

FUZZY OPTIMIZATION IN A GREEN SUPPLY CHAIN CONTEXT: THE BRAZILIAN COFFEE CASE

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ABSTRACT

The analysis focuses on optimizing Brazilian coffee production, its logistical steps, and supply in the American market from a green supply chain perspective. The modeling was carried out with a Life Cycle scope, considering Global Warming Potential as an environmental indicator and costs as an economic indicator. The objective was to reduce both indicators. Fuzzy variables were used to deal with uncertain parameters, proving to be very useful as the results were significantly conditioned on the efficiency of coffee roasting. The optimized arrangement favors less dispersed routes and localized coffee supplies in limited conditions, with consumer centers supplied only by one logistical and roasting route. This study provides elements to improve the production of roasted and ground coffee, as well as modeling aspects to be tested for future developments.

KEYWORDS. Fuzzy optimization. Brazilian coffee. Green supply chain.

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1. Introduction

Coffee is a highly valuable commodity worldwide, with the market projected to reach US\$468 billion in 2024 [Statista n.d., a]. Brazil leads the global agricultural production of coffee, accounting for 39% of the market, equivalent to 66 million bags of 60 kg of coffee. This places Brazil well ahead of its competitors, such as Vietnam (16%), Colombia (7.0%), Indonesia (6.0%), and Ethiopia (5.0%) [Foreign Agricultural Service of U.S. Department of Agriculture n.d.].

Given the size of this market, it is possible that production and commercial arrangements do not represent the closest situations to optimum. In Brazil, management suffers from inefficient transport and inadequate travel routes, which result in the loss of green coffee or inefficiency of industrial roasting processes that could be better monitored to avoid waste. Furthermore, news highlighting the instabilities of this production chain – i.e., its vulnerability to weather conditions, high logistical costs due to fuel prices, and low remuneration for agricultural producers – are broadcast with high frequency, forming an image among consumers of inefficient management of the sector [Pham et al. 2019, Barreto Peixoto et al. 2023].

This context only confirms the importance of building an efficient, productive market less exposed to variables and situations it cannot control. In principle, the coffee market can be considered a ‘*supply chain management*’ case, whose classical conceptualization seeks to produce value from the lowest costs. However, a movement is already aimed at including environmental aspects in this management, called ‘*green supply chain management*’ [Barbosa-Póvoa 2014]. Many researchers who follow this approach, which is considered more environmentally sustainable, have realized that by considering environmental factors and typical performance indicators such as cost reduction, increased profitability, or improved process efficiency, they can gain insights into improving various production and logistics aspects. This approach clarifies potential trade-offs and contributes to more comprehensive decision-making criteria [Barbosa-Póvoa 2014, Zhang et al. 2014]. Various metrics can be employed from an environmental standpoint in ‘*green supply chain management*’. The literature emphasizes the use of Life Cycle Assessment (LCA) [Abdallah et al. 2012, Miranda-Ackerman et al. 2017], as this method assesses the potential impacts of a product, process, or service from raw material acquisition through production and consumption to final disposal [ISO 2006]. In the context of optimizing the coffee cycle, studies focused on ‘*green supply chain management*’ involving LCA. For instance, [Baratsas et al. 2021] propose a framework based on Circular Economy and Mixed-Integer Linear Optimization (MILP) to optimize food supply chains, using coffee as an example. Additionally, [Torabzadeh et al. 2022] conducted an optimization using fuzzy variables for operating conditions in coffee manufacturing and logistics in Iran, while [Sakamoto et al. 2023] utilized multi-objective environmental-economic optimization to cater to the North American coffee market from Brazilian products.

The research conducted by Sakamoto et al. left open an aspect that the present study intends to explore. The authors chose to disregard uncertainties naturally associated with some variables by modeling them in a way that is too deterministic, thus creating a condition far from reality. This study aims to review the economic and environmental optimization of Brazilian coffee processing and its distribution in the American market, using fuzzy modeling to include situations of uncertainty [Bellman and Zadeh 1970] that are intrinsic to the product's supply chain. The results obtained from this research are expected to strengthen the model initially designed to evaluate behavioral trends in the Brazilian coffee market, support decision-making processes in that context, and consider sustainability aspects among the evaluation criteria.

2. Methodology

To achieve the goals outlined in the previous section, we developed a strategy that involved the following steps: (i) identifying variables that could be modeled using the fuzzy approach in collaboration with the study by [Sakamoto et al. 2023]; (ii) creating a new set of equations to represent the problem; (iii) optimizing and analyzing the results, particularly about variations made to the reference study; and (iv) proposing additional interventions based on the findings obtained from this research.

2.1. Case study: green supply chain for Brazilian coffee exported to the American Consumer Market

The study focuses on the production and shipment of coffee from Brazil to the United States (US), the world's largest coffee consumer. The case covers the agricultural production and road transport of green coffee in Brazil, the transoceanic transport between Brazilian and American ports, the road transport of green coffee in the US from receiving ports to the leading American roasting companies, and the roasting and grinding of coffee. Finally, it includes the road transport of processed coffee to the major American cities.

According to data from the Brazilian National Supply Company (CONAB) from 2018–2023 (Table 1), the states of Minas Gerais, Espírito Santo, São Paulo, and Bahia are the largest coffee producers, cultivating Arabica and Robusta (Conilon) varieties [Conab n.d.]. The Brazilian Ministry of Development, Industry, Commerce, and Services indicates that most Brazilian green coffee is shipped to the US from ports of Santos, Rio de Janeiro, and Salvador [Brazilian Ministry of Development, Industry, Commerce and Services n.d.].

Table 1. Brazilian Arabica and Robusta coffee production from 2018 to 2023.

Brazilian State	Variety of coffee	Production year (thousands of 60 kg bags)					
		2018	2019	2020	2021	2022	2023
Minas Gerais (MG)	Arabica	32,970	24,235	34,337	21,859	21,570	28,650
São Paulo (SP)	Arabica	6,302	4,340	6,181	4,007	4,387	5,031
Bahia (BA)	Arabica	1,880	1,200	1,867	1,229	1,271	1,108
	Robusta	2,670	1,800	2,120	2,240	2,333	2,289
Espírito Santo (ES)	Arabica	4,751	3,002	4,765	2,945	4,363	2,859
	Robusta	8,988	10,496	9,193	11,221	12,358	10,155
Total Brazil	Arabica	47,484	34,296	48,737	31,424	32,721	38,905
	Robusta	14,174	15,013	14,311	16,293	18,199	16,167

The top American coffee roasters are Folgers, with 25% of the domestic market; Starbucks (12%), and Maxwell (10%) [Statista n.d., b]. Our supply chain modeling only includes these three companies, as smaller brands, including artisanal ones, fulfill the rest of the demand, making it challenging to gather data and information about them [Sakamoto et al. 2023]. Folgers has a production facility in New Orleans, and the Maxwell's is in Jacksonville, Florida. Meanwhile, Starbucks operates five coffee roasting plants in Augusta, Georgia; Carson Valley, Nevada; Gaston, South California; Kent, Washington; and York, Pennsylvania. The original research considered cities with the highest coffee market revenue as consumers. These cities include New York, Los Angeles, Chicago, San Francisco, Seattle, San Diego, Houston, Philadelphia, Portland, Washington DC, San Jose, Phoenix, Austin, Denver, and Dallas.

Finally, because of the locations of roasters and consumer centers, Sakamoto et al. assumed for logistical modeling purposes that coffee would enter the US through four ports, dividing the American territory into the following quadrants: Seattle to the northwest, Los Angeles to the southwest, New Orleans to the southeast, and New York to the northeast.

2.2. Environmental and Economic Life Cycle Modeling

The life cycle approach was employed to address the system comprehensively, allowing for the examination of the entire process, from raw material consumption, production, and consumption processes to final disposal. This decision facilitates a long-term, multidimensional study, preventing partial solutions that may solve one problem but create others in environmental,

economic, or social domains for different stakeholders [Mazzi 2020]. The study considered environmental and economic variables from this perspective.

The Life Cycle Assessment (LCA) followed the ISO 14044 [ISO 2006] standard. The model was developed using secondary data from the Ecoinvent database, with adjustments made to reflect the study conditions and the specific realities of Brazil and North America. The modeling of Brazilian coffee cultivation was based on the inventory obtained from [Coltro et al. 2006], adapted to the agricultural productivity of Bahia, Espírito Santo, Minas Gerais, and São Paulo between 2018 and 2021 [Conab n.d.]. Energy consumption and production loss rates related to coffee roasting and grinding were sourced from [Giraldi-Díaz et al. 2018].

The Brazilian electricity system was updated to meet the requirements of 2021 [Energy Research Company 2021]. Truck transportation, using vehicles with a load capacity ranging from 7.5 to 16 tons, began to adopt EURO4 technology for Brazilian vehicles and EURO5 for American vehicles. Land and sea travel distances were calculated using maps.google.com [Google n.d] and searates.com [SeaRates n.d.].

For the optimization exercise, only the effects of Global Warming Potential (GWP) were considered and estimated using the method proposed by the Intergovernmental Panel on Climate Change [Myhre et al. 2013]. Previous research indicates that optimization studies considering this indicator have yielded consistent results [Zhang et al. 2014, Baratsas et al. 2021, Torabzadeh et al. 2022]. The LCA utilized the software SimaPro v. 9.2.0.2 from PRé Sustainability®. The economic assessment also incorporated a Life Cycle perspective to standardize approaches and results. In this context, the evaluation considered the following steps: the cost of Brazilian green coffee, the cost of Brazilian road freight, the cost of sea freight, and the cost of American road freight. Section 2.3 provides more detailed information on the process of obtaining these values.

2.3. Fuzzy optimization modeling

The optimization problem to be addressed consists of:

$$\max \left(\sum_{i=1}^F \lambda_i \right) / F \quad (1)$$

A fuzzy additive model was utilized [Arikan 2013] to solve it. In this model, the variables (λ_i) indicate the relevance levels of the fuzzy equations about the original problem's objective functions and constraints. F represents the total of fuzzy variables used in the modeling (in this case, $F = 7$). Furthermore, $L = 6$ represents the coffee agricultural production locations in Brazil, $P = 3$ the total of Brazilian export ports, $Q = 4$ the number of destination ports in the US, $R = 7$ the number of coffee roasting units, and $C = 15$ the main American consumer cities.

In this study, the following variables were used: (x_{ij}), which is the average distance traveled between the coffee cultivation area and the port of origin in Brazil (km); (y_{ij}), which is the amount of coffee shipped from the producer to the port of origin in Brazil (kg); (z_{jm}), which represents the amount of coffee shipped from the port of origin (Brazil) to the port of destination (US) (kg); (w_{mn}), which is the quantity of coffee shipped from the American port to the roasting company (kg) and; (k_{np}), which is the amount of coffee shipped from the roaster to the consumer center in US (kg).

The total environmental impact of delivering coffee to consumption centers in North America (EI) (expressed in kg CO_{2,eq}) was determined using Equation (2):

$$\begin{aligned}
 EI = & \sum_i^L \sum_j^P EIPROD_i y_{ij} + \sum_i^L \sum_j^P EIFBR_{ij} x_{ij} y_{ij} + \sum_j^P \sum_m^Q EIFRE_{jm} z_{jm} \\
 & + \sum_m^Q \sum_n^R EIRST_{mn} w_{mn} + \sum_n^R \sum_p^C EIDIST_{np} k_{np}
 \end{aligned} \quad (2)$$

Where (*EIPROD*) is the environmental impact (kg CO_{2,eq}/kg coffee) for the agricultural production of coffee in each location in Brazil, (*EIFBR*) is the impact due to road freight producer-port of origin (kg CO_{2,eq}/(kg coffee.km)), (*EIFRE*) is the impact of maritime transport between ports in Brazil and the US (kg CO_{2,eq}/kg coffee), (*EIRST*) is the impact of road freight between the US port of destination and the roaster (kg CO_{2,eq}/kg coffee), and (*EIDIST*) is the environmental impact of American road freight between the roaster and the destination city (kg CO_{2,eq}/kg coffee).

The sum of the total cost to supply Brazilian coffee to American cities (expressed in US\$), was obtained using Equation (3):

$$\begin{aligned}
 \$I = & \sum_i^L \sum_j^P CPROD_i y_{ij} + \sum_i^L \sum_j^P \frac{(CDC x_{ij} + LUC + WTC) y_{ij}}{EXC \times CAP \times BAG} + \sum_j^P \sum_m^Q CFRE_{jm} z_{jm} \\
 & + \sum_m^Q \sum_n^R CRST_{mn} w_{mn} + \sum_n^R \sum_p^C CDIST_{np} k_{np}
 \end{aligned} \quad (3)$$

(*CPROD*) represents the cost of coffee production per kilogram (US\$/kg coffee) at each location, (*CFRE*) is the sea freight cost between Brazilian and American ports (US\$/kg coffee), (*CRST*) represents the freight cost to roasters (US\$/coffee), (*CDIST*) is the freight cost from the roasters to the destination cities (US\$/coffee) and (*EXC*) represents the exchange rate between the US dollar and the Brazilian Real. The second term of the equation pertains to the calculation of road freight in Brazil, following the guidelines provided by Brazilian Land Transportation Agency (ANTT) [Brazil 2022]. (*CDC*) represents the cost of transporting coffee from productive regions to shipping ports, with the value set at R\$3.3189 per kilometer. (*LUC*) is the cost of loading and unloading the product of R\$ 279.72. (*WTC*) refers to the weighted toll cost of the origin and destination routes, ranging from R\$ 8.70 to R\$ 487.50, depending on the route taken. These estimates were made for three-axle trucks. The term is also adjusted by the factor (*CAP* × *BAG*), which refers to the total capacity of the truck (450 bags of coffee per vehicle × 60 kg of coffee per bag).

In this modeling, the optimal environmental and economic values were found through the Weighted Sum method for multi-objective optimization. Since there are two objectives, the optimal environmental value (f_{EI}^0) was found by placing all the weight on this objective. Consequently, the maximum economic value ($f_{\$I}^{max}$) was also obtained. Similarly, with the weight fully on the economic objective, the optimal economic value ($f_{\$I}^0$) and the maximum environmental value (f_{EI}^{max}) were obtained. For the fuzzy approach, the equation that represents the environmental impact (*EI*) was given by (4).

$$\lambda_1 \leq \frac{f_{EI}^{max} - EI}{f_{EI}^{max} - f_{EI}^0} \quad (4)$$

and Equation (5) represents the cost (*\$I*):

$$\lambda_2 \leq \frac{f_{\$I}^{max} - \$I}{f_{\$I}^{max} - f_{\$I}^0} \quad (5)$$

Equation (6) associates the deviations from the optimal value of the objective function in the new situation and the trade-off between environmental and economic variables [Shih and Chang, 1995; Huang et al., 2006]:

$$(1 - \omega) \frac{EI - f_{EI}^0}{f_{EI}^0} = \omega \frac{\$I - f_{\$I}^0}{f_{\$I}^0} \quad (6)$$

(ω) represents the relative degree of importance between the economic and environmental variables, with $\omega = 1$ indicating the scenario with complete economic optimization and $\omega = 0$, signifies optimization only of the environmental aspect. It will indicate the weighting between these two objectives that maximizes the value of (λ) . As the Dollar–Real exchange rate is subject to variation, the (EXC) could be tested for different quotes. Therefore, calculations were carried out, varying the exchange rate between the lowest (US\$ 4.72) and the highest value (US\$ 5.30) within the February 2023 and February 2024 range.

The value of (γ) is a factor that refers to the coffee mass after the roasting process. Giraldi-Díaz et al. (2018) considered a weight loss of 25.4%. Conversely, Bicho et al. (2012) indicate a different loss value of 10.1%; thus, this variable can assume values between $RS_{min} = 0.746$ and 0.909. To model this condition in a fuzzy way, the variation range is defined as $RS_{var} = 0.909 - 0.746 = 0.153$, and Equation (7) as follows:

$$\gamma = RS_{min} + RS_{var}\lambda_3 \quad (7)$$

Equation (8) states that each destination city in the United States must receive the quantity of coffee demanded (d_p). This results in 15 constraints. The goal is to determine the amount of Brazilian coffee that needs to be produced and exported to meet the demand in the United States.

$$\sum_n^R k_{np} = d_p \quad (8)$$

The content of Equations (9), (10), and (11) ensure that the distribution of coffee to each roaster is proportional to their market shares (MS). Specifically, Folgers receives 52.3% of the total coffee flow (represented by the constant $MS_{Folgers} = 0.523$), Starbucks (combining all five units) represents 25.8% ($MS_{Star} = 0.258$), and Maxwell accounts for the remaining 21.9% ($MS_{Maxwell} = 0.219$).

$$\sum_p^C k_{Folgers,p} \geq MS_{Folgers} \times \sum_n^R \sum_p^C k_{np} \quad (9)$$

$$\begin{aligned} \sum_p^C k_{StarAug,p} + \sum_p^C k_{StarGast,p} + \sum_p^C k_{StarCarson,p} + \sum_p^C k_{StarKent,p} + \sum_p^C k_{StarYork,p} \\ \geq MS_{Star} \times \sum_n^R \sum_p^C k_{np} \end{aligned} \quad (10)$$

$$\sum_p^C k_{Maxwell,p} \geq MS_{Maxwell} \times \sum_n^R \sum_p^C k_{np} \quad (11)$$

Equation (12) ensures that all the coffee that arrives at a roaster n will leave the facility corrected by a factor (γ) related to the roasting process.

$$\gamma \sum_m^Q w_{mn} - \sum_p^C k_{np} = 0 \quad (12)$$

Equation (13) ensures a balanced distribution in each American port (m). Consequently, all coffee from Brazilian ports must be sent to roasters in the United States.

$$\sum_j^P z_{jm} - \sum_n^R w_{mn} = 0 \quad (13)$$

Equation (14) restates the previous balances from (12) and (13), for the coffee passing through each Brazilian port (j) and ensuring that the total coffee from various producers equals the amount that arrives at the North American ports.

$$\sum_i^L y_{ij} - \sum_m^Q z_{jm} = 0 \quad (14)$$

There must be a proportion of production between Arabica (BA_a, ES_a) and Robusta (BA_r, ES_r) in Bahia and Espírito Santo, represented by the constants $AR_{BA} = 0.6270$ e $AR_{ES} = 0.4085$, respectively. These values are expressed in Equations (15) and (16).

$$y_{BAa,Santos} + y_{BAa,Rio} + y_{BAa,Salvador} - AR_{BA} \times (y_{BAr,Santos} + y_{BAr,Rio} + y_{BAr,Salvador}) = 0 \quad (15)$$

$$y_{ESa,Santos} + y_{ESa,Rio} + y_{ESa,Salvador} - AR_{ES} \times (y_{ESr,Santos} + y_{ESr,Rio} + y_{ESr,Salvador}) = 0 \quad (16)$$

Considering the productivity, the total coffee production in each state is subject to variations. Equations 17 to 20 use the constants (PRO) for modeling the lower limits and (FP) for the productivity variation in each state:

$$\sum_j^P (y_{BAa,j} + y_{BAr,j}) = (PRO_{BA} + FP_{BA}\lambda_4) \sum_i^L \sum_j^P y_{ij} \quad (17)$$

$$\sum_j^P (y_{ESa,j} + y_{ESr,j}) = (PRO_{ES} + FP_{ES}\lambda_5) \sum_i^L \sum_j^P y_{ij} \quad (18)$$

$$\sum_j^P y_{MG,j} = (PRO_{MG} + FP_{MG}\lambda_6) \sum_i^L \sum_j^P y_{ij} \quad (19)$$

$$\sum_j^P y_{SP,j} = (PRO_{SP} + FP_{SP}\lambda_7) \sum_i^L \sum_j^P y_{ij} \quad (20)$$

In this study, the values of (PRO) and (FP) are: $PRO_{BA} = 0.066$, $FP_{BA} = 0.016$, $PRO_{ES} = 0.216$, $FP_{ES} = 0.108$, $PRO_{MG} = 0.506$, $FP_{MG} = 0.089$, $PRO_{SP} = 0.0915$, and $FP_{SP} = 0.0175$.

The study identified locations with the highest coffee production in each state and the fastest access routes to destination ports to determine the distances (x_{ij}). In cases where there was no actual flow of coffee (e.g., from MG to Salvador, from SP to Rio, from SP to Salvador, from BA to Rio, and from ES to Salvador), a distance value of 10,000 km was used. The same approach was also applied to the cost of transporting coffee in the United States, with a base price of US\$ 1,000.00/kg and varying prices for other routes ranging between US\$ 0.004 and US\$ 0.665.

The problem was modeled using the Google Colab platform, involving 184 variables and 53 equations. The Pyomo package [Hart et al. 2011, Bynum et al. 2021] and the Ipopt solver [Wächter and Biegler 2005] were used to effectively address some of the non-linear constraints of the problem using an interior-point method.

3. Results and Discussion

The initial observation from a mathematical and computational standpoint was that using a single (λ) in the objective function was not feasible, as expected based on the study by [Huang et al. 2006]. The algorithm encountered a "locally infeasible point" problem, which meant that while results were generated, they did not adhere to certain constraints. To address this issue, the suggested strategy was to apply an additive method proposed by [Arikan 2013]. This approach made achieving an optimal value possible while respecting all the established constraints for the problem.

The environmental and economic variables were optimized separately, resulting in $f_{EI}^0 = 4,889 \text{ kg } CO_2 \text{ eq}$, $f_{\$I}^0 = US\$ 4,685.71$, $f_{EI}^{max} = 5,871 \text{ kg } CO_2 \text{ eq}$ and $f_{\$I}^{max} = US\$ 5,627.29$. The multi-objective equation with fuzzy parameters yielded $4,925 \text{ kg } CO_2 \text{ eq}$ and $US\$ 4,857.67$. Joint optimization of environmental and economic variables produced more attractive results, especially considering values of $946 \text{ kg } CO_2 \text{ eq}$, and $US\$ 769.62$ difference for every ton of Brazilian coffee supplied to the American consumer. The objective function (average of the fuzzy parameters) achieved an optimal result of 0.82, composed of the values presented in Table 2.

Table 2. Values of fuzzy variables in optimization.

Fuzzy variable	Meaning	Value
λ_1	Deviation of environmental impact from the best value	0.96
λ_2	Deviation of cost from the best value	0.82
λ_3	Variation in mass loss due to roasting	1.00
λ_4	Variation in agricultural productivity in Bahia	1.00
λ_5	Variation in agricultural productivity in Espírito Santo	0.00
λ_6	Variation in agricultural productivity in Minas Gerais	0.98
λ_7	Variation in agricultural productivity in São Paulo	1.00

It is important to note that improving the roasting yield (λ_3) and reducing mass losses in this process results in better environmental and economic performance. By varying the value of (γ) within the possible range (eq. 7), it was possible to generate Figure 1, which illustrates the range between the scenario with more significant loss, resulting in higher cost and environmental impact, and the scenario with lower loss. This difference is mainly due to the smaller volume of coffee to be produced and exported (1,110 kg in the best case and 1,340 kg in the worst case).

The analysis of each stage of the coffee life cycle revealed that agricultural production in Brazil has a significant impact on global results. In the study, the cost amounts to $US\$ 4,405.61$ and the environmental impact is $4,474 \text{ kg } CO_2 \text{ eq}$, which accounts for 90.7% and 90.8% of the total values, respectively. Apart from agricultural production, the most significant cost components are American road transport from roasters to final consumers ($US\$ 205.35$, or 4.2%), and maritime transport between the ports of Brazil and the US ($US\$ 183.07$ or 3.8%). In terms of environmental impact, US road transport from ports to roasters and from roasters to consumer centers contribute with 202 and $220 \text{ kg } CO_2 \text{ eq}$, accounting for 4.1 and 4.5%, of the environmental impact.

The exchange rate between currencies has minimal influence on optimization. For a ratio of $R\$ 4.72/US\$ 1.00$, the economic performance was $US\$ 4,859.46$, representing an increase of $US\$ 1.79$. This occurs because the portion of the cost affected by the exchange rate in Brazilian shipping is insignificant for the total value. However, a lower exchange rate increases the shipping cost, as indicated in the denominator. The cost of Brazilian green coffee, crucial for economic

merit, is influenced by the exchange rate between the Real and the Dollar [Sachs et al. 2019], even though the current problem's solution does not consider such factors. This could be a subject for future studies in the same field.

The values of (λ) show that the best environmental-economic performances occur during times of greater productivity for the states of Bahia, Minas Gerais, and São Paulo. when (λ_4) , (λ_6) and (λ_7) , were 1.0, 0.98, and 1.0, respectively. In this arrangement, agricultural productivity in Espírito Santo (λ_5) may be the minimum predicted by eq. 18 due to the proportion of production in each state and the supply necessary to meet the expected American demand.

The optimal value of $\omega = 0.167$ (eq. 6), shows that the environmental variable has a much more significant weight in this performance. This is reflected in the values of (λ_1) (difference from EI to f_{EI}^0 , with a value of 0.96) and (λ_2) (difference from $\$I$ to $f_{\$I}^0$, of 0.82). In the optimized scenario, the environmental impact is very close to optimal.

The main logistical routes found for the optimal condition were Rio de Janeiro – New Orleans (72.9% of all coffee), Santos – Los Angeles (10.8%), Rio de Janeiro – Seattle (8.1%), and Salvador – New York (5.7%). From the four ports, the division is evident regarding the destination roaster. Folgers and Maxwell are supplied exclusively by the port of New Orleans; Starbucks – Carson Valley receives coffee via the port of Los Angeles, while Starbucks locations in Kent and York are recipients of coffee received by the ports of Seattle and New York. This distribution results from the proximity between the roasting units and those ports. Another aspect that draws attention is the lack of coffee supply at Starbucks units in Augusta and Gaston, a behavior that had also been observed by [Sakamoto et al. 2023]. Table 3 describes the coffee supply for each consumer center, indicating the roasters involved in each situation.

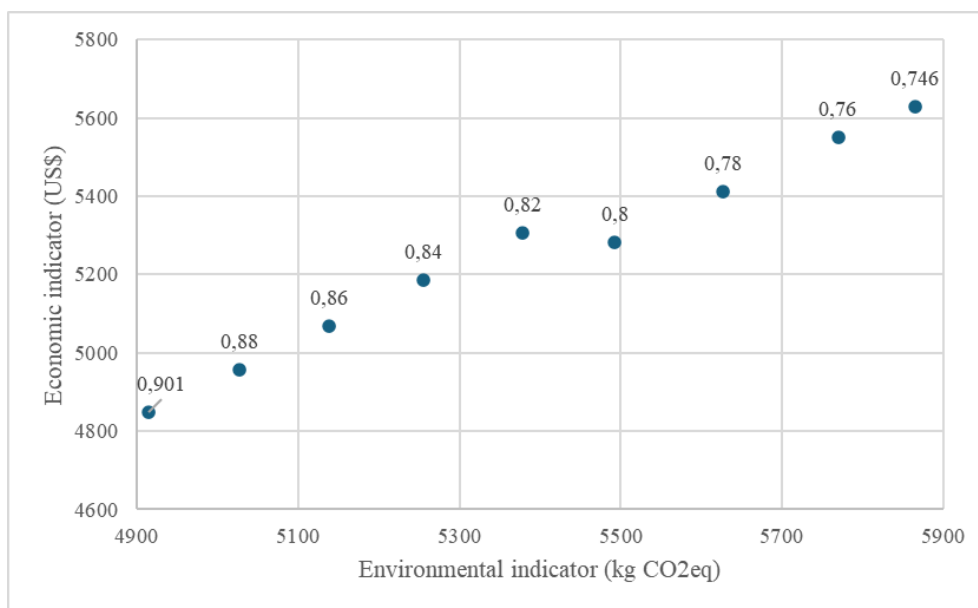


Figure 1. Environmental, and economic performance for different coffee mass percentages after roasting (γ).

The supply of coffee to the US cities is organized as follows: New York must be supplied by all coffee brands due to high demand. In the other cities, only one brand is responsible for meeting the local demand. Starbucks' market is restricted to cities closest to its active roasters: Kent supplies coffee in Seattle and Portland, while Carson Valley distributes to San Francisco and San José, and York, partially to New York. Despite York's proximity to cities like Washington and Philadelphia, Maxwell is responsible for meeting their demands due to the modeling conditions, even though its facility is in a much more distant location (the state of Florida). Due to its extensive

market reach, Folgers can supply its product to the cities of Austin, Houston, and Dallas, as well as the states of California, Colorado, Illinois, and New York close to its headquarters.

Table 3. Coffee supply in each American city by quantity and roasting company.

Cities	Coffee roaster and supply (kg)	Total coffee (kg)
New York	Folgers (107), Maxwell (148), Starbucks (York) (57.7)	314
Los Angeles	Folgers (119.7)	120
Chicago	Folgers (87.1)	87.1
San Francisco	Starbucks (Carson Valley) (75.8)	75.8
Seattle	Starbucks (Kent) (54.9)	54.9
San Diego	Folgers (50.8)	50.8
Houston	Folgers (48.2)	48.2
Philadelphia	Maxwell (37.8)	37.8
Portland	Starbucks (Kent) (37.4)	37.4
Washington	Maxwell (32.8)	32.8
San Jose	Starbucks (Carson Valley) (32.2)	32.2
Phoenix	Folgers (28.7)	28.7
Austin	Folgers (28.5)	28.5
Denver	Folgers (27.4)	27.4
Dallas	Folgers (25.2)	25.2

4. Conclusions and Future Studies

The study conducted a fuzzy optimization with environmental and economic objectives, demonstrating that varying mass losses during roasting can significantly impact performance. Reducing roasting losses could lead to exporting a smaller volume of coffee, positively affecting overall environmental and economic performance. However, changes in roasting processes should be carefully studied due to their impact on product quality, including aroma and flavor. On the other hand, the study found that the variation in the Real–Dollar exchange rate had little noticeable impact on the optimization results. The exchange rate indirectly influences the cost of coffee; incorporating these aspects into the problem modeling could enhance robustness.

Regarding logistics, the optimized arrangement focuses on concentrating product flow on a few routes and distributing coffee as evenly as possible. This involves dedicating ports and roasters to serve specific regions. Future work could include considering all American cities supplied by all companies. Still, it is expected to result in a less favorable environmental and economic performance compared to the findings of this study.

Finally, the research provides insights for future research on improving the roast and ground coffee production process and optimizing the coffee supply chain to meet market and societal demands, promoting the sustainability of this vital product in the world market.

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