Municipal Solid Waste Management in Pachuca De Soto, Hidalgo, Through Reverse Logistics and a Greedy-Variant Heuristic Algorithm

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ABSTRACT

The municipality of Pachuca de Soto, Hidalgo, is the largest generator of municipal solid waste (MSW) in the state and recycles barely 10% of what it collects. One cause of this material leakage is that waste generators do not know which recycler to take their waste to, by which means of transport, or with what economic benefit. The objective of this work was to design and evaluate a greedy heuristic algorithm that, based on the zone of origin, the type of material, and its weight, selects the recycler and the means of transport with the highest net profit within the reverse logistics network of the Pachuca metropolitan area. The eDSR methodology was followed for the design of the artifact and PRISMA for the review of 29 studies. The algorithm was programmed in Python with 40 zones of origin, 31 georeferenced recyclers, seven materials, and four means of transport; a pilot test made it possible to correct five failures, and it was evaluated with eight indicators with previously defined thresholds, applied to 1,120 simulated requests. 93.7% of the recommendations were profitable, a profitable destination was found for 99.5% of the simulated material, and the algorithm never obtained a lower profit than the decision to go to the nearest recycler; it improved on it in 49.6 % of the cases. The indicators were not met for glass in small loads, for public transport in the cost/income ratio, or for trips on foot in travel time. In addition, the pure-profit criterion recommends long trips for minimal differences, so an adjustment with the value of time was proposed, which reduced the mean travel time by 32.0% with a profit loss of less than 0.1%. A sensitivity analysis showed that the share of profitable requests stays above its threshold with price changes of ±20 % and with the 2026 combi fare, the only affected segment being small loads of scrap metal, whereas road circuity mainly lengthens walking trips. Compared with an exhaustive enumeration of transport modes, the greedy rule reached the optimum in 8 of 12 scenarios; the largest gaps appeared in 500 kg loads, which could be moved more cheaply in several car trips. Since all results come from simulation, they describe a recovery potential that still has to be validated with real generators.

Keywords: municipal solid waste, reverse logistics, greedy algorithm, recycling, Pachuca de Soto

INTRODUCTION

The generation of municipal solid waste is one of the main environmental and logistical problems faced by contemporary cities, and worldwide, MSW is projected to grow from 2.1 billion tonnes in 2023 to 3.8 billion in 2050, according to UNEP in 2024. In 2020 only about 19% of this waste was recycled, while 38% was mismanaged in open dumps or through burning (UNEP, 2024).

That same year, the direct cost of its management was about 252 billion dollars, a figure that rises to 361 billion if indirect costs related to pollution, health, and climate change are added, and that could reach 640.3 billion by 2050 if urgent measures are not taken (UNEP, 2024). This trend is driven by consumption, economic growth, urbanization, and population growth (Ceballos Pérez et al. 2022).

The consequences of poor management are concrete: soil, water and air are contaminated through leachates containing heavy metals, organic matter, pathogens and gases such as methane, encouraging pests, foul odors

and the transmission of diseases (Ceballos Pérez et al., 2022). For this reason, waste management cannot be limited to collection and confinement.

According to the UNEP report itself, a scenario that decouples waste generation from economic growth and recovers materials would yield a net benefit of 108.5 billion dollars per year (UNEP, 2024). This shows the need to recover materials that still have value and reincorporate them into production processes (Kaza et al., 2018).

In Mexico, Semarnat's Basic Diagnosis for the Integral Management of Waste estimated a generation of 0.944 kg per inhabitant per day and 120,128 tonnes of MSW per day in the country (Semarnat, 2020). Of that total, 31.56 % corresponds to waste suitable for recovery, 46.42 % to organic waste and 22.03 % to other waste; 100,751 tonnes are collected per day (Semarnat, 2020). However, INECC reported that only 9.6 % of waste was recovered through recycling, a low figure compared to other OECD countries (INECC, 2012, cited in Ceballos Pérez et al., 2022). This shows that a significant fraction of recyclable material is not recovered.

At the regional scale, the municipality of Pachuca de Soto, capital of Hidalgo, reproduces and aggravates this problem. It is the most populous municipality in the state, with 314,331 inhabitants, and generates the largest amount of municipal solid waste in Hidalgo, with 1.4 kg per capita per day, above the national average (Ceballos Pérez et al., 2022; INEGI, 2020), which places it first in MSW production among the 84 municipalities of Hidalgo (Mejía-Pucheta et al., 2023).

Its collection service has been under concession since 2012 and there is no source separation in households; the separation of materials (PET, cardboard, aluminum, glass and paper) is carried out by transfer centers and waste pickers, and the rest is sent to the El Huixmi sanitary landfill, which receives about 380 tonnes per day (Ceballos Pérez et al., 2022). It is estimated that barely 10 % of what is collected is recycled and that 90 % is landfilled due to a lack of recovery projects (Ceballos Pérez et al., 2022). The same study also reports a favorable citizen disposition: 59.6 % of 110 respondents stated that they separate their waste even without being required to (Ceballos Pérez et al., 2022).

Given this situation, reverse logistics offers an alternative, since it involves moving materials from the user to recovery points to promote their reuse, recycling or treatment. Rogers and Tibben-Lembke (1999) define it as the flow of materials from the point of consumption back to the point of origin, with the purpose of recapturing their value or ensuring their proper disposal. For containers, packaging and other post-consumer waste, this flow includes collection, sorting, recycling and treatment, which reduces the impact of final disposal and returns part of the value of the materials to production.

However, for recyclable materials to effectively reach the reverse logistics network, the generator must decide where to take them. In the Pachuca metropolitan area there are various recyclers that accept different materials, pay different prices per kilogram and are located at different distances from each neighborhood, which changes the cost and travel time depending on the means of transport available.

To choose the best option, these variables must be compared simultaneously, so a tool that automates the decision is useful. Heuristic algorithms provide a practical way to solve this type of problem in very short computation times; among them, greedy algorithms choose at each step the locally most convenient option, which makes them simple, fast and easy to replicate (Cormen et al., 2022).

Despite the above, the literature on Pachuca has focused on diagnosing MSW management and its recovery potential (Ceballos Pérez et al., 2022; Mejía-Pucheta et al., 2023), without addressing the design of algorithmic tools that guide generators on which recycler to take their recyclable MSW to, by which means of transport and with what economic benefit, in order to facilitate its reincorporation into the reverse logistics network.

Therefore, the general objective of this work is to design a greedy heuristic algorithm that, based on the generator's location, the type of material and its weight, selects the recycler and the means of transport that offer the highest net profit in order to promote the reincorporation of recyclable MSW into the reverse logistics

network of the metropolitan area of Pachuca de Soto, Hidalgo, and reduce its final disposal in sanitary landfills.

The specific objectives are: (1) to diagnose the current flow of MSW generation, collection and disposal and identify the leakage points of recyclable material; (2) to identify and georeference the recyclers in the area, the materials they accept and the price they pay per kilogram; (3) to model the reverse logistics network between the generation zones and the recyclers, considering distance, means of transport, cost and travel time; and (4) to develop and evaluate the greedy heuristic algorithm through usage scenarios.

The work follows the eDSR methodology (Tuunanen et al., 2024) for the design of the artifact and the PRISMA methodology (Page et al., 2021) for the literature review; its contribution is a replicable algorithmic model for the management of recyclable MSW in cities. The artifact is evaluated in a simulated setting with 1,120 requests, complemented by a sensitivity analysis of the most uncertain inputs and by a comparison with an exhaustive benchmark; validation with real generators is beyond the scope of this stage and is discussed as a requirement for implementation. The article is organized into literature review, theoretical framework, methodology, results and discussion, and conclusions.

LITERATURE REVIEW

As a result of the PRISMA methodology (Page et al., 2021), the synthesis of the 29 articles included in the review is presented: 21 on municipal solid waste (MSW) management and reverse logistics (line A) and 8 on greedy and constructive heuristic algorithms applied to waste collection and recovery (line B). Table 1 summarizes the general characteristics of each study (title, year, place and object of study), and Table 2 brings together the results, the tools used, and the limitations reported.

No.	Article title	Year	Place	What it is about	Citation
1	Municipal solid waste and circular economy in Pachuca, Hidalgo, Mexico	2022	Pachuca, Hidalgo, Mexico	Studies the management, separation, recycling and recovery of MSW in Pachuca and analyzes the possibility of moving towards a circular economy.	Ceballos Pérez et al. (2022)
2	Solid waste management in Mexico: a qualitative analysis of the basic diagnoses	2023	Mexico	Analyzes the evolution of waste management in Mexico through the basic diagnoses and points out institutional and public policy shortcomings.	García-Mondragón et al. (2023)
3	Critical overview of municipal solid waste management in the Guadalajara Metropolitan Area. Progress towards sustainable and inter-municipal management	2024	Guadalajara, Mexico	Examines the MSW management system in Guadalajara, including collection, collection centers, final disposal, recycling, infrastructure and citizen participation.	Rojas Lafarga (2024)
4	Handling and management of municipal solid waste in Mexico City	2025	Mexico City	Analyzes MSW handling in Mexico City from the perspective of the linear and circular economy, considering infrastructure, collection, processing, and regulation.	Vargas Rosas (2025)
5	Assessment of the current state of municipal solid	2025	State of Mexico	Evaluates MSW management in the State of Mexico through	García Valerio &

	waste management in the State of Mexico. Unveiling challenges			indicators of generation, coverage, efficiency, and final disposal.	Adame Martínez (2025)
6	Institutional development in Mexico and municipal solid waste management	2026	Mexico	Analyzes the institutional, territorial, economic, and operational factors that influence MSW management in Mexico.	Orozco Hernández et al. (2026)
7	Environmental management at CUTonalá: The handling and management of solid waste	2025	Tonalá, Jalisco, Mexico	Analyzes solid waste handling and recycling at the Tonalá University Center of the University of Guadalajara, including environmental education and participation.	González Arruti & Díaz Flores (2025)
8	Reverse logistics research of municipal hazardous waste: a literature review	2021	China	Reviews research on reverse logistics applied to municipal hazardous waste, including collection, transport, recovery and disposal	Xin et al. (2021)
9	Reverse logistics models for the collection of plastic waste: A literature review	2021	Chile	Analyzes different reverse logistics models for collecting plastic waste, relating them to reverse supply chains, recycling and the circular economy.	Valenzuela et al. (2021)
10	Study on the effective way to convert waste into resources—game analysis of reverse logistics implementation based on value chain	2022	China	Studies how reverse logistics can convert waste into resources, considering the value chain, government regulation, and the participation of logistics companies.	Zhang & He (2022)
11	Municipal solid waste management in Mexico: a case study from an organizational perspective	2022	Guadalajara, Jalisco, Mexico	Case study of the Integral Waste Management Unit of Guadalajara based on a holistic organizational analysis of its components and performance.	Toledo Cervantes & Quintero Castellanos (2022)
12	Reverse logistics in the management of packaging waste in the context of COVID-19	2021	Sonora, Mexico	Reviews the literature on reverse logistics to analyze how the increase in plastic packaging during the pandemic affected waste management in Mexico, proposing return and reuse practices.	Montes Castillo & Rodríguez López (2021)
13	Solid waste recovery logistics networks in Mexico: a macroscopic analysis using geographic information systems	2023	Metropolitan Area of the Valley of Mexico	Uses GIS to analyze the logistics network for the recovery of recoverable waste in the Metropolitan Area of the Valley of Mexico, integrating concepts of urban logistics, reverse logistics and circular economy.	Gómez Maturano (2023)
14	Recovery of Municipal	2024	Cuernavaca,	Proposes a materials recovery	Arce-García

	Solid Waste: A comprehensive and sustainable approach		Morelos, Mexico	system for the Historic Center of Cuernavaca, Morelos, with economic scenarios that include informal recyclers seeking to generate municipal revenue.	& Torres-Salazar (2024)
15	Solid waste management in León, Guanajuato: signs of circular economy and of the sustainable development goals	2022	León, Guanajuato, Mexico	Qualitative study of the Integral Public Cleaning System of León, which shows initial progress towards a circular economy even though the agency prioritizes its finances over robust recovery projects.	Tagle Zamora & Carrillo González (2022)
16	Social return on investment for managing municipal solid waste in Metepec, Mexico	2020	Metepec, State of Mexico	Evaluates the social return on investment (SROI) of MSW management strategies in Metepec, linking waste recovery with economic and social benefits for the community.	Hochstrasser Castillo et al. (2020)
17	The dignification of waste picking: an analysis of municipal solid waste recycling in the city of Chihuahua	2024	Chihuahua, Mexico	Analyzes, through participatory action research, the role of waste pickers at the Chihuahua sanitary landfill as a key (informal) link in the reverse recycling chain.	Terrazas-Chavira et al. (2024)
18	Flow, classification and recycling potential of municipal solid waste in a locality whose main activity is agriculture	2022	San Pedro Benito Juárez, Mexico	Characterizes the flow and composition of MSW in a Mexican farming community, estimating its recycling potential as a basis for designing recovery chains (reverse logistics) at the local level.	Pérez Magaña & Rodríguez Ruiz (2022)
19	Impact of management and reverse logistics on recycling in a war scenario	2023	Portugal	Analyzes how management and reverse logistics influence recycling in the face of the rising cost of raw materials caused by the war in Europe.	Pereira et al. (2023)
20	Investigation of the factors driving the implementation of reverse logistics for waste reduction in Vietnam	2023	Vietnam	Identifies the factors driving the implementation of reverse logistics to reduce waste in companies from five industries in Vietnam.	Le (2023)
21	Reverse logistics and its relationship with the integral and sustainable management of solid waste in productive sectors	2013	Colombia	Reviews the relationship between reverse logistics and the integral and sustainable management of solid waste in productive sectors, and the models used for its analysis.	Peña Montoya et al. (2013)
22	Nearest greedy for solving the waste collection vehicle routing problem: A case study	2017	Northern Malaysia	Applies the nearest-neighbor greedy constructive heuristic (Nearest Greedy) to design the routes of a company's waste	Mat et al. (2017)

				collection vehicles.	
23	Greedy randomized adaptive search procedure to design waste collection routes in La Palma	2019	La Palma, Canary Islands, Spain	Designs collection routes for recyclable waste (paper, cardboard, containers and cans), giving priority to containers with the highest fill level.	Brito Santana et al. (2019)
24	Design of collection routes using the ant colony optimization algorithm	2019	Milpa Alta, Mexico City	Designs MSW collection routes in the Villa Milpa Alta neighborhood and contrasts them with the intuitive greedy collection of traveling all streets until the truck is full.	Márquez Cortés et al. (2019)
25	Exact and heuristic approaches for multi-objective garbage accumulation points location in real scenarios	2020	Montevideo, Uruguay, and Bahía Blanca, Argentina	Locates garbage accumulation points considering accessibility, investment cost and collection frequency.	Rossit et al. (2020)
26	Iterated greedy with variable neighborhood search for a multiobjective waste collection problem	2020	Not specified (generated and real instances)	Solves a waste collection problem with four objectives: travel cost, balance of route length and route time, and number of routes.	Delgado-Antequera et al. (2020)
27	Waste collection routing problem: A mini-review of recent heuristic approaches and applications	2022	International review	Reviews recent heuristic and metaheuristic approaches to the waste collection routing problem and their applications.	Liang et al. (2022)
28	Waste collection optimisation: A path to a green and sustainable city of Makkah	2023	Mecca, Saudi Arabia	Optimizes the MSW collection routes of Mecca to reduce operating cost and fuel consumption.	Algethami & Alhothali (2023)
29	Application of greedy algorithm and simulated annealing algorithm on the asymmetric capacitated vehicle routing problem model in designing optimal garbage transportation routes	2026	Palembang, Indonesia	Compares a greedy algorithm with simulated annealing to design garbage transport routes in four zones of a district.	Arisha et al. (2026)

Table 1: General characteristics of the articles included in the review

Note. Own elaboration based on the selected articles.

Table 1 shows that the reviewed literature is recent: 25 of the 29 studies (86.2 %) were published between 2020 and 2026. Regarding place, 16 works (55.2 %) were carried out in Mexico, in cities such as Guadalajara, Mexico City, Cuernavaca, León, Metepec and Chihuahua, but only one focuses on Pachuca (Ceballos Pérez et al., 2022).

The line A studies deal mainly with the diagnosis of MSW management, its recovery and reverse logistics. Those of line B are located in Malaysia, Spain, Uruguay, Argentina, Saudi Arabia, Indonesia and Mexico, and address the design of collection routes and the location of containers using heuristic algorithms.

No.	Article title	Results	Tools	Limitations	Citation
1	Municipal solid waste and circular economy in Pachuca, Hidalgo, Mexico	Pachuca has limitations in the separation, use and recovery of MSW; a circular economy would make it possible to reduce what is sent to final disposal.	Analysis of MSW generation and handling, review of waste information and evaluation of material use from a circular economy approach.	The analysis focuses on Pachuca, so its results cannot necessarily be generalized to other municipalities. In addition, there are limitations related to the quality of information on waste separation and use.	Ceballos Pérez et al. (2022)
2	Solid waste management in Mexico: a qualitative analysis of the basic diagnoses	MSW management varies between municipalities, with shortcomings in planning, infrastructure, collection and final disposal; better diagnoses and capacities are required.	Qualitative and documentary analysis of the basic solid waste diagnoses in Mexico, using information provided by different states and municipalities to identify problems and patterns in management.	The information depends on the quality and availability of the diagnoses prepared by the authorities. Differences in the way information is collected and reported make it difficult to carry out homogeneous comparisons between municipalities.	García-Mondragón et al. (2023)
3	Critical overview of municipal solid waste management in the Guadalajara Metropolitan Area. Progress towards sustainable and inter-municipal management	There is a lack of coordination between the municipalities of the metropolitan area; sustainable management requires institutional cooperation and inter-municipal strategies.	Review and analysis of information on MSW management, considering territorial, institutional and inter-municipal aspects to identify problems and opportunities for improvement.	The study is focused mainly on the Guadalajara Metropolitan Area, so its results have a limited territorial scope, and there are difficulties arising from coordination between different municipalities and institutions.	Rojas Lafarga (2024)
4	Handling and management of municipal solid waste in Mexico City	The high volume of waste makes its separation, collection, treatment and disposal difficult; integral management and greater citizen participation are required.	Documentary analysis and review of information related to the generation, collection, handling and disposal of MSW, considering environmental and public management aspects.	The large quantity and diversity of waste generated in Mexico City makes it difficult to establish uniform solutions. In addition, the study depends on available information on management processes and on the particular characteristics of the city.	Vargas Rosas (2025)

5	Assessment of the current state of municipal solid waste management in the State of Mexico. Unveiling challenges	There are challenges in infrastructure, separation, collection and final disposal, as well as institutional problems; the recovery of recyclable materials is proposed.	Evaluation of the MSW management system through a review of information on generation, collection, infrastructure, separation and final disposal.	The size and territorial diversity of the State of Mexico make it difficult to obtain a completely homogeneous view. There are also differences between municipalities in infrastructure, economic resources and institutional capacity.	García Valerio & Adame Martínez (2025)
6	Institutional development in Mexico and municipal solid waste management	Institutional capacity influences the efficiency of MSW management; coordination between levels of government and better public policies are required.	Analysis of the relationship between institutional development and MSW management, using documentary information and elements related to the capacities of the institutions in charge of waste handling.	Management depends on political, administrative and economic factors that can change between municipalities and periods. In addition, strengthening institutions requires resources and coordination between different levels of government.	Orozco Hernández et al. (2026)
7	Environmental management at CUTonalá: The handling and management of solid waste	Environmental culture and the participation of the university community improve waste separation and use.	Diagnosis and analysis of environmental management within an educational institution, considering handling practices, waste separation and the participation of the university community.	The study is carried out in a specific university context, so its results may not represent the behavior of the entire population; in addition, the participation and habits of users may also vary over time.	González Arruti & Díaz Flores (2025)
8	Reverse logistics research of municipal hazardous waste: a literature review	Reverse logistics favors the recovery of municipal waste through organized systems and coordination between government, companies and citizens.	Literature review on reverse logistics applied to municipal hazardous waste, analyzing models and processes of collection, recovery, transport and treatment.	Being a literature review, it depends on previously published studies and on the availability of scientific information.	Xin et al. (2021)
9	Reverse logistics models for the	Reverse logistics models optimize	Bibliographic review of different	The models may be difficult to implement	Valenzuela et al. (2021)

	collection of plastic waste: A literature review	plastic collection routes and points; their success depends on economic and social factors and on incentives.	reverse logistics models for the collection of plastic waste, considering collection, transport, recovery and system optimization strategies.	under real conditions due to economic, technological and social factors. In addition, the characteristics of collection systems vary between cities and countries.	
10	Study on the effective way to convert waste into resources—game analysis of reverse logistics implementation based on value chain	Reverse logistics depends on cooperation in the value chain; incentives favor the transformation of waste into resources.	Game theory analysis applied to the implementation of reverse logistics and to the interaction between the participants of the value chain, considering incentive and cooperation mechanisms.	Theoretical models simplify the behavior of participants and may not fully represent the real decisions of consumers and companies; in addition, the effectiveness of incentives also depends on economic, social and institutional factors.	Zhang & He (2022)
11	Municipal solid waste management in Mexico: a case study from an organizational perspective	The management unit shows low institutionalization: lack of manuals, external budget control, scarce technical expertise and low motivation.	The study used W. Richard Scott's organizational theoretical framework (which analyzes five components: participants, goals, structure, technology and environment), combined with the "Critical Path for the Strategic Analysis of Organizations" (RC-AEO) methodology. It was a mixed-methods case study that used semi-structured interviews and questionnaires.	Being a single case study, its findings are not directly generalizable to other municipal administrations without adaptation to the local context, and it relies heavily on subjective perceptions gathered in interviews, which may introduce bias; the authors themselves point out inconsistencies in the information provided by the organization.	Toledo Cervantes & Quintero Castellanos (2022)
12	Reverse logistics in the management of packaging waste in the context of	The increase in packaging during the pandemic intensified the challenges of reverse logistics; a	Essay based on a literature review on reverse logistics; proposes a conceptual	Being an essay, it lacks primary data or a case study; the authors themselves state that it only lays	Montes Castillo & Rodríguez López (2021)

	COVID-19	framework of enablers and barriers is proposed for Sonora.	framework of enablers and barriers to its adoption.	the theoretical foundations for future descriptive research and case studies.	
13	Solid waste recovery logistics networks in Mexico: a macroscopic analysis using geographic information systems	The informal network for the recovery of recoverable MSW is mapped, which sustains the transition from a linear to a circular economy.	Geospatial analysis with Geographic Information Systems (QGIS software), supported by a statistical perspective, applied to the Metropolitan Area of the Valley of Mexico (ZMVM).	The analysis is "macroscopic" at the network level, not at the level of individual actors, so it does not delve into the socioeconomic dynamics of recyclers or empirical data on exact flows, relying on secondary geospatial sources.	Gómez Maturano (2023)
14	Recovery of Municipal Solid Waste: A comprehensive and sustainable approach	The proposed system is viable and recovers the initial investment in the first year.	Documentary compilation, interviews with local authorities and companies, and waste sampling; simulation of three economic scenarios of material recovery	It is a proposal/simulation and not a real implementation, so its results depend on economic assumptions such as sponsorships, and the scenarios must be validated in practice.	Arce-García & Torres-Salazar (2024)
15	Solid waste management in León, Guanajuato: signs of circular economy and of the sustainable development goals	Per capita generation fell 38 % (2009–2020); a 2.8 MW biogas plant for public lighting stands out.	Qualitative study based on in-depth interviews with actors of the Integral Public Cleaning System (SIAP), complemented with public information and specialized literature.	The authors themselves state that they did not delve into the contribution of waste pickers or informal recyclers and that the operating agency prioritizes its finances over a robust circular economy project.	Tagle Zamora & Carrillo González (2022)
16	Social return on investment for managing municipal solid waste in Metepec, Mexico	Investment in waste management generates a positive social return with economic and community benefits.	Social Return on Investment (SROI) methodology, which translates the social and environmental benefits of MSW management strategies into monetary terms.	SROI depends on assumptions about the monetary valuation of intangibles (social/environmental benefits), which introduces subjectivity into the results and limits their direct comparability with other municipalities.	Hochstrasser Castillo et al. (2020)
17	The dignification of waste picking:	Waste pickers are a key, albeit informal,	Participatory action research with the	Being a qualitative/participato	Terrazas-Chavira et al.

	an analysis of municipal solid waste recycling in the city of Chihuahua	link in recycling; actions are proposed to dignify their work.	waste pickers of the Chihuahua sanitary landfill.	ry study focused on a single site, its findings are not generalizable to other cities without contextual adaptations.	(2024)
18	Flow, classification and recycling potential of municipal solid waste in a locality whose main activity is agriculture	The locality generates 3.46 t/day; 93.93 % could be prevented from reaching the sanitary landfill through separation and recycling.	Quantitative and field-based. Survey of 253 people + waste monitoring for 8 days.	A single locality was studied; part of the waste data came from previous research and the results are conditioned by the characteristics of San Pedro Benito Juárez	Pérez Magaña & Rodríguez Ruiz (2022)
19	Impact of management and reverse logistics on recycling in a war scenario	Reverse logistics recovers materials, reduces waste sent to final disposal and reincorporates raw materials.	Official reports, company data, bibliographic review and analysis of the waste process	It is based on a business/regional case and mainly on secondary information.	Pereira et al. (2023)
20	Investigation of the factors driving the implementation of reverse logistics for waste reduction in Vietnam	The main drivers were economic, competitive and environmental; regulation and reputation had little influence.	Likert questionnaire, SPSS and AMOS, analysis of relationships between variables	Sample limited to five industries in Vietnam and based on managers' perceptions.	Le (2023)
21	Reverse logistics and its relationship with the integral and sustainable management of solid waste in productive sectors	Reverse logistics reincorporates materials into the production cycle with economic and environmental benefits.	Review of articles, projects and works; multicriteria analysis, optimization and simulation identified in the literature	It does not experimentally validate a specific system; application in Colombia was still incipient.	Peña Montoya et al. (2013)
22	Nearest greedy for solving the waste collection vehicle routing problem: A case study	The routes obtained with the greedy heuristic reduced the total distance traveled by 11.07 % compared with the company's current routes.	Nearest Greedy constructive heuristic applied to the waste collection vehicle routing problem (WCVRP) with real data from six areas of up to 103 customers.	Case of a single region; it is compared only against existing routes and not against other algorithms; it reports only distance, without costs or computation times.	Mat et al. (2017)
23	Greedy randomized adaptive search	The procedure improves current planning according to	Eco-efficient vehicle routing model solved with	Partial result of a transfer project; applied to a single	Brito Santana et al. (2019)

	procedure to design waste collection routes in La Palma	eco-efficient metrics and obtains solutions in reduced computation times.	GRASP (randomized greedy construction plus local search) and estimation of container filling with historical data.	island and dependent on the quality of historical filling data.	
24	Design of collection routes using the ant colony optimization algorithm	In 30 runs, the total distance of three trucks ranged between 69.28 and 73.09 km, with a mean of 71.35 km.	Arc routing model (CARP) on an OpenStreetMap graph; ant colony with step-by-step route construction and 2-opt local search.	The routes were not compared with the current ones; a single neighborhood was studied; the parameters were taken from the literature and the cartographic data may be outdated.	Márquez Cortés et al. (2019)
25	Exact and heuristic approaches for multi-objective garbage accumulation points location in real scenarios	The constructive heuristics proved competitive against the exact method for generating solutions with different trade-offs between criteria.	Exact augmented ε-constraint method (AUGMECON2) and a family of constructive heuristics that traverse the nodes ordered by relevance (PageRank).	NP-hard problem with a high computational cost for the exact method; results based on two cities.	Rossit et al. (2020)
26	Iterated greedy with variable neighborhood search for a multiobjective waste collection problem	The algorithm outperformed NSGA-II and SPEA2 in approximating the Pareto front with short computation times.	Iterated greedy algorithm (greedy destruction and reconstruction of the solution) combined with variable neighborhood search (VNS).	It focuses on the routing of the municipal fleet; it does not consider the generator's decision or the sale of recyclable materials.	Delgado-Antequera et al. (2020)
27	Waste collection routing problem: A mini-review of recent heuristic approaches and applications	It identifies ant colony, simulated annealing, genetic algorithms, large neighborhood search and GRASP as the most widely used approaches, and compares their performance in a real case.	Literature review with a performance comparison of heuristics and of approaches based on geographic information systems.	Being a mini-review, its coverage is limited and it depends on published studies.	Liang et al. (2022)
28	Waste collection optimisation: A path to a green and sustainable	The greedy initial solution improved route quality and reduced computation	Mixed-integer programming in Gurobi; time-oriented nearest-	Tested on nine instances from a single city; it does not detail the magnitude	Algethami & Alhothali (2023)

	city of Makkah	time by 55.7 % in the instances tested.	neighbor greedy heuristic for the initial solution and re-optimization with Google OR-Tools.	of the cost improvement.	
29	Application of greedy algorithm and simulated annealing algorithm on the asymmetric capacitated vehicle routing problem model in designing optimal garbage transportation routes	Both algorithms obtained almost identical distances (101.76 km with the greedy and 101.66 km with simulated annealing); the greedy was faster.	Asymmetric capacitated vehicle routing problem (ACVRP) model solved with a greedy algorithm and with simulated annealing.	A single district was studied; it does not report the simulated annealing parameters or the measured computation times.	Arisha et al. (2026)

Table 2: Results, tools and limitations of the articles included in the review

Note. Own elaboration based on the selected articles.

Table 2 shows that line A mainly uses documentary analysis, case studies, interviews, surveys and tools such as geographic information systems, social return on investment or statistical analysis. In contrast, line B uses vehicle routing models solved with greedy heuristics (nearest neighbor, iterated greedy and GRASP) or with metaheuristics such as ant colony and simulated annealing.

As results, greedy algorithms were able to reduce distance by up to 11.07 % compared with existing routes (Mat et al., 2017) and obtained solutions almost similar to those of more complex methods with less computation time (Algethami & Alhothali, 2023; Arisha et al., 2026). The most frequent limitations are the study of a single site and the dependence on secondary information; in addition, in line B the algorithms focus on the routing of the municipal fleet and not on the generator's decision.

The review makes it possible to identify four lines of research. The first groups the diagnoses of MSW management in Mexico, which agree in describing a predominantly linear model, centered on collection and final disposal. The studies in Pachuca (Ceballos Pérez et al., 2022), Guadalajara (Rojas Lafarga, 2024), Mexico City (Vargas Rosas, 2025) and the State of Mexico (García Valerio & Adame Martínez, 2025) observe shortcomings in separation, infrastructure and the use of materials.

Added to this are institutional weaknesses: the low institutionalization of operating agencies (Toledo Cervantes & Quintero Castellanos, 2022), the gap between normative discourse and concrete action (García-Mondragón et al., 2023) and the dependence on the institutional capacity of each municipality (Orozco Hernández et al., 2026).

The second line addresses the recovery and use of waste, since, as local experiences show, there is considerable potential: León reduced its per capita generation by 38 % and uses biogas for public lighting (Tagle Zamora & Carrillo González, 2022); in an agricultural locality, 93.93 % of waste could be prevented from reaching the sanitary landfill (Pérez Magaña & Rodríguez Ruiz, 2022).

In addition, recovery proposals can recoup their investment in the first year (Arce-García & Torres-Salazar, 2024) and generate a positive social return (Hochstrasser Castillo et al., 2020). Likewise, the role of environmental education (González Arruti & Díaz Flores, 2025) and of waste pickers and informal networks,

which today sustain a large part of material recovery in the country, is recognized (Terrazas-Chavira et al., 2024; Gómez Maturano, 2023).

The third line focuses on reverse logistics, since international reviews indicate that it makes it possible to recover municipal waste through organized collection, transport and treatment systems (Xin et al., 2021; Peña Montoya et al., 2013), and that the models applied to plastic collection seek to optimize routes and collection points to increase the material recovered (Valenzuela et al., 2021).

Its implementation depends on cooperation between the actors of the value chain (Zhang & He, 2022) and on mainly economic and environmental drivers (Le, 2023), and it becomes more relevant in crisis contexts, such as the COVID-19 pandemic (Montes Castillo & Rodríguez López, 2021) or war scenarios (Pereira et al., 2023).

The fourth line contains greedy and constructive heuristic algorithms applied to the waste. The nearest-neighbor heuristic was used in Malaysia to reduce the collection distance by 11.07% (Mat et al., 2017). It was also used in Mecca to improve the routes for the initial solution with a reduction in computation time of 55.7% (Algethami & Alhothali, 2023). GRASP and iterated greedy are variants of greedy construction and local search that improve the planning of recyclable collection routes (Brito Santana et al., 2019). In a multi-objective garbage collection problem, an iterative greedy algorithm combined with variable neighborhood search better approximated the Pareto front than NSGA-II and SPEA2 (Delgado-Antequera et al., 2020).

The review by Liang et al. (2022) identified ant colony optimization, simulated annealing, genetic algorithms, wide neighborhood search, and GRASP as the most commonly used approaches. More recently, Arisha et al. (2026) found that a greedy algorithm obtained distances nearly identical to those of simulated annealing in less computation time, and Rossit et al. (2020) used constructive heuristics to locate garbage accumulation points.

In Mexico, Márquez Cortés et al. (2019) implemented ant colony optimization in Milpa Alta, but they did not compare their routes with the existing routes.

The literature analyzed relates to diagnosis, conceptual frameworks, economic evaluation and routing models for the municipal fleet in general. The main limitations are the one study site and secondary information. The works that stress the location of collection points and the organization of collection as determinants of reverse logistics efficiency are (Valenzuela et al., 2021; Xin et al., 2021).

Greedy algorithms are also fast and effective in routing (Mat et al., 2017; Arisha et al., 2026) However, none of the studies reviewed apply these algorithms to the decision of the generator on which recycler to take their recyclable MSW to in a Mexican municipality, and in particular in Pachuca. This difference motivates the design of the greedy heuristic algorithm proposed in this paper.

THEORETICAL FRAMEWORK

The study is based on two complementary theoretical axes: reverse logistics, which describes the physical network through which recyclable waste returns to production processes, and decision-making through greedy heuristics, which provides the mechanism for selecting to which recycler and by which means of transport it is convenient to take each material within that network.

Municipal solid waste (MSW). This is the waste generated in dwellings as a result of discarding the materials used in domestic activities, the products consumed and their containers, wrappings or packaging, as well as waste from other activities with household characteristics (Cámara de Diputados del H. Congreso de la Unión, 2003). In this work, the recyclable fraction (PET, cardboard, aluminum, glass and paper) is a particularly important factor, as it is the one that can be reincorporated into production processes.

Reverse logistics. This is the process of efficiently planning, implementing and controlling the flow of materials and information from the point of consumption to the point of origin, in order to recover their value or ensure their proper disposal (Rogers & Tibben-Lembke, 1999). Fleischmann et al. (1997) point out that its

management involves quantitative problems of network design and distribution planning, including the collection of materials at multiple dispersed points. In this study, the reverse logistics network is made up of the generation zones (neighborhoods of Pachuca and Mineral de la Reforma), the recyclers that buy the materials and the means of transport that connect them.

Recycler selection problem. For each request, defined by a zone of origin, a type of material and a weight in kilograms, the problem consists of choosing, among the recyclers that accept that material, the one that maximizes the generator's net profit; the distance between the origin and each recycler is also considered and is estimated with the Haversine formula, which calculates the distance over the Earth's surface from geographic coordinates (Sinnott, 1984).

With that distance, the round-trip cost (base fare plus cost per kilometer), the travel time (round-trip distance divided by the speed of the means of transport), the gross income (price per kilogram multiplied by the weight) and the net profit (gross income minus transport cost) are calculated. Unlike the classic vehicle routing problem, which plans the routes of a fleet from a central depot (Dantzig & Ramser, 1959), here the decision is made from the generator's side and for a single trip.

Greedy heuristic algorithm. A greedy algorithm builds the solution through a sequence of decisions, choosing at each step the alternative that seems best at that moment (local optimum), without reconsidering previous decisions (Cormen et al., 2022). Its variants include the nearest neighbor, which adds the closest point at each step, and GRASP, which introduces controlled randomness into the greedy construction and complements it with local search (Feo & Resende, 1995).

In this study, the algorithm operates in five steps: (1) it filters the recyclers that accept the material; (2) it calculates the distance to each one; (3) it assigns, through a greedy rule, the simplest means of transport that is feasible by weight and distance: on foot (up to 12 kg and 2.5 km), public transport (up to 25 kg and 10 km), private car (up to 160 kg) or pickup truck (more than 160 kg); (4) it calculates the cost, time, income and net profit of each option; and (5) it sorts the options from highest to lowest net profit and presents the top three with their route link.

Its main advantage is its simplicity and speed of calculation, which makes it easy for any citizen to use without knowledge of optimization; its limitation is that it does not guarantee the global optimum, since it does not combine several materials or several recyclers in the same trip and uses straight-line distances instead of street distances. Road distances in urban networks exceed straight-line distances by a circuity factor that ranges from 1.12 to 2.10 between countries (Ballou et al., 2002) and tends to be higher in short local trips (Merchán et al., 2020).

Optimality and alternative decision approaches. For a single request, the choice of recycler is a small discrete problem. The algorithm evaluates every recycler that accepts the material, so once the means of transport is fixed, the option it returns is the exact maximum of net profit and not an approximation. The greedy simplification lies in the transport rule, which keeps the first feasible means instead of comparing all of them. Two kinds of alternatives are therefore useful for judging the artifact. The first is an exact benchmark that enumerates every combination of recycler, means of transport and number of trips; at this scale it is computationally trivial and shows how much profit the simple rule leaves out. The second is multi-criteria decision making, for example TOPSIS (Hwang & Yoon, 1981), which ranks the options by several attributes at once, such as profit, time and distance. The time-adjusted criterion tested in this study is a simple weighted version of that idea, in which time is converted into money.

Figure 1 integrates these constructs into the conceptual model of the study: based on the generator's input data, the greedy algorithm evaluates the available recyclers and recommends the option with the highest net profit, with the aim of having the recyclable material reincorporated into the reverse logistics network instead of being sent to the sanitary landfill.

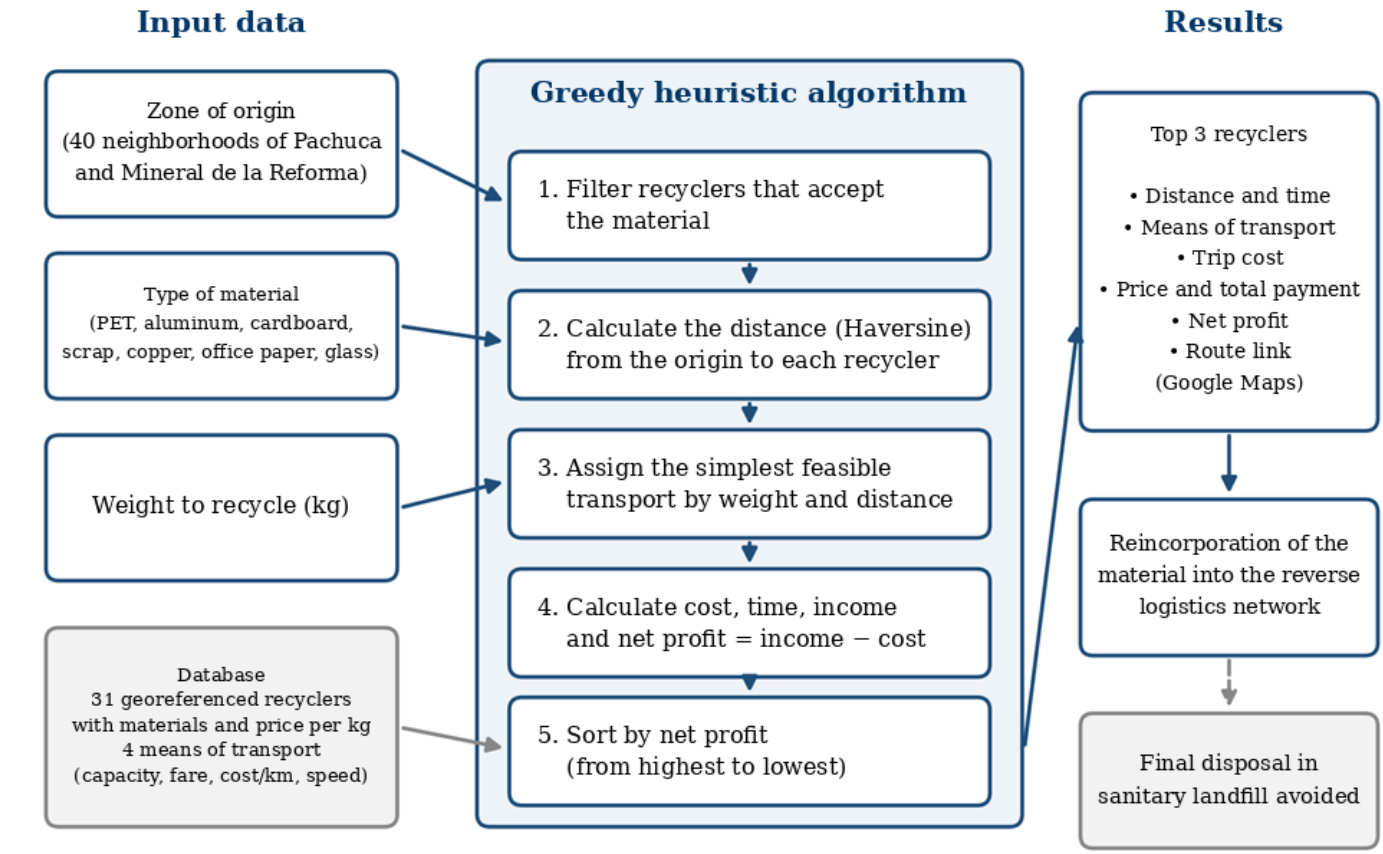


Figure 1: Conceptual model of the greedy heuristic algorithm for the selection of recyclers in the Pachuca reverse logistics network

Note. Own elaboration.

METHODOLOGY

Phase 1. Problem analysis (PRISMA: identification)

In this phase, MSW management and the flow of recyclable materials in the metropolitan area of Pachuca de Soto were diagnosed based on official sources (Semarnat, 2020; INEGI, 2020; UNEP, 2024) and previous studies on the municipality (Ceballos Pérez et al., 2022; Mejía-Pucheta et al., 2023). In parallel, the PRISMA identification stage was carried out in two search lines. Line A was applied in SciELO, Redalyc, DOAJ, ScienceDirect, SpringerLink, MDPI and PubMed Central with the string ("residuos sólidos urbanos" OR "municipal solid waste") AND ("logística inversa" OR "reverse logistics" OR reciclaje OR recycling).

Line B was applied in ScienceDirect, SAGE Journals, MDPI, DOAJ, Redalyc, AIP Publishing and institutional repositories with the string (greedy OR voraz OR "nearest neighbor" OR "vecino más cercano" OR GRASP OR "constructive heuristic") AND ("waste collection" OR "recolección de residuos" OR "reverse logistics" OR "logística inversa").

In both lines, the search was carried out in title, abstract and keywords, and four filters were applied: period 2013–2026, Spanish or English language, peer-reviewed journal or conference articles, and full text available. The period was set to cover the literature of the last decade and some antecedents of reverse logistics in Mexico and Colombia. The strings were applied as written in every database, adapting only the field selector of each search engine to title, abstract and keywords. The number of records retrieved in each line is reported in Table 3 and Figure 2.

Phase 2. Definition of objectives and requirements (PRISMA: screening)

Based on the diagnosis, the general objective and the specific objectives of the study were defined, as well as the requirements of the algorithm: (a) input data: zone of origin, type of material and weight in kilograms; (b) decision criterion: maximize the generator's net profit; (c) constraints: capacity and range of each means of transport; and (d) output data: the top three options with distance, time, means of transport, trip cost, price per kilogram, total payment, net profit and route link.

In the PRISMA screening stage, the titles and abstracts of the identified records were reviewed with a relevance criterion: that the study addressed MSW management, reverse logistics or recycling (line A), or a greedy or constructive heuristic algorithm applied to waste collection or recovery (line B). With this criterion, 43 articles were preselected (30 from line A and 13 from line B) and 3 duplicate records were removed, identified by matching DOI or title.

Phase 3. Design and development (PRISMA: eligibility and inclusion)

The remaining 40 articles were evaluated in full text with four exclusion criteria. Criterion E1 excluded studies outside the focus of the artifact: 4 centered on reverse vending machines and incentive systems, and 1 that uses a swarm metaheuristic without a greedy constructive component. Criterion E2 excluded 2 documents of non-peer-reviewed gray literature (a commercial blog and a social media post).

Criterion E3 excluded 3 studies published before 2013, and criterion E4, 1 study that does not describe the heuristic method used. Thus, 11 articles were excluded and 29 were included in the literature review (Tables 1 and 2): 21 from line A and 8 from line B. Table 3 summarizes the filters, techniques and criteria applied at each stage, and Figure 2 shows the PRISMA flow diagram.

Stage	Filter or criterion	Technique	Result
Identification	Boolean strings of lines A and B; search in title, abstract and keywords; filters: 2013–2026, Spanish or English, peer-reviewed articles, full text	Systematic database search with AND and OR operators	n = [complete] records
Screening	Thematic relevance: MSW, reverse logistics or recycling (A); greedy or constructive heuristic applied to waste (B)	Reading of title and abstract	43 preselected (A = 30; B = 13)
Duplicates	Same DOI or same title	Comparison of records in a control matrix	3 removed
Eligibility	E1 outside the focus; E2 non-peer-reviewed gray literature; E3 outside the period 2013–2026; E4 does not describe the heuristic method	Full-text reading	11 excluded (E1 = 5; E2 = 2; E3 = 3; E4 = 1)
Inclusion	Meet all of the above criteria	Data extraction in a matrix: year, place, object, results, tools and limitations (Tables 1 and 2)	29 included (A = 21; B = 8)

Table 3: Filters, techniques and criteria applied at each stage of the PRISMA review

Note. Own elaboration based on Page et al. (2021). A = MSW and reverse logistics line; B = greedy heuristics line.

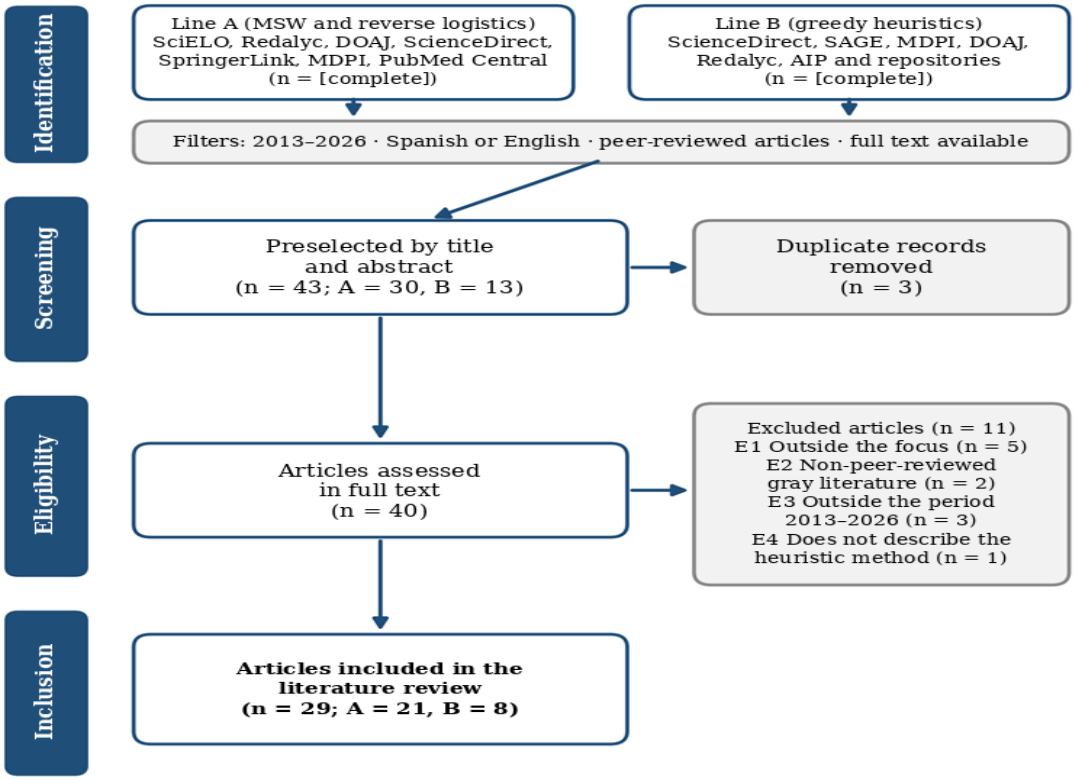


Figure 2: Flow diagram of the systematic review according to PRISMA

Note. Own elaboration

The design of the artifact began with the construction of a database with three components. The first is 40 zones of origin (neighborhoods and housing developments of Pachuca de Soto and Mineral de la Reforma), each represented by its geographic coordinates. The second is 31 recyclers in Pachuca de Soto and Mineral de la Reforma, taken from a directory prepared by the authors using Google Maps (Table 4). Each one was approximately georeferenced at the center of its neighborhood or postal code. Because exact street addresses could not be confirmed for every establishment, this positional error, which is of the order of the size of a neighborhood, is examined together with road circuity in the sensitivity analysis.

Nine establishments keep the price per material recorded in the price survey; the remaining 22 were assigned materials according to their line of business (general, collection center, paper and cardboard, metals, or copper and non-ferrous) and the average price of each material in that survey, as a working assumption. The low dispersion of the recorded prices supports this assumption: for each material, the recorded values differ from the assigned average by between −5.3 % and +6.7 %, with coefficients of variation between 1.6 % and 4.2 % (Table 4). On this basis, a range of ±10 % around the assigned prices was considered plausible, and ±20 % was used as a stress test in the sensitivity analysis. The third is four means of transport, characterized by their load capacity, base fare, cost per kilometer and average speed (Table 5). Seven types of material were considered: PET, aluminum, cardboard and paper, iron or scrap, copper, white office paper and glass.

No.	Recycler	Neighborhood (ZIP)	Line of business	PET	Alum.	Cardboard	Scrap	Copper	Off. p.	Glass	R/A
1	Bodega Recicladora	Loma Bonita (42088)	General	6.30	—	2.40	—	—	3.10	—	R

2	Cartonera Pachuca	Coscotitlán (42092)	Paper and cardboard	—	—	2.25	—	—	3.20	—	A
3	Centro de Acopio (Tepancingo)	Parque de Poblamiento 1a. Secc. (42032)	Collection center	6.65	24.37	2.25	—	—	3.20	—	A
4	Centro de Acopio de Papel y Cartón	San Cayetano el Bordo (42084)	Paper and cardboard	—	—	2.25	—	—	3.20	—	A
5	Centro de Acopio Parque Ecológico Cubitos	Privada La Paz (42094)	Collection center	6.65	24.37	2.25	—	—	3.20	—	A
6	Centro de Reciclaje (Col. Felipe Ángeles)	Felipe Ángeles (42090)	General	6.70	23.50	—	—	—	—	0.90	R
7	Centro de Reciclaje (El Huixmí)	Santa Gertrudis (42111)	General	6.70	23.50	—	—	—	—	0.90	R
8	Centro de Reciclaje (San Antonio)	San Antonio (42111)	General	6.70	23.50	—	—	—	—	0.90	R
9	Compra de Chatarra (Bosques del Peñar)	Adolfo López Mateos (42094)	Metals	—	24.37	—	3.99	132.00	—	—	A
10	Compra Venta de Metales El Minero	Centro (42000)	Metals	—	24.37	—	3.99	132.00	—	—	A
11	Compra y Venta de Desperdicios Industriales "El Saucillo"	El Saucillo (42186)	General	6.65	24.37	2.25	3.99	—	3.20	—	A
12	Compro Cobre-Bronce-Níquel	Geovillas (42185)	Copper and non-ferrous	—	24.37	—	—	132.00	—	—	A
13	CRIH - Centro de Acopio	Arboledas de San Javier (42088)	Collection center	6.65	24.37	2.25	—	—	3.20	—	A
14	Depósito de Reciclaje	El Huixmí (42115)	General	6.65	24.37	2.25	3.99	—	3.20	—	A

	Morales										
15	Desperdicios Industriales El Güero	Ampliación Santa Julia (42080)	General	6.90	24.80	2.25	4.00	131.00	—	—	R
16	El Minero Recicladora	Centro (42000)	Metals	—	25.00	—	4.10	135.00	3.20	—	R
17	Fierro Viejo (El Saucillo)	El Saucillo (42186)	Metals	—	24.37	—	3.99	132.00	—	—	A
18	Grupo Recima	Loma Bonita (42088)	General	6.65	24.37	2.25	3.99	—	3.20	—	A
19	Integración Comercial de Metales y Reciclaje	Álamo (42096)	Metals	—	24.37	—	3.99	132.00	—	—	A
20	Materiales para Reciclar Desperdicios	Santa Julia (42000)	General	6.65	24.37	2.25	3.99	—	3.20	—	A
21	Metales Pachuca	Ampliación Santa Julia (42080)	Metals	—	24.37	—	3.99	132.00	—	—	A
22	MJP Reciclados	11 de Julio 2da. Secc. (42096)	General	6.65	24.37	2.25	3.99	—	3.20	—	A
23	Punto Verde Pachuca	San Bartolo (42039)	Collection center	6.65	24.37	2.25	—	—	3.20	—	A
24	RECICLA-T	El Huixmí (42111)	General	6.65	24.37	2.25	3.99	—	3.20	—	A
25	Recicladora Dos7	San Pedro Nopancalco (42084)	General	6.50	24.00	2.20	3.80	—	—	—	R
26	Recicladora Gabriel Nájera Hernández	Parque de Poblamiento 2a. Secc. (42032)	General	6.80	24.50	2.20	3.90	—	—	—	R
27	Recicladora Percha	Parque Esmeralda (42084)	Metals	6.60	24.20	—	4.00	132.00	—	—	R
28	Recicladora Renova Compra y Venta	Ricardo Flores Magón (42030)	General	6.65	24.37	2.25	3.99	—	3.20	—	A
29	Reciclados de Hidalgo	Bosques del Peñar	Metals	—	24.37	—	3.99	132.00	—	—	A

	(NIVAJOA Metals)	(42094)									
30	RECICLUM	Santa Julia (42080)	General	6.65	24.37	2.25	3.99	—	3.20	—	A
31	Se Compra Chatarra "El Patrón"	El Saucillo (42186)	Metals	—	24.37	—	3.99	132.00	—	—	A

Note. Own elaboration based on the directory of recyclers prepared by the authors from Google Maps. Prices in MXN/kg (Alum. = aluminum; Scrap = scrap metal; Off. p. = white office paper); — indicates that the recycler does not buy the material. R/A: R = price recorded in the original survey; A = average per material assigned as an assumption according to the line of business. Coordinates approximated to the center of the neighborhood (see source code).

Means of transport	**Capacity (kg)**	**Base fare (MXN)**	**Cost per km (MXN)**	**Speed (km/h)**	**Assignment rule**
On foot	12	0.00	0.00	4.5	Weight ≤ 12 kg and distance ≤ 2.5 km
Public transport (Tuzobús / combi)	25	20.00	0.00	18	Weight ≤ 25 kg and distance ≤ 10 km
Private car	160	15.00	3.80	30	Weight ≤ 160 kg
Pickup truck / freight	1,200	180.00	12.50	25	Weight > 160 kg

Table 5: Parameters of the means of transport considered by the algorithm

Note. Own elaboration.

The base fare of public transport corresponds to a round trip on the Tuzobús bus rapid transit system, whose fare remained at 10 MXN per ride in 2025 and 2026 (Criterio Hidalgo, 2025; La Silla Rota, 2026). On 6 May 2026, the fare of combis and conventional colectivos rose to 12 MXN per ride in Pachuca and 25 other municipalities of Hidalgo (El Universal, 2026; La Silla Rota, 2026), so a round trip by combi now costs 24 MXN; this value was tested as an alternative scenario. The base fares and costs per kilometer of the private car and the pickup truck are working assumptions of the authors. Since their variable cost is proportional to distance, the circuity scenarios of the sensitivity analysis are equivalent to increasing that cost by 20 % to 100 %.

The algorithm was programmed in Python. For each request, it filters the recyclers that accept the indicated material and calculates the distance between the zone of origin and each recycler with the Haversine formula (Sinnott, 1984), considering an Earth radius of 6,371 km. It then assigns the means of transport with the greedy rule of Table 5, which chooses the simplest means that is feasible by weight and distance.

With this, it calculates the round-trip cost as C = base fare + cost per km × 2d, the time as t = 2d / speed, the gross income as I = price per kg × weight and the net profit as G = I − C. Finally, it sorts the recyclers from highest to lowest net profit and presents the top three options, together with a route link in Google Maps. The interface works through the console by means of numbered menus of zones and materials.

Tools for the algorithm. The development and evaluation of the algorithm were supported by free software tools (Table 6). The Python language (Python Software Foundation, 2024) was chosen for its simple syntax and because it has libraries for data handling, verification of calculations and the preparation of graphs. Appendix A includes a condensed version of the source code.

The calculation functions of the algorithm (Haversine, assignment rule, costs and sorting) use only the Python standard library, so the program runs on any computer with Python without installing additional packages. The other tools were used to record the evaluation data, verify the calculations, run the pilot tests and prepare the results graphs.

Tool	Version	Role in the project
Python	3.13	Programming language of the algorithm and of the evaluation scripts
math (standard library)	3.13	Trigonometric functions of the Haversine formula and calculation of the number of trips
urllib.parse (standard library)	3.13	Construction of the Google Maps route link
time (standard library)	3.13	Measurement of computation time with perf_counter (indicator I7)
pandas	3.0.5	Recording of the 1,120 requests in CSV files and calculation of the indicators (McKinney, 2010)
GeographicLib	2.1	Geodesic distance on the WGS84 ellipsoid to verify the Haversine formula (Karney, 2013)
pytest	9.1.1	Automated execution of the pilot tests (Krekel et al., 2004)
Matplotlib	3.11.2	Preparation of the results graphs (Hunter, 2007)
Google Maps	Web	Visualization of the recommended route from the generated link
Command console	—	User interface through numbered menus of zones and materials

Table 6: Tools used in the development, testing and evaluation of the algorithm

Note. Own elaboration.

Phase 4. Demonstration

Pilot tests. Before the demonstration and evaluation, a technical pilot test of the program was carried out to detect calculation and data handling errors. Twelve test cases were designed (Table 7), some with several inputs, for a total of 21 automated runs with pytest. The cases verify the Haversine formula with a known value (one degree of latitude is equivalent to 111.19 km on a sphere with a radius of 6,371 km), the assignment rule at the weight and distance limits of Table 5, the recycler filter, the order of the options, the manual calculation of a scenario and the route link. Extreme or invalid inputs were also tested: a weight of 1,500 kg, weights of 0 and −5 kg, and a non-existent material and zone.

```
collected 21 items

test_pilot.py::test_PP01_haversine_one_degree_of_latitude PASSED                    [  4%]
test_pilot.py::test_PP02_haversine_same_point PASSED                                [  9%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[12-2.5-On foot] PASSED       [ 14%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[12.01-1.0-Public transport] PASSED [ 19%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[12-2.51-Public transport] PASSED [ 23%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[25-10.0-Public transport] PASSED [ 28%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[25-10.01-Private car] PASSED [ 33%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[160-50.0-Private car] PASSED [ 38%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[160.01-1.0-Pickup truck] PASSED [ 42%]
test_pilot.py::test_PP04_recycler_filter[Glass-1] PASSED                            [ 47%]
test_pilot.py::test_PP04_recycler_filter[Copper-5] PASSED                           [ 52%]
test_pilot.py::test_PP04_recycler_filter[Aluminum-9] PASSED                         [ 57%]
test_pilot.py::test_PP05_descending_order_by_profit PASSED                          [ 61%]
test_pilot.py::test_PP06_calculation_vs_manual_verification PASSED                  [ 66%]
test_pilot.py::test_PP07_route_link PASSED                                          [ 71%]
test_pilot.py::test_PP08_weight_above_maximum_capacity FAILED                       [ 76%]
test_pilot.py::test_PP09_invalid_weight[0] FAILED                                   [ 80%]
test_pilot.py::test_PP09_invalid_weight[-5] FAILED                                  [ 85%]
test_pilot.py::test_PP10_unregistered_material FAILED                               [ 90%]
test_pilot.py::test_PP11_unregistered_zone FAILED                                   [ 95%]
test_pilot.py::test_PP12_batch_response_time PASSED                                 [100%]
```

```
collected 21 items

test_pilot.py::test_PP01_haversine_one_degree_of_latitude PASSED                    [  4%]
test_pilot.py::test_PP02_haversine_same_point PASSED                                [  9%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[12-2.5-On foot] PASSED       [ 14%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[12.01-1.0-Public transport] PASSED [ 19%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[12-2.51-Public transport] PASSED [ 23%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[25-10.0-Public transport] PASSED [ 28%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[25-10.01-Private car] PASSED [ 33%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[160-50.0-Private car] PASSED [ 38%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[160.01-1.0-Pickup truck] PASSED [ 42%]
test_pilot.py::test_PP04_recycler_filter[Glass-1] PASSED                            [ 47%]
test_pilot.py::test_PP04_recycler_filter[Copper-5] PASSED                           [ 52%]
test_pilot.py::test_PP04_recycler_filter[Aluminum-9] PASSED                         [ 57%]
test_pilot.py::test_PP05_descending_order_by_profit PASSED                          [ 61%]
test_pilot.py::test_PP06_calculation_vs_manual_verification PASSED                  [ 66%]
test_pilot.py::test_PP07_route_link PASSED                                          [ 71%]
test_pilot.py::test_PP08_weight_above_maximum_capacity PASSED                       [ 76%]
test_pilot.py::test_PP09_invalid_weight[0] PASSED                                   [ 80%]
test_pilot.py::test_PP09_invalid_weight[-5] PASSED                                  [ 85%]
test_pilot.py::test_PP10_unregistered_material PASSED                               [ 90%]
test_pilot.py::test_PP11_unregistered_zone PASSED                                   [ 95%]
test_pilot.py::test_PP12_batch_response_time PASSED                                 [100%]
```

ID	Test case	Input	Expected result	v1.0	v1.1
PP-01	Haversine with a known value	1° of latitude	111.19 km ± 0.01	Passed	Passed
PP-02	Haversine with the same point	Origin = destination	0 km	Passed	Passed
PP-03	Assignment rule at the limits	7 inputs: 12 kg and 2.5 km; 12.01 kg; 2.51 km; 25 kg and 10 km; 10.01 km; 160 kg; 160.01 kg	Correct means at each limit	7/7	7/7
PP-04	Recycler filter	Glass, copper and aluminum	3, 11 and 28 options	3/3	3/3
PP-05	Order of the options	PET, 100 kg, Pachuquilla	G from highest to lowest	Passed	Passed
PP-06	Calculation vs. manual verification	Aluminum, 100 kg, Centro Histórico	C = 19.30; I = 2,500.00; G = 2,480.70	Passed	Passed
PP-07	Route link	PET, 5 kg, Centro Histórico	Google Maps URL with coordinates	Passed	Passed
PP-08	Weight greater than maximum capacity	Scrap, 1,500 kg	Profitable option in several trips	Failure: runtime error	Passed (2 trips)
PP-09	Invalid weight	0 kg and −5 kg	Rejection with message	0/2: accepts the input	2/2
PP-10	Unregistered material	Styrofoam	Rejection with message	Failure: empty list without warning	Passed
PP-11	Unregistered zone	Non-existent neighborhood	Rejection with message	Failure: technical error	Passed
PP-12	Batch response time	1,120 requests	Less than 1 s	Passed	Passed
Total		**21 runs**		**16/21 (76.2 %)**	**21/21 (100 %)**

Table 7: Pilot test cases and results in versions 1.0 and 1.1 of the algorithm

Note. Own elaboration with pytest output. Cases with several inputs are reported as passed runs over total runs.

In the initial version (1.0), 16 of the 21 runs were correct (76.2 %). The five failures revealed that the program stopped with an error when the weight exceeded the capacity of the pickup truck (1,200 kg), accepted zero or negative weights, returned an empty list without warning for an unregistered material and displayed a technical error for a non-existent zone.

Based on these findings, version 1.1 was generated, which validates the inputs with clear messages and divides loads greater than 1,200 kg into several pickup truck trips, multiplying the cost and time by the number of trips. Version 1.1 passed all 21 runs (100 %) and was used in the demonstration and evaluation; since the requests evaluated do not exceed 500 kg, the corrections do not modify the results of the following phases. The complete pytest output of both versions is presented in Appendix B, and a condensed version of the source code of version 1.1 in Appendix A.

Demonstration scenarios

To demonstrate the operation of the artifact, the algorithm was run in 12 usage scenarios (Table 9) that combine three representative zones of origin, Centro Histórico (center), Felipe Ángeles (north) and Villas de Pachuca (south); three materials of high, medium and low value (aluminum, PET and cardboard), and four weight levels (5, 20, 100 and 500 kg), chosen to activate each of the means of transport of Table 5.

The console output of each run was kept as evidence (Figure 3). In each scenario, the calculations were verified manually; for example, for 100 kg of aluminum from the Centro Histórico, the recommended recycler (El Minero Recicladora) is located at d = 0.566 km, so $C = 15.00 + 3.80 \times 2 \times 0.566 = 19.30$ MXN, $I = 25.00 \times 100 = 2{,}500.00$ MXN and $G = 2{,}500.00 - 19.30 = 2{,}480.70$ MXN, values identical to those reported by the algorithm.

Phase 5. Evaluation

The performance evaluation was designed as a system of eight parameters, each with an indicator, its formula, unit, measurement condition and acceptance threshold, explicitly linked to the general objective and to specific objectives 3 and 4 (Table 8). The parameters respond to the problem identified: if the generator does not obtain an economic benefit (P1), if the trip consumes a significant part of the income (P3) or of the available time (P4), or if the recommendation is not feasible with the assigned means of transport (P5), the recyclable material does not reach the reverse logistics network and ends up in the sanitary landfill (P8). The thresholds were set as design criteria before running the tests, so that the evaluation would not be adjusted to the results.

Parameter	Indicator and formula	Unit	Measurement condition	Acceptance threshold	Linked objective
P1. Economic benefit	I1. Profitable requests = $n(G > 0) / N \times 100$	%	N = 1,120 requests; G = I − C of the recommended option	≥ 80 %	GO, SO4
P2. Decision quality	I2. $\Delta G = G - G_{ref.}$	MXN, %	Reference: nearest recycler that accepts the material	$\Delta G \geq 0$ in 100 %; $\Delta G > 0$ in ≥ 30 %	SO3, SO4
P3. Trip efficiency	I3. C/I = cost / gross income	Dimensionless	Profitable requests only	C/I ≤ 0.30 in ≥ 80 %	SO3
P4. Time accessibility	I4. $t = 2d / v \times 60$	min	Round trip; speeds from Table 5	t ≤ 60 min in ≥ 90 %	SO3
P5. Operational feasibility	I5. Assignments that respect capacity and range	%	Assignment rules of Table 5	100 %	SO3

P6. Calculation accuracy	I6. |G − G verif.| and relative error of d vs. WGS84 geodesic	MXN, %	Independent recalculation; GeographicLib (Karney, 2013)	≤ 0.01 MXN; ≤ 0.5 %	SO4
P7. Computational performance	I7. Computation time per request	ms	Python 3.13; time.perf_counter	≤ 1,000 ms	SO4
P8. Environmental contribution	I8. kg reincorporated = Σ weight(G > 0) / Σ weight × 100	kg, %	Material with a profitable option is considered diverted from the sanitary landfill	≥ 90 %	GO

Table 8: Parameters, indicators, measurement conditions and evaluation thresholds of the algorithm

Note. Own elaboration. G = net profit; I = gross income; C = round-trip cost; d = distance; v = speed of the means of transport; GO = general objective; SO = specific objective.

Measurement procedure. The parameters were applied through a full factorial design of 40 zones of origin × 7 materials × 4 weight levels (5, 20, 100 and 500 kg), that is, 1,120 requests. For each request, 22 fields were automatically recorded in a CSV file: zone, sector, material, weight, number of recyclers that accept the material, recommended recycler and means, distance, time, cost, income, net profit, reference recycler with its distance, time and profit, ΔG, C/I ratio, distance error, profit error, feasibility and computation time. The reference decision was to take the material to the nearest recycler that accepts it, with the means assigned by the same rule of Table 5.

Accuracy (P6) was verified with an independent implementation that recalculates cost, income and profit, and by comparing the Haversine distance with the geodesic distance on the WGS84 ellipsoid calculated with GeographicLib (Karney, 2013). Computation time (P7) was measured with the perf_counter function of Python 3.13. The material of a request was considered to be reincorporated into the reverse logistics network when its best option has G > 0. The coordinates of the zones and of the 31 recyclers correspond to the approximate center of their neighborhood or postal code [verify in the field or in Google Maps].

RESULTS AND DISCUSSION

Evidence of the application of the parameters

In addition to the pilot tests (Table 7), which verified the calculation, the assignment rule and the handling of invalid inputs, Figure 3 shows two runs recorded in the console. In case (a), 20 kg of aluminum from the Centro Histórico, the algorithm filtered 28 recyclers, assigned public transport and recommended El Minero Recicladora, at 0.57 km, with a net profit of 480.00 MXN, 12.60 MXN more than the nearest recycler.

In case (b), 5 kg of cardboard from Pachuquilla, in Mineral de la Reforma, none of the 18 recyclers that buy cardboard is profitable: the most convenient is 7.30 km away and the public transport fare (20.00 MXN) exceeds the payment for the material (12.00 MXN). In this case, the algorithm advises the user to accumulate more material before transporting it.

(a) Aluminum, 20 kg, Centro Histórico

```
>>> python greedy_recycle.py
Origin: Centro Histórico | Material: Aluminum | Weight: 20 kg
Recyclers that accept the material: 28   (calculation: 0.168 ms)
------------------------------------------------------------------
1. El Minero Recicladora
   Distance: 0.57 km | Means: Public transport | Time r/t: 3.8 min
   Trip cost: $20.00 | Price: $25.00/kg | Payment: $500.00
   NET PROFIT: $480.00
2. Desperdicios Industriales El Güero
   Distance: 3.51 km | Means: Public transport | Time r/t: 23.4 min
   Trip cost: $20.00 | Price: $24.80/kg | Payment: $496.00
   NET PROFIT: $476.00
3. Recicladora Gabriel Nájera Hernández
   Distance: 1.98 km | Means: Public transport | Time r/t: 13.2 min
   Trip cost: $20.00 | Price: $24.50/kg | Payment: $490.00
   NET PROFIT: $470.00
------------------------------------------------------------------
Reference (nearest): Compra Venta de Metales El Minero -> G = $467.40
Algorithm benefit: ΔG = $12.60
```

(b) Cardboard, 5 kg, Pachuquilla

```
>>> python greedy_recycle.py
Origin: Pachuquilla | Material: Cardboard | Weight: 5 kg
Recyclers that accept the material: 18   (calculation: 0.108 ms)
------------------------------------------------------------------
1. Bodega Recicladora
   Distance: 7.30 km | Means: Public transport | Time r/t: 48.7 min
   Trip cost: $20.00 | Price: $2.40/kg | Payment: $12.00
   NET PROFIT: $-8.00  (NOT PROFITABLE: accumulate more material)
2. Cartonera Pachuca
   Distance: 7.52 km | Means: Public transport | Time r/t: 50.2 min
   Trip cost: $20.00 | Price: $2.25/kg | Payment: $11.25
   NET PROFIT: $-8.75  (NOT PROFITABLE: accumulate more material)
3. Centro de Acopio (Tepancingo)
   Distance: 8.46 km | Means: Public transport | Time r/t: 56.4 min
   Trip cost: $20.00 | Price: $2.25/kg | Payment: $11.25
   NET PROFIT: $-8.75  (NOT PROFITABLE: accumulate more material)
------------------------------------------------------------------
Reference (nearest): Compra y Venta de Desperdicios Industriales "El
Algorithm benefit: ΔG = $0.75
```

Figure 3: Evidence of the console execution of the algorithm for two test requests

Note. Own elaboration with the output of the greedy_recycle.py program.

Table 9 summarizes the 12 demonstration scenarios. Each weight level activated the expected means of transport: on foot for 5 kg, public transport for 20 kg, car for 100 kg and pickup truck for 500 kg. The algorithm matched or exceeded the reference decision in all 12 scenarios, and the difference grew with weight: from 0.00 to 12.60 MXN in loads of 5 and 20 kg, and from 22.43 to 305.66 MXN in loads of 500 kg. In Felipe Ángeles, the trip on foot with 5 kg of PET to the recommended recycler (2.35 km) requires 62.6 minutes, which anticipates the time problem of this means.

Zone	Material	Weight (kg)	Recommended recycler	Means	d (km)	t (min)	C	G	G ref.	ΔG
Centro Histórico	Aluminum	5	El Minero Recicladora	On foot	0.57	15.1	0.00	125.00	121.85	3.15
Centro Histórico	Aluminum	20	El Minero Recicladora	Public transport	0.57	3.8	20.00	480.00	467.40	12.60
Centro Histórico	Aluminum	100	El Minero Recicladora	Private car	0.57	2.3	19.30	2,480.70	2,420.54	60.16

Centro Histórico	Aluminum	500	El Minero Recicladora	Pickup truck	0.57	2.7	194.14	12,305.86	12,000.20	305.66
Felipe Ángeles	PET	5	Recicladora Gabriel Nájera Hernández	On foot	2.35	62.6	0.00	34.00	33.25	0.75
Felipe Ángeles	PET	20	Desperdicios Industriales El Güero	Public transport	5.64	37.6	20.00	118.00	113.00	5.00
Felipe Ángeles	PET	100	Recicladora Gabriel Nájera Hernández	Private car	2.35	9.4	32.84	647.16	644.79	2.37
Felipe Ángeles	PET	500	Recicladora Gabriel Nájera Hernández	Pickup truck	2.35	11.3	238.69	3,161.31	3,127.86	33.46
Villas de Pachuca	Cardboard	5	Depósito de Reciclaje Morales	On foot	1.37	36.6	0.00	11.25	11.25	0.00
Villas de Pachuca	Cardboard	20	Bodega Recicladora	Public transport	3.48	23.2	20.00	28.00	25.00	3.00
Villas de Pachuca	Cardboard	100	Depósito de Reciclaje Morales	Private car	1.37	5.5	25.44	199.56	199.56	0.00
Villas de Pachuca	Cardboard	500	Bodega Recicladora	Pickup truck	3.48	16.7	266.93	933.07	910.64	22.43

Table 9: Results of the demonstration scenarios

Note. Own elaboration. d = straight-line distance; t = round-trip time; G ref. = net profit at the nearest recycler that accepts the material; $\Delta G = G - G$ ref. Amounts in MXN.

Results of the indicators against the thresholds

Table 10 and Figure 4 compare each indicator with its threshold. At the global level, all eight indicators meet the established criterion. 93.7 % of the 1,120 requests (1,049) obtained a positive net profit, above the 80 % threshold. The median net profit was 269.94 MXN and the mean distance to the recommended recycler was 2.73 km.

The algorithm never produced a lower profit than the reference decision ($\Delta G \geq 0$ in 100 % of cases) and improved on it in 556 requests (49.6 %), with a cumulative additional profit of 83,285.18 MXN, equivalent to 1.95 % more than the reference decision. All 1,120 transport assignments respected the defined capacity and range (I5). The profit of every request was recalculated independently, and the verification found no differences, with a maximum error of 0.00 MXN.

The Haversine distance differed from the WGS84 geodesic by 0.22 % on average and 0.44 % at most, below the 0.5 % threshold. The mean computation time was 0.076 ms per request, far below the 1 s limit, even with 31 recyclers, which confirms the speed attributed to greedy algorithms (Cormen et al., 2022).

Indicator	**Value obtained**	**Threshold**	**Verdict**
I1. Profitable requests	93.7 % (1,049 of 1,120)	≥ 80 %	Met; not met for glass at 5 and 20 kg
I2. Decision quality	$\Delta G \geq 0$ in 100 %; $\Delta G > 0$ in 49.6	$\Delta G \geq 0$ in 100 %;	Met

	% (556); +83,285.18 MXN (+1.95 %)	$\Delta G > 0$ in ≥ 30 %	
I3. C/I ratio	85.0% with C/I ≤ 0.30; median 0.052	≥ 80 %	Met; not met for public transport (66.0 %)
I4. Round-trip travel time	96.7 % ≤ 60 min; median 16.9 min; maximum 66.5 min	≥ 90%	Met; not met on foot (84.5 %)
I5. Feasibility	100% (1,120 of 1,120)	100 %	Met
I6. Accuracy	Error in G: 0.00 MXN; error in d: 0.22 % mean, 0.44 % maximum	≤ 0.01 MXN; ≤ 0.5 %	Met
I7. Computation time	0.076 ms mean; 0.484 ms maximum	≤ 1,000 ms	Met
I8. Reincorporated material	99.5 % (174,045 of 175,000 kg)	≥ 90 %	Met

Table 10: Values obtained for the indicators and verdict against the acceptance threshold

Note. Own elaboration based on the record of 1,120 requests. I8 measures the material that has a profitable destination in the simulation (recovery potential), not material actually delivered to recyclers.

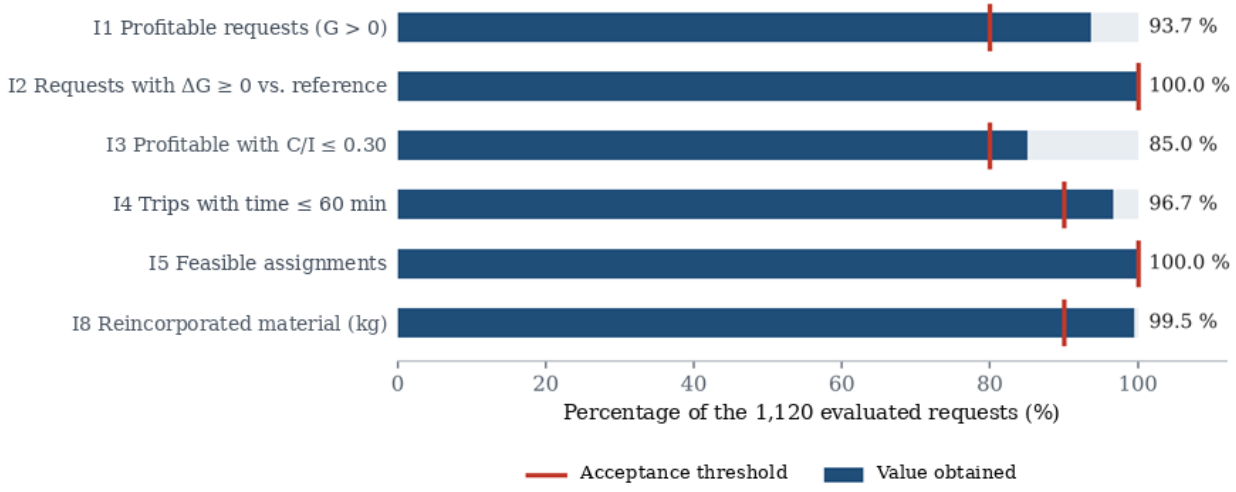


Figure 4: Compliance of the percentage indicators with their acceptance threshold

Note. Own elaboration. Indicators I6 and I7 are expressed in MXN, percentage error and milliseconds, so they are reported in Table 10.

Global compliance is not uniform. When the results are disaggregated by means of transport (Table 11) and by material (Figure 5), three segments appear that do not reach the threshold. The first is glass in small loads: only 37.5 % of the 5 kg requests and none of the 20 kg requests were profitable, because glass is paid at 0.90 MXN/kg and only three recyclers buy it, so the payment does not cover the public transport fare.

The second is public transport in the C/I ratio: only 66.0 % of its profitable trips meet C/I ≤ 0.30, and it is the only means with unprofitable requests (22.1%), because its fixed fare weighs heavily on loads of 5 to 25 kg; all 71 unprofitable requests in the study correspond to this means. The third is trips on foot, of which only 84.5 % are completed in 60 minutes or less, because at 4.5 km/h a round trip of 2.5 km each way requires 66.7 minutes.

Assigned means	Requests	Distance (km)	Time (min)	Cost (MXN)	C/I	Profitable (%)
On foot	239	1.57	41.81	0.00	0.00	100.0
Public transport	321	4.05	26.99	20.00	0.24	77.9
Private car	280	2.32	9.27	32.62	0.06	100.0
Pickup truck	280	2.62	12.56	245.39	0.11	100.0
Total	**1,120**	**2.73**	**22.11**	**75.23**	**0.05**	**93.7**

Table 11: Performance of the recommendations by assigned means of transport

Note. Own elaboration. Mean values per request, except C/I, which is reported as the median.

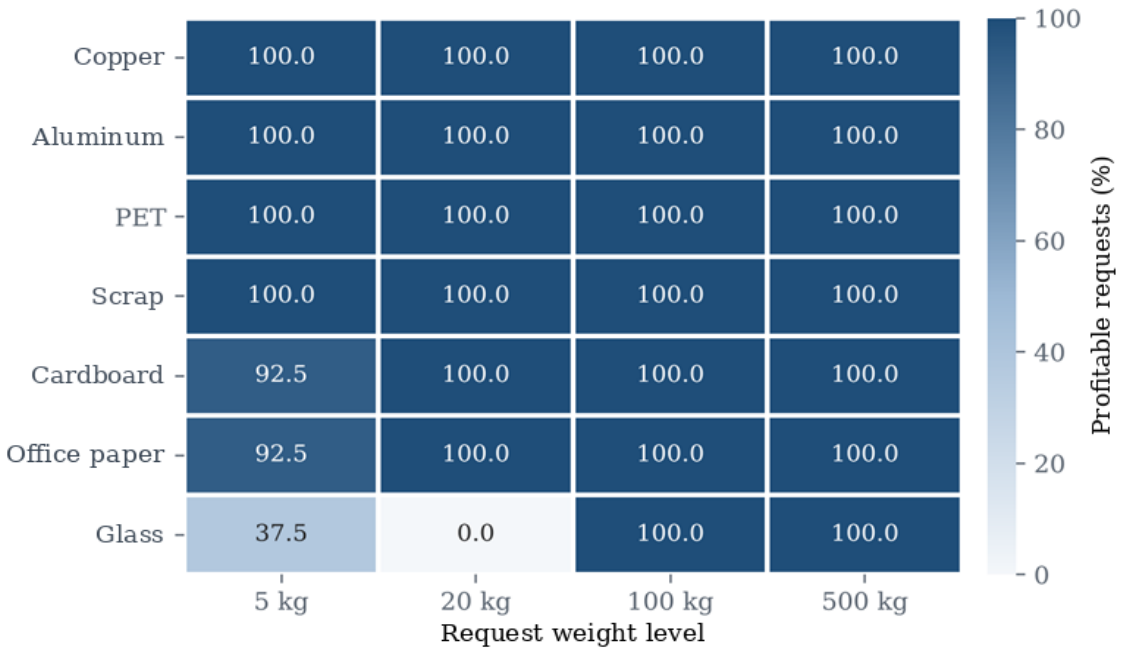


Figure 5: Percentage of profitable requests by material and weight level

Note. Own elaboration based on the record of 1,120 requests.

The break-even weight, that is, the minimum weight for the payment to cover the 20.00 MXN public transport fare at the best available price, explains these results: it is 0.1 kg for copper, 0.8 kg for aluminum, 2.9 kg for PET, 4.9 kg for scrap metal, 6.2 kg for white office paper, 8.3 kg for cardboard and 22.2 kg for glass. In the case of glass, that weight is close to the capacity of public transport (25 kg), which leaves a maximum profit of 2.50 MXN; in practice, glass is only profitable when loads of 100 kg or more are accumulated.

Relationship of the results to the objectives and the problem

The results make it possible to assess the fulfillment of the specific objectives. Regarding objective 2, the database of 31 recyclers covers all seven materials, although unevenly: aluminum has 28 buyers, PET and scrap metal 20, cardboard 18, white office paper 16, and copper 11, while glass has only 3. Regarding objective 3, the network modeled with four means of transport was feasible in 100% of the requests. The algorithm met all eight global indicators for objective 4.

In relation to the problem, in Pachuca about 10 % of what is collected is recycled and 90 % is landfilled (Ceballos Pérez et al., 2022); in the evaluated scenario, the algorithm found a profitable option for 99.5% of

the simulated kilograms (174,045 of 175,000 kg).

This finding is consistent with Le (2023), who identified economic factors as the main driver of reverse logistics, and with Valenzuela et al. (2021) and Xin et al. (2021), who point out that the location of collection points determines the efficiency of collection. The results by sector confirm this: in Mineral de la Reforma, the mean distance to the recommended recycler was 4.32 km, compared with 1.61 km in central Pachuca, and the proportion of profitable requests fell to 90.7 %, compared with 96.1% in the center, which reveals lower coverage of recyclers in that area.

In addition, three establishments (El Minero Recicladora, the Centro de Reciclaje in the Felipe Ángeles neighborhood, and Desperdicios Industriales El Güero) concentrated 56.3% of the recommendations, and two were never recommended. This evidence suggests that price competition directs flows towards a few nodes of the network, in line with the concentrated recovery network described by Gómez Maturano (2023) for the Valley of Mexico.

This result should be read with caution, because 69.5% of the recommendations correspond to the nine establishments with a recorded price, whose prices tend to exceed the average assigned to the rest. Finally, the citizen willingness to separate waste reported in Pachuca (59.6%; Ceballos Pérez et al., 2022) could be leveraged if the tool is accompanied by strategies to accumulate the material up to its break-even weight.

Effect of the decision criterion and proposed adjustment

The evaluation revealed a limitation of the pure net profit criterion. In the 556 requests in which the algorithm departed from the nearest recycler, the median additional profit was only 12.91 MXN in exchange for 11.6 more minutes of round-trip travel, and in 126 of these requests the additional profit was less than 10.00 MXN with more than 15 minutes of additional travel (Figure 6). In 5 kg loads, the median additional profit was 1.00 MXN for 20.6 more minutes of travel. This occurs because the greedy criterion compares only monetary values and does not take into account the generator's time, allowing a minimal price difference to justify a much longer trip.

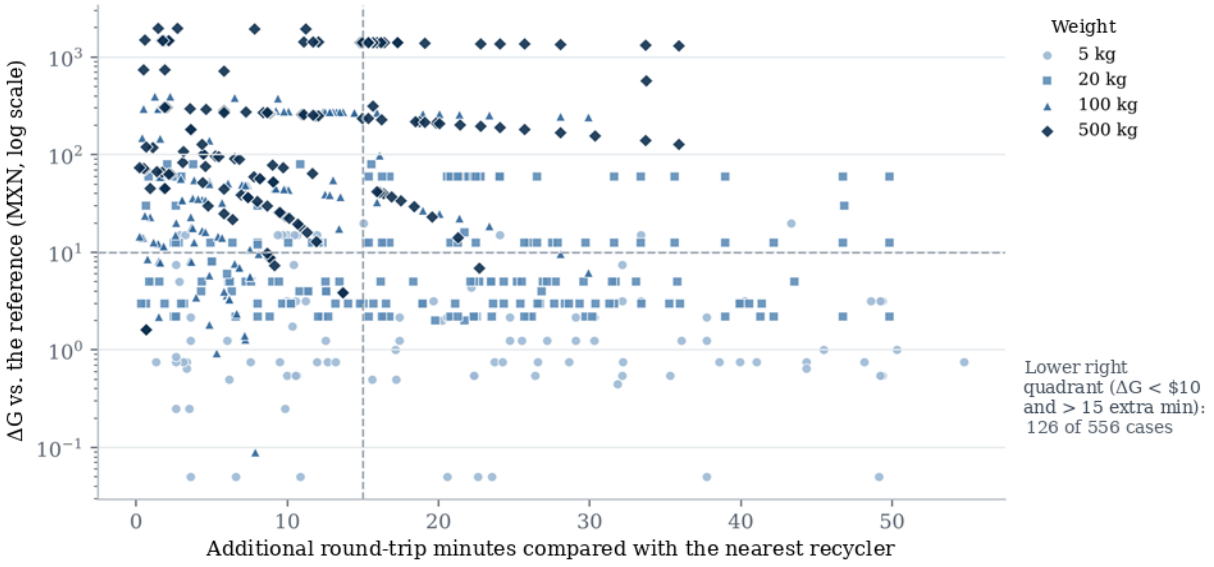


Figure 6: Additional profit versus additional travel time when the algorithm recommends a recycler other than the nearest one

Note. Own elaboration. Each point is one of the 556 requests with $\Delta G > 0$. The dotted lines mark $\Delta G = 10$ MXN and 15 additional minutes.

Based on this result, an adjustment of the decision criterion was tested: sorting the options by the adjusted

profit $G_{aj} = G - v \cdot t$, where v is the value of time, which was estimated as the general minimum wage in force in 2026 (315.04 MXN per day; Comisión Nacional de los Salarios Mínimos [CONASAMI], 2025) divided by a 480-minute workday, that is, 0.656 MXN/min. Table 12 compares both versions across the same 1,120 requests.

The adjustment changed the recommendation in 353 cases (31.5 %), almost all of 5 and 20 kg; it reduced the mean round-trip travel time from 22.1 to 15.0 minutes (−32.0%), with a mean saving of 22.4 minutes per modified recommendation, in exchange for giving up on average 2.79 MXN of profit in those cases, that is, 985.33 MXN in total, less than 0.1% of the total net profit.

Indicator	**v1: net profit (G)**	**v2: adjusted profit (G − v·t)**
Recommendations modified with respect to v1	—	353 (31.5 %)
Mean round-trip travel time (min)	22.1	15.0 (−32.0 %)
Mean time saving per modified recommendation (min)	—	22.4
Profit given up per modified recommendation (MXN)	—	2.79
Total profit given up (MXN)	—	985.33 (< 0.1% of the total)
Changes by weight level (5 / 20 / 100 / 500 kg)	—	173 / 163 / 14 / 3

Table 12: Comparison between the net profit criterion (v1) and the criterion adjusted by the value of time (v2)

Note. Own elaboration. v = 315.04 MXN / 480 min = 0.656 MXN/min.

Sensitivity of the results to prices, fares and road distances

Prices. In the ten demonstration scenarios in which the algorithm departed from the nearest recycler, the switching margin ranged from 0.02 to 0.63 MXN/kg, that is, from 0.35 % to 6.25 % of the price of the recommended recycler (calculated from Table 9). These margins are of the same size as the dispersion of the recorded prices, so the identity of the recommended recycler is sensitive to price errors, especially for PET and cardboard. In the demonstration scenarios, all recommendations that differ from the nearest recycler correspond to establishments with a recorded price, which reduces this risk, but the recommendations that rest on assigned prices should be treated as provisional until those prices are confirmed.

Profitability (I1) is much less sensitive than the choice of recycler. Table 13 shows the break-even weights. For 20 kg loads carried by public transport, every material except glass remains profitable with a price reduction of 20 % and with the combi fare of 24 MXN; the largest break-even weight among those materials is 12.5 kg (cardboard with both changes at once). For 5 kg loads, only scrap metal changes status: its break-even weight rises from 4.9 kg to 5.4 kg with a 10 % price reduction and to 5.9 kg with the combi fare. Even if all 40 requests of 5 kg of scrap metal became unprofitable, I1 would drop from 93.7 % to 90.1 %, still above the 80 % threshold. Glass shows the opposite case: a 20 % price increase would lower its break-even weight to 18.5 kg and make its 20 kg loads profitable.

Material	**Best price (MXN/kg)**	**F=20, −20 %**	**F=20, −10 %**	**F=20, base**	**F=20, +10 %**	**F=20, +20 %**	**F=24, −10 %**	**F=24, base**
Copper	135.00	0.2	0.2	0.1	0.1	0.1	0.2	0.2
Aluminum	25.00	1.0	0.9	0.8	0.7	0.7	1.1	1.0

PET	6.90	3.6	3.2	2.9	2.6	2.4	3.9	3.5
Scrap metal	4.10	6.1	5.4	4.9	4.4	4.1	6.5	5.9
White office paper	3.20	7.8	6.9	6.2	5.7	5.2	8.3	7.5
Cardboard	2.40	10.4	9.3	8.3	7.6	6.9	11.1	10.0
Glass	0.90	27.8	24.7	22.2	20.2	18.5	29.6	26.7

Table 13: Break-even weight (kg) for public transport by material, price change and fare

Note. Own elaboration with the prices of Table 4. F = round-trip public transport fare (MXN): 20 = two Tuzobús rides; 24 = two combi rides at the fare in force since May 2026. Break-even weight = F / (p × (1 + Δp)).

CONCLUSION

A greedy heuristic algorithm was successfully designed, programmed and evaluated that recommends to which recycler to take recyclable MSW, by which means of transport and with what net profit, for the metropolitan area of Pachuca de Soto, based on a directory of 31 recyclers. Evaluated with eight indicators with thresholds defined in advance on 1,120 requests, the algorithm met all the global criteria: 93.7 % of the recommendations were profitable, a profitable destination was found for 99.5 % of the simulated material, 100 % of the assignments were feasible, it never obtained a lower profit than the intuitive decision of going to the nearest recycler, and it responded in fractions of a millisecond.

The pilot test also made it possible to detect and correct five failures in input handling before the evaluation. This fulfills the general objective and specific objective 4, and suggests that information on prices and distances could help reduce the leakage of recyclable material to the sanitary landfill, a hypothesis that still has to be tested with real generators. These figures represent a recovery potential obtained by simulation; they do not yet show that material was diverted from the landfill or that emissions were avoided.

The limitations are that the results come from simulated requests and not from real users, and the pilot test was technical, without the participation of generators; the coordinates of zones and recyclers are approximated to the center of their neighborhood; 22 of the 31 recyclers use an assumed average price; the distance is calculated in a straight line, which underestimates the real street route; prices are static; and the algorithm does not combine several materials or several recyclers in the same trip. In addition, the pure profit criterion does not consider the generator's time. By segment, the algorithm did not meet the thresholds for glass in loads of 5 and 20 kg, for the C/I ratio of public transport and for the time of trips on foot. The sensitivity analysis showed that these simplifications mainly affect the choice of a specific recycler and the duration of walking trips, while the share of profitable requests remains above its threshold with price changes of ±20 % and with the combi fare of 24 MXN. The algorithm was compared with the nearest-recycler rule over all requests, but with the exhaustive enumeration of transport modes only in the demonstration scenarios; a comparison with multi-criteria methods over the full set of requests is still pending.

Areas of opportunity include carrying out a pilot with real generators from different neighborhoods that measures ease of use and whether they follow the recommendation; surveying the real prices of the 22 recyclers without a recorded price; repeating the evaluation with the exact coordinates of each establishment; replacing the Haversine distance with street distances obtained from a routing service; updating prices periodically; incorporating trips with several materials and several stops; expanding the coverage of glass buyers and of recyclers in Mineral de la Reforma; and replacing the simplest-feasible transport rule with an enumeration of the means available to each user, including several car trips for heavy loads, which in the benchmark increased the net profit of 500 kg loads by 0.95 % to 10.85 %.

The contributions to improvement begin with the evaluation of three specific adjustments to the proposal.

First, changing the decision criterion to the profit adjusted by the value of time (v2), which in the tests reduced the mean travel time by 32.0 % with a profit loss of less than 0.1 %. Second, incorporating the break-even weight of each material into the output of the algorithm, so that, when the best option is not profitable, the tool indicates how many kilograms to accumulate before transporting them (for example, 8.3 kg of cardboard or 6.2 kg of white office paper).

Third, for glass, whose individual profitability is almost nil in small loads, proposing neighborhood collection points or grouped collection that make it possible to gather loads of 100 kg or more. These adjustments turn the evaluation results into direct changes to the artifact for the next iteration of the eDSR cycle.

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APPENDIX A

Source Code of the Algorithm (Version 1.1)

A condensed version of the code of the greedy_recycle.py file, written in Python 3.13 and without external dependencies, is presented below. The four means of transport, the Haversine formula, the greedy transport assignment rule, the input validation added after the pilot tests and the sorting of the options by net profit are kept in full; of the databases of 40 zones and 31 recyclers, only a few illustrative records are shown. It is run with the command py greedy_recycle.py.

```
# -*- coding: utf-8 -*-

"""Greedy heuristic: chooses recycler and transport (Pachuca MA). v1.1 condensed.

Approximate coordinates (center of neighborhood or ZIP code); verify in the field or in Google Maps."""

import math, time

EARTH_RADIUS = 6371.0  # km

MATERIALS = ["PET", "Aluminum", "Cardboard", "Scrap", "Copper", "White office paper", "Glass"]

# Zones: name -> (lat, lon). 4 of the 40 in the full file are shown.

ZONES = {"Centro Histórico": (20.1265, -98.7335), "Col. Doctores": (20.1150, -98.7380),

        "Cubitos": (20.1310, -98.7400), "Pachuquilla": (20.0760, -98.6940)}  # ... 36 more

# Recyclers (Table 4): 3 of the 31 are shown. prices in $/kg; source: Recorded | Average

RECYCLERS = [

    {"id": 1, "name": "Bodega Recicladora", "coord": (20.093, -98.7615), "price_source": "Recorded",

     "prices": {"PET": 6.3, "Cardboard": 2.4, "White office paper": 3.1}},

    {"id": 3, "name": "Centro de Acopio (Tepancingo)", "coord": (20.1335, -98.747), "price_source": "Average",

     "prices": {"PET": 6.65, "Aluminum": 24.37, "Cardboard": 2.25, "White office paper": 3.2}},

    {"id": 16, "name": "El Minero Recicladora", "coord": (20.1215, -98.7345), "price_source": "Recorded",

     "prices": {"Aluminum": 25.0, "Scrap": 4.1, "Copper": 135.0, "White office paper": 3.2}},

]  # ... 28 more

# Means of transport (Table 5), from simplest to most complex

TRANSPORTS = [

    {"mode": "On foot", "cap": 12, "dmax": 2.5, "base": 0.00, "km": 0.00, "speed": 4.5},

    {"mode": "Public transport", "cap": 25, "dmax": 10.0, "base": 20.00, "km": 0.00, "speed": 18},

    {"mode": "Private car", "cap": 160, "dmax": math.inf, "base": 15.00, "km": 3.80, "speed": 30},
```

```
    {"mode": "Pickup truck", "cap": 1200, "dmax": math.inf, "base": 180.00, "km": 12.50, "speed": 25},
]
def haversine(p1, p2):
    la1, lo1, la2, lo2 = map(math.radians, (*p1, *p2))
    a = math.sin((la2 - la1) / 2) ** 2 + math.cos(la1) * math.cos(la2) * math.sin((lo2 - lo1) / 2) ** 2
    return 2 * EARTH_RADIUS * math.asin(math.sqrt(a))
def assign_transport(weight, d):
    """Greedy rule: first feasible means by weight and distance. v1.1: if the weight exceeds
    the maximum capacity, the pickup truck is used in several trips."""
    for t in TRANSPORTS:
        if weight <= t["cap"] and d <= t["dmax"]:
            return t, 1
    t = TRANSPORTS[-1]
    return t, math.ceil(weight / t["cap"])
def validate(zone, material, weight):  # v1.1: input validation
    if zone not in ZONES: raise ValueError(f"Unregistered zone: {zone!r}")
    if material not in MATERIALS: raise ValueError(f"Unregistered material: {material!r}")
    if not isinstance(weight, (int, float)) or weight <= 0: raise ValueError("Weight must be greater than 0 kg")
def evaluate(zone, material, weight):
    """Options sorted from highest to lowest net profit."""
    validate(zone, material, weight)
    origin, options = ZONES[zone], []
    for r in RECYCLERS:                          # 1. filter by accepted material
        if material not in r["prices"]:
            continue
        d = haversine(origin, r["coord"])        # 2. distance
        t, trips = assign_transport(weight, d)   # 3. transport (greedy rule)
        cost = trips * (t["base"] + t["km"] * 2 * d)   # 4. cost, time, income, profit
        income = r["prices"][material] * weight
```

```
        options.append({"recycler": r["name"], "id": r["id"], "distance_km": d, "mode": t["mode"],
                        "trips": trips, "cost": cost, "time_min": trips * 2 * d / t["speed"] * 60,
                        "price": r["prices"][material], "income": income, "profit": income - cost})
    return sorted(options, key=lambda o: o["profit"], reverse=True)   # 5. sort
def nearest(ops):  # reference decision
    return min(ops, key=lambda o: o["distance_km"])
def print_top(zone, material, weight, top=3):
    t0 = time.perf_counter(); ops = evaluate(zone, material, weight); ms = (time.perf_counter() - t0) * 1000
    print(f"Origin: {zone} | Material: {material} | Weight: {weight} kg | {len(ops)} options ({ms:.3f} ms)")
    for k, o in enumerate(ops[:top], 1):
        warning = "" if o["profit"] > 0 else " (NOT PROFITABLE: accumulate more material)"
        print(f"{k}. {o['recycler']}: {o['distance_km']:.2f} km, {o['mode']}, {o['time_min']:.1f} min, "
              f"cost ${o['cost']:.2f}, payment ${o['income']:.2f}, NET PROFIT ${o['profit']:.2f}{warning}")
    c = nearest(ops)
    print(f"Reference (nearest): {c['recycler']} -> G = ${c['profit']:.2f}; "
          f"ΔG = ${ops[0]['profit'] - c['profit']:.2f}")
if __name__ == "__main__":
    print_top("Centro Histórico", "Aluminum", 20)
```

APPENDIX B. OUTPUT OF THE PILOT TESTS WITH PYTEST

The tests were run in PowerShell with the command py -m pytest -v test_pilot.py, selecting the version of the algorithm with the VERSION variable. In the output, PASSED indicates a passed test and FAILED a failed test; the characters \xfa and \xf3 correspond to the letters ú and ó, which the terminal displays encoded.

Version 1.0 (initial). Command: $env:VERSION="greedy_recycle_v10"; py -m pytest -v test_pilot.py

```
============================================= test session starts =============================================

collecting ... collected 21 items

test_pilot.py::test_PP01_haversine_one_degree_of_latitude PASSED                    [  4%]

test_pilot.py::test_PP02_haversine_same_point PASSED                                [  9%]

test_pilot.py::test_PP03_assignment_rule_at_boundaries[12-2.5-On foot] PASSED       [ 14%]

test_pilot.py::test_PP03_assignment_rule_at_boundaries[12.01-1.0-Public transport] PASSED [
```

```
19%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[12-2.51-Public transport] PASSED [
23%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[25-10.0-Public transport] PASSED [
28%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[25-10.01-Private car] PASSED [
33%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[160-50.0-Private car] PASSED [
38%]
test_pilot.py::test_PP03_assignment_rule_at_boundaries[160.01-1.0-Pickup truck] PASSED [
42%]
test_pilot.py::test_PP04_recycler_filter[Glass-3] PASSED [ 47%]
test_pilot.py::test_PP04_recycler_filter[Copper-11] PASSED [ 52%]
test_pilot.py::test_PP04_recycler_filter[Aluminum-28] PASSED [ 57%]
test_pilot.py::test_PP05_descending_order_by_profit PASSED [ 61%]
test_pilot.py::test_PP06_calculation_vs_manual_verification PASSED [ 66%]
test_pilot.py::test_PP07_route_link PASSED [ 71%]
test_pilot.py::test_PP08_weight_above_maximum_capacity FAILED [ 76%]
test_pilot.py::test_PP09_invalid_weight[0] FAILED [ 80%]
test_pilot.py::test_PP09_invalid_weight[-5] FAILED [ 85%]
test_pilot.py::test_PP10_unregistered_material FAILED [ 90%]
test_pilot.py::test_PP11_unregistered_zone FAILED [ 95%]
test_pilot.py::test_PP12_batch_response_time PASSED [100%]
========================================== short test summary info
==========================================
FAILED test_pilot.py::test_PP08_weight_above_maximum_capacity - TypeError: 'NoneType' object is not
subscriptable
FAILED test_pilot.py::test_PP09_invalid_weight[0] - Failed: DID NOT RAISE ValueError
FAILED test_pilot.py::test_PP09_invalid_weight[-5] - Failed: DID NOT RAISE ValueError
FAILED test_pilot.py::test_PP10_unregistered_material - Failed: DID NOT RAISE ValueError
FAILED test_pilot.py::test_PP11_unregistered_zone - KeyError: 'Nonexistent Neighborhood'
========================================= 5 failed, 16 passed in 0.13s
=========================================
```

Version 1.1 (corrected). Command: $env:VERSION="greedy_recycle"; py -m pytest -v test_pilot.py

```
============================================= test session starts ==============================================

collecting ... collected 21 items

test_pilot.py::test_PP01_haversine_one_degree_of_latitude PASSED                                [  4%]

test_pilot.py::test_PP02_haversine_same_point PASSED                                            [  9%]

test_pilot.py::test_PP03_assignment_rule_at_boundaries[12-2.5-On foot] PASSED                   [ 14%]

test_pilot.py::test_PP03_assignment_rule_at_boundaries[12.01-1.0-Public transport] PASSED       [ 19%]

test_pilot.py::test_PP03_assignment_rule_at_boundaries[12-2.51-Public transport] PASSED         [ 23%]

test_pilot.py::test_PP03_assignment_rule_at_boundaries[25-10.0-Public transport] PASSED         [ 28%]

test_pilot.py::test_PP03_assignment_rule_at_boundaries[25-10.01-Private car] PASSED             [ 33%]

test_pilot.py::test_PP03_assignment_rule_at_boundaries[160-50.0-Private car] PASSED             [ 38%]

test_pilot.py::test_PP03_assignment_rule_at_boundaries[160.01-1.0-Pickup truck] PASSED          [ 42%]

test_pilot.py::test_PP04_recycler_filter[Glass-3] PASSED                                        [ 47%]

test_pilot.py::test_PP04_recycler_filter[Copper-11] PASSED                                      [ 52%]

test_pilot.py::test_PP04_recycler_filter[Aluminum-28] PASSED                                    [ 57%]

test_pilot.py::test_PP05_descending_order_by_profit PASSED                                      [ 61%]

test_pilot.py::test_PP06_calculation_vs_manual_verification PASSED                              [ 66%]

test_pilot.py::test_PP07_route_link PASSED                                                      [ 71%]

test_pilot.py::test_PP08_weight_above_maximum_capacity PASSED                                   [ 76%]

test_pilot.py::test_PP09_invalid_weight[0] PASSED                                               [ 80%]

test_pilot.py::test_PP09_invalid_weight[-5] PASSED                                              [ 85%]

test_pilot.py::test_PP10_unregistered_material PASSED                                           [ 90%]

test_pilot.py::test_PP11_unregistered_zone PASSED                                               [ 95%]

test_pilot.py::test_PP12_batch_response_time PASSED                                             [100%]

============================================== 21 passed in 0.16s ==============================================
```