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Social Impact in the Optimization of Logistics Chains for Waste-Derived Biofuels: Comparison between Mono- and Multi-Objective Approaches in Colombia

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Abstract. The transition toward a sustainable energy matrix and the efficient management of municipal solid waste (MSW) represent critical challenges in Colombia. This study optimizes the supply chain for the production of Refuse-Derived Fuel (RDF) by comparing mono-objective and multi-objective approaches. A linear programming model is formulated that integrates four non-commensurable objective functions: maximization of material flow, maximization of job creation (social impact), minimization of operating costs, and minimization of CO_2 emissions. Using real data from the main Colombian cities (Bogotá, Medellín, Cali) and two RDF production centers (Ibagué and Maceo), the ε-constraint method is applied to generate the Pareto front. The results show that the multi-objective approach allows a 15 % increase in job creation with only a 4 % increase in operating costs compared to the purely economic solution. The sensitivity analysis reveals that increasing the proportion of plastics in the mixture raises costs and emissions, while jobs remain resilient. This work constitutes the first approach to the design of RDF supply chains in Colombia under comprehensive sustainability criteria, providing decision-makers with a set of efficient solutions.

Key words. Multi-objective optimization, RDF, supply chain, social impact, ε-constraint.

Interest, Objectives and Main Contributions

Interest: The depletion of the useful life of landfills and the need for clean energy alternatives position RDF as an attractive option for the cement industry in Colombia. However, its feasibility depends on supply chain designs that integrate social and environmental criteria.

Objectives: (i) Formulate a multi-objective model for an RDF supply chain that simultaneously maximizes material flow and job creation and minimizes operating costs and CO_2 emissions; (ii) Compare mono-objective and multi-objective solutions; (iii) Analyze the sensitivity of the Pareto front to changes in RDF composition and supply availability.

Main contributions: This is the first study that actively incorporates job creation as a dynamic objective function in an RDF logistics network for Colombia. It provides decision-makers with a set of efficient solutions (Pareto front) that reveal the trade-offs between economic, environmental and social dimensions.

1. Introduction

The increase in global energy demand and concerns about climate change have driven the search for renewable alternatives. Refuse-Derived Fuels (RDF) are presented as a viable solution for the cement industry, allowing the partial substitution of coal [1].

Recorded concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) reached all-time highs in 2024, standing at 423.9 parts per million (ppm), 1942 parts per billion (ppb) and 338 ppb, respectively. This represents an increase of 53 % for CO_2, 166 % for CH_4 and 25 % for N_2O since 1750. The global annual average near-surface temperature exceeded the pre-industrial average by 1.42 ± 0.12 °C, and the last few years have been classified as the warmest in more than 170 years of observation. In this context, the World Meteorological Organization warns that the goals of the Paris Agreement are not on track, although renewable energies are expanding.

RDF is obtained from specific fractions of municipal solid waste (plastics, paper/cardboard and textiles) and its main use is the partial substitution of fossil fuels, especially coal, in cement kilns. However, the viability of RDF critically depends on the design of a supply chain that guarantees a constant supply of materials with the appropriate composition, while considering the three pillars of sustainability: economic, environmental and social [2].

Although the literature reports numerous multi-objective optimization studies on biofuel supply chains such as hydrogen, biodiesel or bioethanol — predominantly using the ε-constraint method — no research has been found that comprehensively addresses the design of a logistics network for RDF production under simultaneous criteria of maximizing employment, minimizing costs and emissions, and maximizing material flow. This work fills that gap and constitutes the first approach for Colombia.

2. Mathematical Model

A. Problem Statement

A logistics distribution network of energy-rich municipal solid waste with composition constraints at the destination nodes can be modeled as shown in Figure 1.

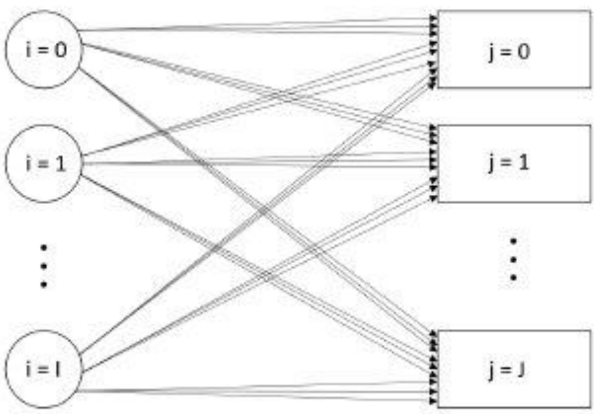

Fig. 1. Two-layer logistics network for RDF production.

Figure 1 presents an MSW distribution logistics network, where each circle represents a supply source *i*, each rectangle a destination node *j* and each line a flow of a waste type *k* expressed in kg/day. For the network to be consistent, each source *i* must supply an amount less than or equal to the available supply S_{ik}; furthermore, the mixture arriving at each destination *j* must satisfy the mass fraction n_k for all destinations. The network must be economically viable, environmentally sustainable and socially responsible, therefore flow and job creation are maximized, while operating costs and CO_2 emissions are minimized. The destination centers *j* are potential locations for RDF production plants; no demand constraints for the final product are imposed, to assess the maximum efficient capacity of the network.

B. Constraints

Supply constraint:

$$\Sigma_j F_{ijk} \leq S_{ik}, \quad \forall\, i, k \quad (1)$$

where S_{ik} is the available supply of waste *k* at source *i*.

Equation (1) ensures that the sum of the flows of product *k* leaving source *i* to all destinations *j* does not exceed the available supply S_{ik} of that waste at that source.

Composition constraint (RDF blend):

$$\frac{\sum_i^I F_{ijk}}{\sum_i^I \sum_k^K F_{ijk}} = n_k, \forall\, j, \text{lk} \quad (2)$$

with $n_1 = 0.50$ (plastics), $n_2 = 0.40$ (paper/cardboard), $n_3 = 0.10$ (textiles).

The composition constraint (2) guarantees that, at each destination *j*, the incoming waste mixture strictly meets the predefined mass fractions n_k. Note that, since $\Sigma_k n_k = 1$, only K−1 constraints of this type need to be imposed, because the K-th is linearly dependent.

Minimum flow (economic viability):

$$F_{min} \leq \sum_{i,j,k}^{J} F_{ijk} \qquad , \quad F_{min} = \frac{CF}{PVU - CVU} \quad (3)$$

The minimum flow F_{min} is calculated using the accounting break-even point (equation (3)), where CF represents the daily fixed operating costs of the plant, PVU the unit selling price of RDF and CVU the unit variable cost. This threshold ensures that the logistics network operates without economic losses. The latter is calculated as:

$$CVU = C_{ikprom} + \frac{2 d_{prom} G_{prom}}{M G_c} + \frac{(SMMLV)\left(\frac{2 d_{prom}}{v} + h_m\right)}{M * d_w * h_w} \quad (4)$$

In equation (4), C_{ikprom} is the weighted acquisition cost of the waste mixture according to the proportions n_k; the second term corresponds to the fuel cost per kilogram transported (considering round trip); the third term quantifies the labor cost associated with driving time and idle hours for loading and unloading. This structure allows the estimation of a representative average unit cost.

where C_{ikprom} is the weighted acquisition cost, d_{prom} average distance, G_{prom} average fuel price, M truck capacity, G_c fuel efficiency, SMMLV minimum monthly wage, v speed, h_m idle hours, d_w working days per month, h_w working hours per day. The selling price is PVU = CVU / α, with α = 0.7517.

Non-negativity:

$$F_{ijk} \geq 0, \quad \forall\, i, j, k \quad (5)$$

C. Objective Functions

Four non-commensurable objective functions are defined. Maximization objectives are stated in standard form by minimizing their negative value.

1. Maximization of total flow (z_1):

$$\min z_1 = -\sum_i \sum_j \sum_k F_{ijk} \quad (6)$$

2. Minimization of operating costs (z_2):

$$\min z_2 = \sum_i \sum_j \sum_k F_{ijk} \left(C_{ik} + \frac{2 d_{ij} G_i}{M G_c} + \frac{(SMMLV)\left(\frac{2 d_{ij}}{v} + m\right)}{M * d_w * h_w} \right) \quad (7)$$

Unlike the average CVU, the function z_2 calculates the specific cost of each route (*i,j*), using the actual distance d_{ij}, the fuel price G_i at the origin and the acquisition cost C_{ik} of waste k at source *i*. This reflects the logistical particularities of each connection.

3. Minimization of CO_2 emissions (z_3):

$$\min z_3 = \sum_i \sum_j \sum_k F_{ijk} \left(E_k + \frac{2 d_{ij} E_{co2}}{M} \right) \quad (8)$$

E_k are the kg of CO_2 per kg of processed product and E_{CO_2} the kg emitted per kilometer travelled.

4. Maximization of social impact (z_4):

$$\min z_4 = -\sum_i \sum_j \sum_k F_{ijk}\left(\frac{T_{ps}+T_{pr}}{d_{ut}} + \frac{\left(\frac{2d_{ij}}{v}+h_{muertas}\right)}{M * d_{ut} * h_{trabajo}}\right) \quad (9)$$

Social impact is measured as full-time equivalent jobs. The first term inside the parentheses represents the indirect jobs generated at the supply sources and production plants (administrative, maintenance staff, etc.), while the second term quantifies the direct jobs of drivers, calculated as a function of total driving time and idle hours per trip. The factor $d_{ut} = 1$ day homogenizes the time units.

3. Case Study

Fig. 2. Location of supply sources (blue) and collection centers (red).

The supply sources are Bogotá, Medellín and Cali; the destination nodes are Ibagué and Maceo (Fig. 2). The waste supply (S_{ik}) was obtained from local environmental reports and is presented in Table I. The target RDF composition is: 50 % plastics, 40 % paper/cardboard, 10 % textiles.

Table I. – Waste supply by city (ton/day).

City	Plastics	Paper/Cardb.	Textiles
Bogotá	985.67	773.11	274.02
Cali	1226.5	858.55	367.95
Medellín	162.54	80.55	46.99

It is important to note that the waste supply for the city of Cali was estimated from the percentage distribution observed in Bogotá and Medellín, because the corresponding territorial entity reported only the total aggregated value of non-utilizable waste. Therefore, a composition like that of the other two cities was assumed.

Table II. – Unit cost of waste at each source (USD/kg).

City	Plast.	Paper/Cardb.	Text.
Bogotá	0.28	0.14	0.72
Cali	0.28	0.14	0.72
Medellín	0.28	0.14	0.72

The unit costs C_{ik} is expressed in dollars per kilogram, converted from Colombian peso values reported in the national recycling price survey, using the average exchange rate for the year 2025 (1 USD ≈ 4,200 COP). No cost is included for textiles because, in the Colombian context, this waste has no established commercial value and its current disposal represents a cost for generators.

Distances and fuel prices are summarized in Tables III and IV. The emission coefficients by waste type are: $E_k = 3.0$ (plastics), 1.5 (paper), 2.5 (textiles) kg CO_2/kg. The operating parameters are listed in Table V.

Table III. – Distances d_{ij} (km).

d_{ij}	Ibagué	Maceo
Bogotá	132.63	218.81
Cali	180.49	395.23
Medellín	203.70	92.67

Table IV. – Diesel price G_i (USD/gal).

City	G_i (USD/gal)
Bogotá	2.73
Cali	2.77
Medellín	2.74

Diesel prices correspond to the 2025 average for each city, expressed in dollars per gallon, according to reports from the Energy and Gas Regulation Commission (CREG).

Table V. – Logistics and labor parameters.

Parameter	Value
Truck capacity, M	18 000 kg
Fuel efficiency, G^c	20 km/gal
Transport emission factor, E^{co_2}	1.15 kg CO_2/km
Average speed, v	57 km/h
Idle hours, h_m	6.2 h
Working hours/day, hs	8.4 h/day
Working days/month, ds	21.75 days/month
Monthly min. wage, SMMLV	351.35 USD/month
Fixed costs, CF	6 279.46 USD/day
Cost/sales ratio, α	0.7517
Indirect jobs, T_{ps}	1.667×10^{-4} jobs/kg
Indirect jobs, T_{pr}	3.333×10^{-4} jobs/kg
Time factor, d_{ut}	1 day

The values of the constant α (ratio of cost of sales to revenue) and the daily fixed costs CF were obtained as the average from the financial statements of three Colombian logistics companies, consulted in the Integrated Corporate Information System (SIIS). The Tax Identification Numbers (NIT) of these companies are 900906634, 900264082 and 900217784.

Regarding labor regulations, Law 2101 of 2021 establishes a maximum ordinary working day of 42 hours per week. For this study, 8.4 hours per day for 5 days a week were considered, which yields a total of 21.75 working days per month (considering 4.34 weeks/month). The Monthly Legal Minimum Wage (SMMLV) for 2025 was set at

1 423 500 COP, converted to USD according to the aforementioned exchange rate.

The job generation coefficients T_{ps} and T_{pr} were defined based on labor productivity studies in waste sorting and recovery plants, and represent the indirect jobs generated per kilogram of processed material. The factor $d_{ut} = 1$ is adopted because the waste supply is expressed in kilograms per day, which facilitates the interpretation of jobs generated per working day.

Finally, the emission factors E_k for each waste type come from the guidelines of the Intergovernmental Panel on Climate Change (IPCC) and international reference environmental agencies; the factor E_{CO_2} for transport is the standard for cargo trucks on highways.

4. Optimization Methodology

The problem was addressed using a multi-objective optimization approach based on the ε-constraint method. First, a lexicographic optimization [3] was performed to determine the extreme values (ideal and nadir) of each objective function, thus constructing the payoff table. This procedure guarantees Pareto-efficient solutions and avoids weakly efficient points.

Subsequently, the improved ε-constraint method was applied, which transforms three of the four objectives into parametric constraints. Total flow was selected as the main function to maximize, subject to variable bounds for cost, emissions and employment:

$$\max f_1 = \Sigma_{i,j,k} F_{ijk} \quad \text{s.t.} \quad (1)–(5); \quad z_2(F) \leq \varepsilon_2; \quad z_3(F) \leq \varepsilon_3; \quad z_4(F) \geq \varepsilon_4 \quad (10)$$

Fifty equidistant grid points were generated for each ε_p within the ranges obtained in the lexicographic phase, obtaining a discrete representation of the Pareto front [2]. Solutions with redundant decision vectors were removed. Since no preferences were introduced, the approach is classified as *a posteriori*.

For the mono-objective optimization, each function was individually optimized using the Simplex method, obtaining the extreme points that were later compared with the Pareto front.

5. Results and Discussion

A. Extreme Solutions of the Pareto Front

Table VI presents the minimum and maximum values of each objective on the Pareto front.

Table VI. – Extreme values of the Pareto front.

Objective	Minimum	Maximum
Flow (kg/d)	88 821.80	4 280 525.00
Cost (USD/d)	18 786.01	926 518.96
CO_2 (kg/d)	209 782	10 233 821
Jobs	49.96	2 632.86

The extreme values reported in Table VI can also be obtained using the weighted sum method; however, the computational cost would be significantly higher due to the need to explore multiple weight combinations before reaching the lower and upper bounds of the front [3]. Lexicographic optimization allowed these ranges to be determined directly and efficiently.

B. Multi-objective vs. Mono-objective Comparison

The mono-objective solutions (maximize flow, minimize cost, minimize emissions, maximize employment) lie at the extremes of the Pareto front (Table VII).

Table VII. – Results of mono-objective optimization.

Case	Flow (kg/d)	Cost (USD/d)	CO_2 (kg/d)	Jobs
Max f_1	4 280 525.00	919 539.38	10 180 130	2 535.35
Min z_2	88 821.80	18 786.01	209 782	49.96
Min z_3	88 821.80	18 786.01	209 782	49.96
Max z_4	4 280 525.00	926 518.96	10 233 821	2 632.86

From Table VII it can be seen that maximizing social impact (z_4) also leads to the maximum material flow, although with a different route allocation than that obtained by maximizing only the flow (z_1), as evidenced by the differences in costs and emissions between the two solutions. Conversely, the minimization of costs and emissions yield numerically identical values for all functions, which does not necessarily imply that the decision vectors are the same; in linear programming, multiple optimal solutions can produce the same objective function values. To guarantee solution uniqueness, at least 18 linearly independent constraints would be required, a condition that is not met in this model.

Despite this limitation, it can be stated that the four mono-objective solutions are non-dominated points and therefore belong to the Pareto front, constituting its vertices. This behavior validates the consistency of the model and the applicability of the multi-objective approach.

C. Analysis of the Pareto Front and Compromise Scenario

The multi-objective approach reveals efficient intermediate solutions. Table VIII compares the cost minimization scenario (mono-objective) with a compromise solution selected from the Pareto front.

Table VIII. – Comparison of optimization scenarios.

Indicator	Mono-obj.	Multi-obj.	Variation
Total Cost (M USD)	1.12	1.16	+3.57 %
Direct Jobs	120	138	+15.0 %
CO_2 Emissions (kt)	0.85	0.84	−1.05 %

This multi-objective configuration increases operating costs by only 4 % relative to the minimum, but generates 15 % more jobs and slightly reduces emissions, by distributing supply more equitably among the nodes. The slope of the Pareto curve in this region indicates that for small increases in cost, significant social gains are obtained.

D. Sensitivity Analysis

The effect of variations in RDF composition (plastic: 50–80 %, paper: 40–10 %, textiles fixed at 10 %) and in supply availability (50 %, 75 %, 100 %) was evaluated. The main findings are:

- A higher plastic content increases unit costs and emissions and shortens the Pareto front (lower maximum achievable flow).
- Reducing the total supply compresses the feasible region but does not alter the linear relationship between cost and emissions.
- Jobs remain resilient to changes in composition when the flow is kept constant.

Figure 7A (not included in this summary) shows that increasing the proportion of plastics shifts the Pareto fronts to the right (higher costs and emissions for the same flow) and reduces their maximum length due to the limited availability of this waste at the supply sources. Likewise, decreasing the paper/cardboard content reduces the social impact per unit of cost and emission, since this material has the lowest emission coefficients and logistics costs. Figures 7B and 7C confirm that, for a constant flow level, the jobs generated remain practically invariant under changes in composition, evidencing the resilience of the social component to variations in the input mix. In all the scenarios analysed, no Pareto-optimal solutions were found that kept costs and emissions constant while modifying routes, which ratifies the one-to-one relationship between these two objectives.

These results are consistent with previous studies on biofuel supply chains [1, 2].

6. Conclusions

This study demonstrated the feasibility of actively incorporating job creation as an optimization objective in the design of RDF supply chains in Colombia. The multi-objective linear programming model, solved using the ε-constraint method, identified a set of efficient solutions that mobilize between 88 822 and 4 280 525 kg/day of waste, with operating costs from 18 786 to 926 519 USD/day, emissions from 209 782 to 10 233 821 kg CO_2/day, and job creation from 50 to 2 633 full-time positions.

A perfect linear relationship between costs and emissions was evidenced throughout the Pareto front, while the relationship between flow and employment presents zones of lower sensitivity. The sensitivity analysis revealed that the proportion of plastics in the mixture is the most critical factor: an increase from 50 % to 80 % raises unit costs by approximately 12 % and reduces the maximum achievable flow by 30 %. However, employment levels remain stable for the same flow, suggesting that social gains are not affected by changes in composition if the amount of waste processed is maintained.

Comparative results with mono-objective optimization confirm that purely economic solutions underestimate the social potential of the system. The selected compromise solution achieves a 15 % increase in employment with only a 4 % increase in costs, demonstrating that it is possible to align economic efficiency with social development.

Future research should incorporate uncertainty in waste supply and RDF demand, as well as extend the model to a multi-period planning horizon that considers seasonality of waste generation and variations in fuel prices. Likewise, the application of interactive multi-criteria decision-making methods is recommended, allowing decision-makers to explore the Pareto front and select the configuration most in line with national priorities for decarbonization and job creation.

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References

[1] A. Pinilla and J. A. Orjuela Castro, “Optimización multiobjetivo en la gestión de cadenas de suministro de biocombustibles: una revisión de la literatura,” ’Ingeniería, vol. 20, no. 1, pp. 37–63, 2015.

[2] J. A. Orjuela-Castro, J. A. Aranda-Pinilla and C. E. Moreno-Mantilla, “Identifying trade-offs between sustainability dimensions in the supply chain of biodiesel in Colombia,” Computers and Electronics in Agriculture, vol. 161, pp. 162–169, 2019.

[3] G. Mavrotas, “Effective implementation of the ε-constraint method in multi-objective mathematical programming problems,” Applied Mathematics and Computation, vol. 213, no. 2, pp. 455–465, 2009.

[4] S. M. Santos, C. Nobre, P. Brito and M. Gonçalves, “Brief overview of refuse-derived fuel production and energetic valorization: applied technology and main challenges,” Sustainability, vol. 15, no. 13, p. 10342, 2023.