternatives), with $a_{ii} = 1$ and reciprocity $a_{ij} = 1/a_{ji}$, where a_{ij} represents the relative importance of element i compared with element j, as assessed using Saaty's fundamental scale (Table 1). To minimize the impact of subjectivity on weight assignment, a multidisciplinary panel of fifteen experts was established. The panel was selected based on criteria relating to competence, stakeholder representativeness, and independence. The panel comprised:

- Three academics specializing in environmental engineering and waste management.
- Three technical staff from the municipal waste collection company responsible for operational planning and system monitoring.
- Three field operators directly involved in daily collection activities who could provide insights into technical and operational feasibility.
- Two citizen representatives identified through local associations to capture user perception and social acceptability.
- Two ANCI (Associazione Nazionale Comuni Italiani) representatives to protect and promote the interests of Italian municipalities, metropolitan cities, and unions of

municipalities while providing technical support, institutional coordination, and initiatives for local administrations.

- Two environmental association representatives to integrate environmental protection and public interest perspectives.

To ensure transparency and replicability in weight assignment, the experts' judgements were collected individually by compiling pairwise comparison matrices using Saaty's fundamental scale. For each matrix, the local weights (normalized principal eigenvector) and the CR were calculated. Where CR > 0.10, the experts were asked to revise their judgements to ensure the evaluations were internally consistent.

Once the individual matrices had been verified, the Aggregation of Individual Judgements (AIJ) approach was used to aggregate the judgements by applying the element-wise geometric mean as follows:

$$a_{ij}^{(G)} = \left(\prod_{k=1}^{m} a_{ij}^{(k)} \right)^{1/m}$$

where $a_{ij}^{(k)}$ is the judgment expressed by expert k and m is the total number of experts. This aggregation method preserves the matrices' reciprocity property and reduces the influence of extreme values. Collective weights were then derived from the aggregated matrix by solving $A^{(G)}w^{(G)} = \lambda_{\max} w^{(G)}$ and normalizing so that $\sum_i w_i^{(G)} = 1$. The consistency of the group judgment was verified by calculating $CR^{(G)}$; this was always found to be below the threshold value of 0.10.

3. Case Study

The developed AHP model has been applied to a case study of the Gorizia province, in the Friuli-Venezia Giulia region in north-eastern Italy. In 2020, the total production of municipal waste in the Gorizia province amounted to 70,947 tons/year, equivalent to a per capita production of 508.4 kg/inhabitant × year. Of the aforementioned waste, 68% was collected separately, according to the division into homogeneous commodity fractions shown in Table 2, which highlights the predominance of the organic fraction in the collection, followed by paper, glass, and plastic.

Table 2. Gorizia province waste management data.

Waste Fraction	**Amount [1000 × Tons/Year]**
Organic fraction (municipal)	10.61
Organic fraction (green)	10.04
Paper	7.79
Glass	5.69
Plastic	3.09
Metals	2.48
Wood	3.24
WEEE	0.99
Bulky	1.49
Construction and demolition waste	1.37
Street sweeping waste	1.27
Textile	0.37
Others	0.42
TOTAL	**48.84**

In this context, three waste collection scenarios were set up in the Gorizia province. For each collection method illustrated in the previous chapter, the services will now be characterized in terms of the following:

- Total equipment required for collection, which is necessary to establish the number of collection shifts;
- The number of vehicles required for collection and their mileage, which is necessary for calculating the CFP. The calculation of the CFP allows for the estimation of the greenhouse gas emissions caused by a product, service, organization, event, or individual, generally expressed in tons of CO_2 equivalent (i.e., taking the effect of all greenhouse gases as a reference). The CFP calculation was carried out in accordance with the international Greenhouse Gas Protocol (GHG Protocol) standard. Specifically, the free software available on the GHG Protocol website has been used [28].

For each scenario, the following considerations were made:

- A service execution period of one calendar year (365 days);
- A territorial scope of 140,000 citizens (equivalent to the residents in the province of Gorizia, rounded from 138,666 for calculation convenience—year 2020) [29].

The minimum equipment and technical standards, as previously mentioned, were calculated based on the annexes in the reference document "Definition of technical standards for urban hygiene" [30]. The CFP considered for this work is strictly related to the operation of the trucks used for waste collection and their subsequent delivery to authorized facilities. The footprint related to disposable equipment (e.g., 120 L bags for plastic collection) provided by the service manager was not considered, as this contribution to the total CFP is not significant compared with the impact of vehicular traffic. In fact, simulations carried out in the "Intensive door-to-door separate collection" scenario showed that the CFP related to the annual supply of bags to users amounted to about 39 tons of CO_{2eq} (considering a footprint of 0.978 kg CO_{2eq} per m^3 of waste collected in plastic bags [31]) compared with about 3779 tons of CO_{2eq} attributable to vehicular traffic. Therefore, it was deemed more significant to consider disposable bags in a parameter that takes into account their supply in numerical units across the three different scenarios.

3.1. Street Collection Mode

Based on the parameters provided by the ANPA reference document the following useful project data are derived:

- Total annual kilometers traveled:
  (a) With vehicles' gross weight of 17.1–26 tons: 1,609,083 km.
  (b) With vehicles' gross weight of 7.5–17 tons: 0 km.
  (c) With vehicles' gross weight < 7.5 tons: 0 km.

  equivalent to a total CFP of 1151.06 tons CO_{2eq}.
- Total equipment used:
  (a) Roadside and/or condominium bins: 9738.
  (b) For door-to-door, reusable (bins): 0.
  (c) For door-to-door, disposable (bags): 0.
- Days of waste exposure on the street awaiting collection (total number of days of door-to-door collection): 0.
- Average number of operators needed per collection shift: 1.5.
- EAU (evaluation from comparison with industry operators): low.

3.2. Mixed Street–Door-to-Door Mode

Based on the parameters provided by the ANPA reference document, the following useful data are derived:

- Total annual kilometers traveled:

(a) With vehicles' gross weight of 17.1–26 tons: 1,443,167 km.
(b) With vehicles' gross weight of 7.5–17 tons: 600,949 km.
(c) With vehicles' gross weight < 7.5 tons: 300,475 km.

equivalent to a total CFP of 1382.66 tons CO_{2eq}.

- Total equipment used:
  (a) Roadside and/or condominium bins: 8711.
  (b) For door-to-door, reusable (bins): 46,667.
  (c) For door-to-door, disposable (bags): 1,213,333.
- Days of waste exposure on the street awaiting collection (total number of days of door-to-door collection):
  (a) Bi-weekly alternating collection of paper/cardboard and plastic/cans: 52 collections per year.

  for a total of 52 days/year.
- Average number of operators needed per collection shift: 2.
- EAU (evaluation from comparison with industry operators): medium.

3.3. Door-to-Door Mode

Based on the parameters provided by the ANPA reference document, the following useful project data are derived:

- Total annual kilometers traveled:
  (a) With vehicles' gross weight of 17.1–26 tons: 2,475,735 km.
  (b) With vehicles' gross weight of 7.5–17 tons: 2,329,212 km.
  (c) With vehicles' gross weight < 7.5 tons: 880,409 km.

  equivalent to a total CFP of 3779.35 tons CO_{2eq}.
- Total equipment used:
  (a) Roadside and/or condominium bins: 6067.
  (b) For door-to-door, reusable (bins): 121,333.
  (c) For door-to-door, disposable (bags): 5,096,000.
- Days of waste exposure on the street awaiting collection (total number of days of door-to-door collection):
  (a) Bi-weekly organic waste collection: 104 collections/year.
  (b) Weekly residual dry waste collection (the frequency of residual dry waste is not counted as it is collected on the same day as one of the two weekly organic waste collections): not counted.
  (c) Bi-weekly alternating collection of paper/cardboard and plastic/cans: 52 collections/year.

  for a total of 156 days/year.
- Average number of operators needed per collection shift: 3.
- EAU (evaluation from comparison with industry operators): high.

For the selection of the "weights" of the individual parameters, the expert panel chose to follow the criterion dictated by the waste management objectives defined by the reference legislation:

- Protection of the environment and human health: the legislation places these two aspects on the same level and in a correlated manner.
- Technical–economic feasibility: an aspect subordinate to the previous two.

At the level of environmental parameters, a greater weight was given to the "% SWC" parameter compared with the "CFP", as SWC is the first binding legal objective for managing entities.

4. Results

The assessment has been carried out by implementing it in the software SuperDecisions V3.2. Figure 2 reports the judgment matrixes for the goal and each criterion and sub-criterion compiled by the expert panel with the respective CRs, while the calculated relative and absolute weight of each criterion and sub-criterion are reported in Table 3. The first assessment involves the pairwise comparison of criteria with reference to the main goal. The consistency analysis applied to the weights assigned by the experts reported a consistency ratio of 0.09. The comparison matrix is acceptable since the consistency ratio is below the threshold of 0.1. Regarding the criteria weights, the environmental one appears to be the most relevant with a weight of 0.699. The social one ranked second with a weight of 0.237 and the technical one was found to be the least important with a weight of 0.064.

Goal: CR=0.0904

	ENV	TECH	SOC
ENV	1	8	4
TECH	1/8	1	1/5
SOC	1/4	5	1

Environmental criteria: CR =0

	%SWC	CFP
%SWC	1	8
CFP	1/8	1

Technical criteria: CR=0.03548

	UoS	RB	DB
UoS	1	8	1/2
RB	1/8	1	1/9
DB	2	9	1

Social criteria: CR=0.06852

	UD	NO	EAU
UD	1	9	4
NO	1/9	1	1/5
EAU	1/4	5	1

%SWC sub-criteria: CR=0.06852

	Mixed	Street	DtD
Mix	1	4	5
Street	1/4	1	1/9
DtD	1/5	9	1

CFP sub-criteria: CR=0.06852

	Mixed	Street	DtD
Mix	1	1/4	5
Street	4	1	9
DtD	1/5	1/9	1

UoS sub-criteria: CR=0.05156

	Mixed	Street	DtD
Mix	1	1/6	3
Street	6	1	9
DtD	1/3	1/9	1

RB sub-criteria: CR=0.07069

	Mixed	Street	DtD
Mix	1	1/6	3
Street	6	1	8
DtD	1/3	1/8	1

DB sub-criteria: CR=0.06852

	Mixed	Street	DtD
Mix	1	1/4	5
Street	4	1	9
DtD	1/5	1/9	1

UD sub-criteria: CR=0.06852

	Mixed	Street	DtD
Mix	1	1/5	4
Street	5	1	9
DtD	1/4	1/9	1

NO sub-criteria: CR=0.07348

	Mixed	Street	DtD
Mix	1	1/4	4
Street	4	1	7
DtD	1/4	1/7	1

EAU: CR=0.06852

	Mixed	Street	DtD
Mix	1	1/5	4
Street	5	1	9
DtD	1/4	1/9	1

Figure 2. Judgment matrixes of the goal, with each criterion and sub-criterion (for brevity, the following abbreviations are employed: ENV = environmental, TECH = technical, SOC = social, UoS = usability of service, RB = reusable bins, DB = disposable bins, UD = urban décor, NO = number of operators, DtD = door-to-door).

Regarding the sub-criteria weights, while considering the environmental ones, the percentage of separate collection (%SWC) happens to be the favored one with a relative weight of 0.889 and an absolute one of 0.62, while the CFP is characterized by a relative and absolute weight of 0.111 and 0.077, respectively. Moving to the social sub-criteria, the urban décor ranked first with a relative weight of 0.708 and an absolute one of 0.167. The SO ranked second with a relative weight of 0.231 and an absolute one of 0.054, while the number of operators is the one characterized by a lower relevance with a relative and

absolute weight of 0.06 and 0.014, respectively. When considering the technical criteria instead, the use of disposable containers ranked first with a relative weight of 0.589 and an absolute weight of 0.038, followed by usability with relative and absolute weights of 0.356 and 0.022, respectively. The use of roadside bins, with a relative weight of 0.054 and an absolute weight of 0.003, ranked last.

Table 3. Summary of weight computation.

Criteria	Relative Weight	Sub-Criteria	Relative Weight	Absolute Weight
Environmental	0.699	CFP	0.111	0.077
		%SWC	0.889	0.62
Technical	0.064	Use of roadside bins	0.054	0.003
		Use of disposable bins	0.589	0.038
		Usability of service	0.356	0.022
Social	0.237	Urban décor	0.708	0.167
		Number of operators	0.06	0.014
		Users environmental awareness	0.231	0.0504

Software processing has enabled the determination, from the perspective of the urban hygiene service manager (particularly in terms of waste separation collection), of the scenario with the best "environmental performance". Analyzing the comparison between scenarios with respect to the individual parameters analyzed, the results identify the following ranking in terms of best environmental performance:

1. Intensive door-to-door collection mode, with an absolute priority of 0.485;
2. Street collection mode, with an absolute priority of 0.318;
3. Mixed street–door-to-door collection mode, with an absolute priority of 0.197.

4.1. Discussion

The scenario related to intensive door-to-door waste separation collection thus proves to be the one with the best environmental performance, primarily considering the excellent results it achieves in terms of the percentage of waste separation collection targets set by regulations. The mixed "street–door-to-door" model, on the other hand, compared with the set of parameters and their "weight" attributed in the analysis, proves to be the one with the worst environmental performance, failing to appreciably enhance the positive aspects characterizing the two "pure" models from which it derives.

The street model, characterized by high mechanization and thus by an intensive optimization of waste collection and transportation processes pays in terms of the actual yield of waste separation collection, which achieves unsatisfactory results.

The aspect to which the greatest weight was deliberately given, is the waste separation collection efficiency; from this point of view, the "intensive door-to-door" model proved to be the only one that can achieve the results required by regulations.

The CFP parameter, considering the greater mileage required for the other systems, if evaluated alone in absolute terms, would favor a choice towards the pure street system; however, it would not be correct to attribute excessive weight to this overall evaluation of environmental performance, considering aspects that are purely related to technical design even before regulatory considerations (such as compliance with the minimum percentage target for waste separation collection).

While the scenario related to street collection, characterized by high mechanization through high-capacity and productivity trucks, has already reached its near-maximum optimization, the door-to-door system can significantly mitigate its CFP already in the short term.

In the pure street system, almost exclusively high-tonnage trucks are used with diesel fuel as the only alternative power source that makes their intensive use possible. Technological research has not yet provided solutions for a rapid transition to alternative engines (especially electric, but also hydrogen and biomethane) for these heavy vehicles, so it is unlikely that we will see the end of diesel engines before 2040 [32]; considering this time frame, it is therefore foreseeable that large-scale alternative solutions will not be available soon.

On the contrary, in the door-to-door system, thanks to the extensive use of lower tonnage vehicles, many valid alternatives to diesel/gasoline fuel, such as electric, biomethane, or hydrogen engines, are already available on the market, which would significantly reduce the impacts in terms of CFP.

Another aspect that was given significant weight in the comparative analysis is the sensitization of users on environmental issues, in which the intensive door-to-door system shows the best performance. The implementation of an intensive door-to-door waste separation system, unlike the other two systems that allow greater freedom to the user, is characterized by high interaction and a close relationship between the service manager and the user. The advantage for the service manager is to create a collaborative relationship that makes the user an active part of the service's organizational process, thus investing in strengthening a potential weak link in the chain, which would nullify the efforts made in other seemingly more profitable areas in terms of direct investments, such as strengthening company staff and equipment.

Correctly separating one's waste according to the most homogeneous possible material fractions allows for the maximum recoverability of materials from waste, avoiding the use of raw materials, with all the benefits in terms of reduced environmental impacts that this entails.

A sensitized user will also adopt environmentally correct behaviors beyond the specific scope of waste separation collection, for example through the following:

- Reducing episodes of poor waste disposal (e.g., littering);
- Reducing food waste;
- Reducing resource and energy waste;
- Making more conscious purchases, preferring products and companies that are more respectful of the environment, for example, the Ecolabel, which distinguishes products and services that, while guaranteeing high performance standards, are characterized by a reduced environmental impact throughout their life cycle [33];
- Paying greater attention to the use and proper maintenance of public spaces and areas;
- Participating in active citizenship actions for environmental protection (e.g., ecological days).

In the analysis of the results, it should be considered that the software in the final reporting phase "weighs" each of the input parameters according to the real importance they hold for the "decision-maker" in determining the best "environmental performance".

The various "weights" were assigned based on the "evaluation rules" set for this work, namely those identified from the perspective of the service manager who must make evaluations according to their objectives and action perimeters.

Therefore, due considerations regarding more "indirect" issues such as the perception and usability of the service by users must always be weighed and then evaluated, for example, also taking into account the techno–economic resources actually available to the manager. It should not be forgotten that the latter must also comply with stringent economic–financial planning and reporting criteria by law.

Finally, it is important to emphasize how "environmental performance", evaluated according to the AHP method, lends itself to being a particularly flexible tool even for

analyses conducted from the perspective of other actors in waste management, besides the urban hygiene service manager.

A practical example could be a stakeholder interested in maximizing employment impact in the territory and therefore interested in giving greater "weight" in the evaluation of environmental performance to the parameter "number of operators employed". This would lead to different analysis results than those conducted from the perspective of the service manager.

Indeed, assuming a social context characterized by limited access to the labor market for certain segments of the population, employing a greater number of workers (at the expense of intensive mechanization) would be an added value that would create greater employment opportunities, especially for those segments of the population with greater difficulty in entering the workforce. These stakeholders could be Social Cooperatives, entities that operate for the inclusion of socially disadvantaged individuals [34] and to which some public entities/administrations reserve quotas in public tenders [35].

4.2. Sensitivity Analysis

A sensitivity analysis is also performed in SuperDecisions V3.2 in order to determine the impacts of varying the criteria weights on the preferred alternative. Concerning this, the different alternative ranking variations deriving from the modifications of the specific weight of each criterion have been identified. As reported previously, with the current set of weights determined by the interviewed operators, the door-to-door mode represents the preferred collection strategy, followed by street collection, with the mixed strategy as the last. Considering the weight of the environmental criteria, an equivalence between the door-to-door and the street collection strategies can be found for a value of 0.56, with higher values leading to a preference for the door-to-door strategy and a lower value prioritizing the street collection. The mixed strategy is never the preferred one; however it represents the second choice for a weight value below 0.22 and above 0.89. Moving to the social criteria, the equivalence point between the door-to-door and street collection strategy happens at a value of 0.38, with higher values leading to a preference for the street strategy and a lower value prioritizing the door-to-door collection. Also in this case, the mixed strategy is never the preferred one; however it represents the second choice for a weight value below 0.02 and above 0.76. Concerning the technical criteria for weight values above 0.25 the street collection strategy is the preferred one, while the door-to-door strategy is the prioritized one for values below 0.25. Similarly to the previous cases the mixed strategy is never the preferred one; however it represents the second choice for a weight value above 0.7. This analysis confirms the previous results regarding the mixed strategy showing to fail to appreciably enhance the positive aspects characterizing the two "pure" models from which it derives.

5. Conclusions

In this study an AHP model has been developed with the aim of evaluating the impact of urban waste separate collection, analyzing three scenarios based on different collection models, separate collection in street-only mode, separate collection in mixed street/door-to-door mode, separate collection in enhanced door-to-door mode, with the objective of evaluating which model is the most "performant", while simultaneously identifying possible corrective/integrative actions to enhance its peculiarities and minimize its criticalities.

A set of parameters has been identified that allows urban hygiene service managers to evaluate the "environmental performance" using data already available within the company.

The main findings of the study can be summarized as follows:

- The analysis allowed us to identify the strength and weaknesses of each waste collection method. Considering these, the following improvement actions can be hypothesized for the scenario "Enhanced separate collection only door-to-door":
    - CFP reduction:
        - Implement alternative fuels like electric vehicles, hydrogen, or biomethane;
        - The optimization of collection paths thanks also to the implementation of satellite systems;
        - Incentivize, while preserving a "door-to-door" service, the creation of "converging" points (e.g., even for small residential buildings) in order to reduce the number of collection points and vehicle start and stop operations.
    - Improving service usability for users:
        - Create "itinerant" delivery points to allow users with issues related to the "door-to-door" strategy to deliver waste without waiting for the specific collection day;
        - Promote ad hoc days ("ecological days") during which users can deliver various waste fractions, such as bulky and hazardous waste.
- The developed model is a support tool based on environmental performance for urban hygiene services which are often strongly constrained by economic and financial aspects.

In this study, the life cycle emission and complete economic analysis of the different strategies have not been considered. Nevertheless, taking into consideration these metrics could allow for more informed decision-making. Future work should incorporate an LCA to quantify cradle-to-grave environmental impacts and integrate complete economic costs. Additional directions include expanding ecological performance parameters and examining worker safety and treatment plant efficiency to support more robust decision-making.

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Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytic Hierarchy Process
AIJ	Aggregation of individual judgments
CFP	Carbon footprint
CI	Consistency index
CR	Consistency ratio
DB	Disposable bins
DtD	Door-to-door

EAU	Environmental awareness of users
ENV	Environmental
KPI	Key performance indicator
LCA	Life cycle assessment
MSW	Municipal solid waste
NO	Number of operators
RB	Reusable bins
RI	Random index
SOC	Social
SWC	Separate waste collection
UD	Urban decor
UoS	Usability of service
TECH	Technical
WEEE	Waste electrical and electronic equipment

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