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Using the Life Cycle Approach for Multiobjective Optimization in the Context of the Green Supply Chain: A Case Study of Brazilian Coffee

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Abstract: This study proposes a multiobjective optimization model (MOO) based on a green supply chain so that coffee produced in Brazil could supply the North American market with lower environmental impacts and costs. Production and distribution arrangements were established considering four coffee-producing regions, three ports of origin in Brazil, four destination ports, seven roasting plants, and fifteen consumption centers, all distributed throughout the American territory. Environmental and economic performances regarding global warming potential (GWP) and costs were determined for a life cycle approach. The results indicate that coffee cultivation has the most significant contributions to the GWP of the arrangements. The transport of the product by road also plays an essential role, especially if extensive distances are covered during the port–roaster–consumer center journey in the United States. The analysis showed differences of 2.0 kg CO_{2eq} and US$8.00 per ton of coffee between the best and worst arrangements, which can be considered significant when projected to the Brazilian annual coffee export scale. In the environmental limit condition, the optimization can lead to non-trivial results compared to the real market. The model conceived for the MOO can be improved to reproduce more realistic conditions by incorporating producer and consumer markets, inserting uncertainties.

Keywords: life cycle assessment; multiobjective optimization; Brazilian coffee; green supply chain

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Citation: Sakamoto, H.; Bruschi, L.T.; Kulay, L.; Yamakami, A. Using the Life Cycle Approach for Multiobjective Optimization in the Context of the Green Supply Chain: A Case Study of Brazilian Coffee. *Sustainability* **2023**, *15*, 13987. https://doi.org/10.3390/su151813987

Academic Editor: Riccardo Testa

Received: 15 August 2023
Revised: 14 September 2023
Accepted: 18 September 2023
Published: 20 September 2023

1. Introduction

As one of the most consumed beverages worldwide, coffee has become a commodity of great economic significance [1]. This is so true that in 2023 alone, the global coffee industry is expected to process just over 167 million 60 kg bags of the product, which at current prices projects a revenue of US$496 billion [2]. In recent years, the coffee supply–demand binomial has become quite polarized: on the one hand, only six countries have the largest share of green bean production, i.e., Brazil (37%), Vietnam (17%), Colombia (8.4%), Indonesia (7.0%), and Ethiopia (4.3%) [3], while on the other hand, the European Union (63%) and the United States, its leading consumer on a global scale (~18%), are frequent destinations for roasting and subsequent consumption [4].

As with other world-class products, coffee production and distribution chains are susceptible to limitations. Examples are (i) the low financial return for the rural producer [5], which was significantly affected by the pandemic of COVID-19 [6]; (ii) the vulnerability of supply in extreme weather scenarios [7]; (iii) the economic disparity between producing and consuming countries, characterized by exchange rate differences [5]; and (iv) distribution logistics difficulties, often due to the poor infrastructure conditions of roads and ports [8].

These problems affect the sustainability of the coffee business and penalize (sometimes severely) the producer [9].

The improvement in coffee production and distribution chains could be seen as a classic supply chain management (SCM) exercise whose objective is "to produce value at lower costs" if the abovementioned factors did not influence this logic. This is because, besides the economic effects, some of these conditions bring environmental consequences of systemic magnitude, affecting different stages of the production arrangement [10]. Therefore, if observed from this perspective, the problem would corroborate the green supply chain management (GSCM) concept of "improving product supply by reducing costs and emissions to the environment" [11]. The GSC transcends the action limit of interventions based on SC principles—aimed only at increasing the profitability of products and services and improving consumer satisfaction—by proposing measures capable of minimizing environmental impacts resulting from their production and consumption (or application). The GSC can evolve into sustainable supply chain management (SSCM) condition if it includes social aspects in its analyses [12].

The need to coordinate the economic, environmental, and social dimensions may lead to trade-offs between these objectives, which increase the complexity of the SCM problems, making their solutions require holistic modeling involving several variables and restrictions [13,14]. The artifice found by the scientific community to deal with cases of simultaneous and conflicting objectives was to improve the existing multiobjective optimization (MOO) techniques. In this field, we highlight the works developed by Asha et al. [14] and Jayarathna et al. [15].

In the search for a consistent set of solutions, MOO techniques use performance indicators to characterize the optimal functions under analysis. The life cycle assessment (LCA) technique can generate these indicators in the environmental domain. In general, LCA quantifies environmental and human health impacts that result from fulfilling a specific function by a product, process, or service [16]. In addition to adhering to the principles of GSC, the synergy between MOO and LCA continues to have research potential [15], although the first available reports in the literature on this combination date back more than two decades [17,18].

The coffee processing and distribution chain has already been the object of LCA application, in which Salomone [19] sought to identify opportunities to improve environmental performance in that arrangement. More recently, Giraldi-Díaz et al. [20] followed the same direction when determining coffee production's carbon, water, and energy footprints in Mexico. After modeling the system from cultivation to coffee preparation (roasting and grounding), the authors concluded that the agricultural steps could accumulate up to two-thirds of the product's total energy and carbon footprint. At the same time, the industrial transformations are responsible for the main contributions (54%) to water footprint.

Phrommarat [21] used LCA to compare three types of Arabica brewing coffee produced in Thailand for an arrangement comprising cultivation, preparation, and consumption. Again, agricultural activities stood out as sources of environmental impacts of the products analyzed. Moreover, the author discouraged preparing the beverage using moka pots because of high electricity consumption, whose local generation occurs predominantly from natural gas and coal.

Nab and Maslin [22] also performed an LCA carbon footprint study for Arabica coffee, considering two producers (Brazil and Vietnam) and one final consumer (United Kingdom). The authors observed a marked difference in environmental impacts in favor of coffee produced from principles of environmental sustainability compared to that obtained from conventional practices. Usva et al. [23] determined the carbon and water footprint of coffees originating in Latin American countries (Brazil, Nicaragua, Colombia, and Honduras) and roasted in Finland for domestic consumption. For these situations, the authors identified agricultural processing as the primary precursor of greenhouse gases (GHGs) in all the production chains analyzed. Finally, Brenes-Peralta et al. [24] used LCA and environmental life cycle costing (E-LCC) to understand the decision-making behavior of smallholder coffee farmers in Costa Rica. Again, in this situation, cultivation was shown to be the majority source of environmental impacts and costs associated with green coffee. The authors also noted that biodiversity and GHG emissions are linking factors, while water consumption is a dependent factor.

If, on the one hand, LCA has contributed to an improvement in the coffee supply chain, on the other hand, only two records were found in the scientific literature on optimization exercises with a sustainability bias for this same arrangement. These are the studies by Torabzadeh et al. [11], who used fuzzy variables to establish optimal conditions for the operation of coffee manufacturing and distribution centers in Iran, and Baratsas et al. [25], who analyzed coffee to create an optimization framework aimed at the circular economy of food supply chains. Furthermore, no publications were found in which coffee supply chain optimization models were developed based on LCA results.

This study aims to fill these gaps, even if partially, by proposing a multiobjective optimization model based on GSC principles so that the coffee produced in Brazil can fully supply the US market with lower environmental impacts and costs. To this end, the coffee supply chain between the two countries was modeled regarding resource consumption, emissions, and expenses according to a life cycle perspective with a scope of "cradle-to-consumer." First, the cultivation of green coffee of the Arabica and Robusta varieties was described based on the technologies practiced in Brazil's four leading producing states. This was followed by modeling this commodity's distribution networks to the final consumer in the US, including the roasting process in that region. Thus, this article aims to contribute in the following respects:

- Check the feasibility of performing multiobjective optimization mainly under the life cycle perspective.
- Understand the behavior of a supply chain more clearly when considering the environmental variable, even when it comes to the limit situation to distrust the economic variable.
- To help managers, farmers, retailers, and other stakeholders that act in the manufacturing chain of national coffee to develop cost reduction strategies and meet the (growing) demands for the product's environmental sustainability.

2. Materials and Methods

To satisfactorily meet the proposed objectives, this study was structured in the following stages: (i) characterization of the production chain (agricultural and industrial) and distribution chain (routes, modals, types of vehicles, and their capacities) of Brazilian (BR) coffee to the final consumer in the United States (US) in technical, resource consumption and emissions, and cost terms; (ii) elaboration of environmental and economic performance indicators for these supply alternatives; (iii) proposition of a model based on MOO so that the demand is met with minimal environmental impacts and costs; and (iv) discussion of the results obtained and suggestion of actions to improve the algorithm.

2.1. General Aspects Related to Brazilian Coffee and the American Consumer Market

For this study, the Brazilian coffee processing and distribution chain for the US was specified as an arrangement that sequences the steps of (i) green coffee (BR) production; (ii) transportation of the agricultural input to the ports of origin; (iii) transoceanic transfer to destination ports (US); (iii) displacement to roasting plants; (iv) green coffee roasting and blend production; and (v) distribution of the final product to consumer centers.

Although complementary in terms of performance, the coffee varieties cultivated in Brazil on a large scale—e.g., Arabica and Robusta (or Conilon)—differ in aspects, such as color, function in the blend, and agricultural productivity. According to Table 1, between 2018 and 2022, the production of these species was concentrated in the states of Minas Gerais (the most significant national producer), Espírito Santo, São Paulo, and Bahia. Therefore, the modeling of agricultural processing considered the technologies used in each of these zones to obtain Arabica and Robusta coffee, which, in addition to the type and variety of cultivars, are conditioned by natural aspects such as sunlight, edaphoclimatic conditions, and relief.

Table 1. Arabica and Robusta coffee production between 2018 and 2022 (in thousands of 60 kg bags).

Brazilian State	Variety of Coffee	Production Year				
		2018	2019	2020	2021	2022 (1)
Minas Gerais (MG)	Arabica	32,970	24,235	34,337	21,859	26,687
São Paulo (SP)	Arabica	6302	4340	6181	4007	4886
Bahia (BA)	Arabica	1880	1200	1867	1229	1704
	Robusta	2670	1800	2120	2240	2256
Espírito Santo (ES)	Arabica	4751	3002	4765	2945	4250
	Robusta	8988	10,496	9193	11,221	11,600
Total Brazil	Arabica	47,484	34,296	48,737	31,424	38,784
	Robusta	14,174	15,013	14,311	16,293	16,959

(1) Estimated value for January/2022. Source: Conab [26].

During the characterization of agricultural technologies, the ten municipalities in each state with the highest productivity of Arabica and Robusta green coffee were also identified. This information was used to establish a single geographic center representative of each agricultural production zone, from which it was possible to estimate the distance to the coffee export ports. According to the Foreign Trade Statistics of the Ministry of Economy (Comex Stat), the ports of Santos, Rio de Janeiro, and Salvador dispose of coffee to the United States [27]. Figure 1 highlights the positions of the coffee zones in the states considered in the modeling and the location of the ports of shipment of this commodity in the Brazilian territory.

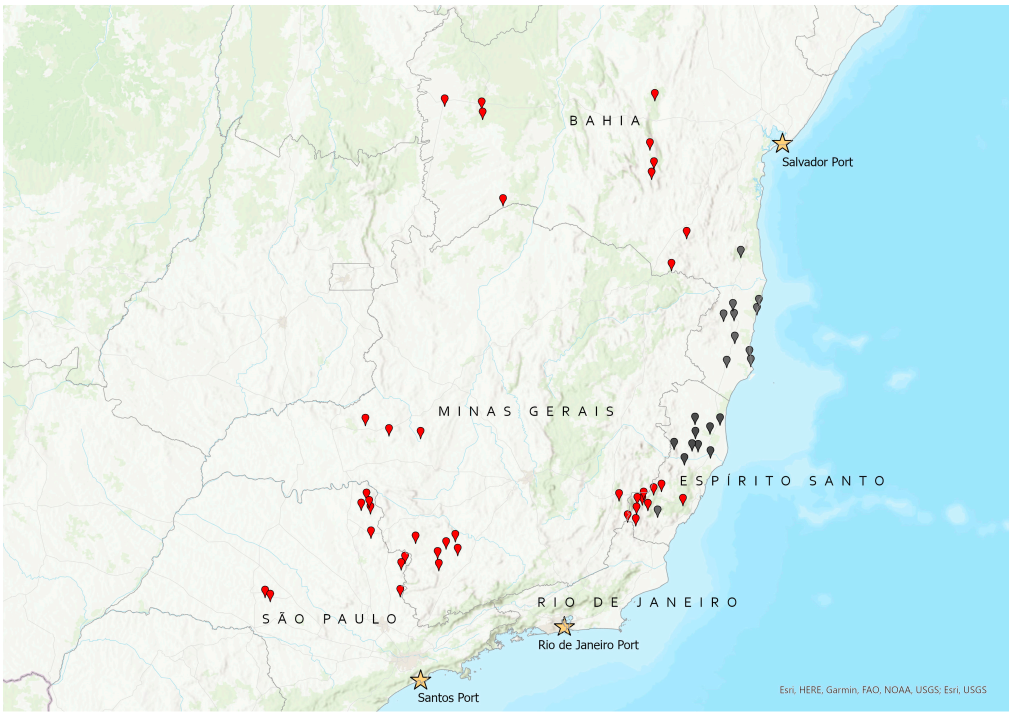

Figure 1. Detail of the map of Brazil indicating Arabica (red pins) and Robusta (black pins) coffee-producing regions and the product's ports of destination (stars) considered in the modeling.

The North American territory was divided into four quadrants to model the alternatives of arriving coffee: northeast, entry via the Port of New York; southeast, via the Port of New Orleans; southwest, Port of Los Angeles; and northwest, Port of Seattle. This breakdown was based on the product's most common destinations and the roasters' location.

The roaster segment in the US is dominated by three companies: Folgers, which serves just over 25% of domestic consumers; Starbucks (12%); and Maxwell House (10%). In addition to them are the so-called private brands, a group composed of numerous small brands (some even artisanal) that control about 11% of the market [28]. Because of this distribution, as well as the availability of data on technical and environmental performance, production costs, and the exact geographical location of the industrial units, it was decided to model this stage of the production chain, considering only the leading suppliers of roasted coffee.

The coffees distributed by Folgers and Maxwell are roasted in single plants but with large production capacities that are located, respectively, in New Orleans [29] and Jacksonville (Florida) [30]. Starbucks, on the other hand, operates with a decentralized model for which it has six roasters set up in Augusta (Georgia), Carson Valley (Nevada), Gaston (South Carolina), Kent (Washington), and York (Pennsylvania) [31] that perform the same process.

Finally, the specification of the distribution model of roasted coffee to the places of consumption was based on the annual value of sales, shipments, receipts, revenue, or business disclosed by the US Census Bureau [32]. This analysis considered only cities with over $100 million in revenues to define coffee consumer centers. From these data, it was possible to identify the 15 cities that consume the most beverage in the American territory: New York, Los Angeles, Chicago, San Francisco, Seattle, San Diego, Houston, Philadelphia, Portland, Washington DC, San Jose, Phoenix, Austin, Denver, and Dallas. Figure 2 concentrates in a single image the ports of entry for coffee in the US, the location of the roasters, and their final destinations in the country.

Figure 2. Detail of map of the United States with markings of coffee entry ports in the country (stars), roasting units (industry icons), and consumer centers (red pins).

2.2. Environmental and Economic Life Cycle Modeling

The system's environmental performance under analysis was determined by the LCA technique in the attributional modality and with a "cradle-to-consumer" scope of application. For this, methodological guidelines established by ISO 14,044 [33] were followed. The reference flow (RF) defined for conducting the analysis consisted of "making available 1.0 kg of roasted and ground Brazilian coffee at the distribution point (i.e., coffee shop, supermarket, store) of a large North American consumer center."

The life cycle inventory (LCI) was developed exclusively from secondary data extracted from the Ecoinvent database and adapted by including information available in scientific articles and technical reports to reflect the conditions under which the diagnosis should be formulated. Regarding data quality, the consumption and emissions were collected for the period 2018–2021 (temporal coverage) and refer, respectively, to the (i) green coffee-producing regions (BR), (ii) the cities where roasting and grinding take place, and (iii) the consumption centers (US) indicated in Section 2.1 (geographical coverage). Finally, agricultural and industrial processing and logistics activities were modeled considering their specific technologies; when this was not possible, conventional practices were adopted to describe their relationship with the environment (technological coverage).

The multifunctional situations identified in the system under analysis were treated by allocation. This procedure used energy content criteria to distribute the environmental loads generated during refining diesel oil (consumed in agricultural machinery and vehicles) and mass criteria to spread the consumption and emissions originating in the transoceanic cargo transportation.

The LCIs of coffee cultivation and harvesting in Brazil were elaborated by adjusting the "Coffee, green bean (BR) | Coffee green bean production, Arabica | APOS, U" and "Coffee, green bean {BR} | coffee green bean production, Robusta | APOS, U" databases of Ecoinvent [34], with data from Coltro et al. [35], and taking into account the average agricultural productivities of Minas Gerais, Espírito Santo, São Paulo, and Bahia for 2018–2019 through 2020–2021 crops [26].

The Brazilian electricity matrix was formulated by a similar procedure, in which the database "Electricity, high voltage, production mix BR | APOS, U" [36] received information from the National Energy Balance of 2021 [37]. Furthermore, electricity, natural gas (US) consumption and the mass ratio between green coffee and ground roasted coffee were obtained from Giraldi-Díaz et al. [20]. Finally, concerning transport operations, the EURO 4 and EURO 5 truck models were used for domestic road travel in Brazil and the US, respectively. For both cases, it was also assumed that the load capacity of the vehicles was 7.5–16 metric tons. The overland distances traveled during the displacements in the two countries were estimated using the site maps.google.com [38]. Similarly, the transoceanic extensions to the routes between ports were calculated by the site SeaRates.com [39].

Because this is an exploratory, prospective study intended to support decision-making processes, we decided that the environmental performance diagnosis should consider an extensive and varied number of impact categories. Thus, we decided to examine the behavior of schemes in terms of the following effects: acidification (terrestrial), ecotoxicity (fresh and marine water and terrestrial), eutrophication (fresh and marine water), fine-particle formation, global warming potential, human carcinogen and non-carcinogenic toxicity, ionizing radiation, land use, ozone formation (human health and terrestrial ecosystems), scarcity of fossil and mineral resources, stratospheric ozone depletion and water consumption.

Conversely, to solve the optimization problem, the global warming potential (GWP) only represented the environmental variable. The indicator was selected (i) because it is frequently used in management processes related to the coffee production chain [20–23], (ii) because it has proven effective in describing the environmental impacts of arrangements similar to that under study in optimization exercises [11,25], and (iii) because it is systemic, by recording contributions from all stages of the manufacturing (agricultural and industrial) and distribution (logistics) chain. GWP was estimated from the method proposed by the Intergovernmental Panel on Climate Change (IPCC) 2013—100 years [40]. The conceptual and mathematical foundations adopted by LCA to quantify environmental impacts during the life cycle impact assessment (LCIA) stage are reported by Moore and Kulay [41]. The LCIs and the LCIA were performed using the software SimaPro v. 9.2.0.2, distributed by PRé Sustainability®.

2.3. Optimization Modeling

This optimization problem can be treated using the weighting sum method [42], and is therefore described in mathematical terms by the relationship presented in Equation (1):

$$\min(1-w)\left(\frac{EI}{f_{EI}^{0}}\right)+w\left(\frac{\$I}{f_{\$I}^{0}}\right) \quad (1)$$

where (EI) refers to the sum of environmental impacts in terms of GWP originating from the distribution of Brazilian coffee to all North American consumption centers, and $(\$I)$ is the sum of costs associated with the same supply. These parameters were converted into normalized indices after being divided by the respective optimal values—e.g., the utopia points [40]; that is, (f_{EI}^{0}) for the environmental dimension and $\left(f_{\$I}^{0}\right)$ for the economic domain. Normalization corrected the difference in magnitude between the objective functions, thus allowing them to be added [43]. Parameter (w) reflects the degree of preference of the decision-maker concerning each dimension (environmental and economic), and its amplitude varies between $0 \leq w \leq 1$ [44].

The value of (EI), expressed in kg $CO_{2,\,eq}$, was calculated by applying Equation (2):

$$\begin{aligned} EI = \; & \sum_{i}^{6}\sum_{j}^{3} EIPROD_{i}y_{ij} + \sum_{i}^{6}\sum_{j}^{3} EIFBR_{ij}x_{ij}y_{ij} + \\ & \sum_{j}^{3}\sum_{m}^{4} EIFRE_{jm}z_{jm} + \sum_{m}^{4}\sum_{n}^{7} EIRST_{mn}w_{mn} + \sum_{n}^{7}\sum_{p}^{15} EIDIST_{np}k_{np} \end{aligned} \quad (2)$$

where $(EIPROD)$: environmental impact (kg $CO_{2,\,eq}$/kg coffee) generated during the agricultural processing of coffee in each producing region of Brazil; $(EIFBR)$: environmental contribution due to road transport from the farm to the port of origin (kg $CO_{2,\,eq}$/(kg coffee.km)); $(EIFRE)$: impact of sea freight between Brazilian and US ports (kg $CO_{2,\,eq}$/kg coffee); $(EIRST)$: impact caused by the road transfer between the American port of destination and the roaster (kg $CO_{2,\,eq}$/kg coffee), and $(EIDIST)$: portion referring to the road transport that takes place on American territory between each roaster and the consumption centers supplied by it (kg $CO_{2,\,eq}$/kg coffee). As already mentioned, the values of each of these plots were determined by applying the LCA technique for the previously described conditions.

On the other hand, the total cost $(\$I)$ associated with the production and distribution cycles of the product, expressed in US$, was determined by applying Equation (3):

$$\begin{aligned} \$I = \; & \sum_{i}^{6}\sum_{j}^{3} CPROD_{i}y_{ij} \\ & + \sum_{i}^{6}\sum_{j}^{3}\left[\frac{(CDCx_{ij}+LUC+WTC)y_{ij}}{(R\$\rightarrow US\$exchange)\times(450\times 60)}\right] \\ & + \sum_{j}^{3}\sum_{m}^{4} CFRE_{jm}z_{jm} + \sum_{m}^{4}\sum_{n}^{7} CRST_{mn}w_{mn} + \sum_{n}^{7}\sum_{p}^{15} CDIST_{np}k_{np} \end{aligned} \quad (3)$$

where $(CPROD)$ is the cost of coffee production (in US$/kg coffee) in each place in Brazil where this occurs, $(CFRE)$ is the cost of maritime freight between the Brazilian and American ports (in US$/kg coffee), $(CRST)$ corresponds to the cost of shipment from the docks to the roasters (in US$/kg coffee) and, finally $(CDIST)$ refers to the freight to be paid to transport the coffee from the roasting plant to the cities where the product will be consumed (in US$/kg coffee).

The $(CPROD)$, the first term of the equation, was estimated from values calculated by the Center for Advanced Studies in Applied Economics (CEPEA) at the Luiz de Queiroz College of Agriculture at the University of São Paulo (Esalq-USP) [45].

The second term of Equation (3) is represented by the algorithm applied by the Agência Nacional de Transportes Terrestres (ANTT) [46] for estimates of road freight values in Brazil. The equation gathers three parameters. The first consists of the compound displacement cost (CDC), which is the cost per kilometer of coffee displacement from the producing regions to the port of boarding. In this study, it was assumed that $CDC = 3.3189\ R\$/\text{km}$.

The following parameter is the loading and unloading cost (LUC) of coffee in trucks, set at 279.72 R$ for the study conditions. Finally, the third parameter (WTC), weighted toll cost, corresponds to the toll costs (TC) of the displacements between the producing regions and the ports of shipment of coffee. The (TC) value is conditioned by the coffee origin and the distance covered during the distribution. During the period of data collection, this parameter varied between $8.70 < TC\ (R\$) < 487.50$ [47]. CDC, LUC, and WTC estimates were made for three-axle trucks.

These results underwent two corrections to align with other plots that integrate that mathematical expression. The first consisted of an exchange rate conversion to American dollars (US$) since the algorithm adopted by ANTT calculates freight values in Brazilian reals (R$). The second adjustment is related to the mass of coffee to be transported. It is due to freight estimates considering the truck's full load (450 bags of coffee/truck $\times$ 60 kg/bag), which is different from the reference established to calculate $(\$I)$ of 1.0 kg of roasted and ground Brazilian coffee delivered at the distribution point at the United States.

The contributions of $(CFRE)$ were influenced by the unavailability of precise data for many of the transoceanic displacements considered in the model. Because of this, we decided to carry out a projection test to dampen this undesirable effect and obtain results for this parameter with a degree of consistency equivalent to those of the other components of Equation (3). Initially, the cost of maritime freight between the main ports of origin (Santos) and the destination (New Orleans) [48] of the coffee was collected from the literature.

The value of $(CFRE)$ calculated from the references consulted, of 0.16 US$/kg coffee, proved consistent with those released by Brazilian official bodies for this class of transport [48]. From this, we estimated the freight costs of the other sea journeys assuming that they would vary linearly with the distances covered.

The $(CRST)$ and $(CDIST)$ terms, referring to road freight in the United States, were obtained from average costs for carrying out this service in the country's west, south central, midwest, southeast, and northeast regions [49]. For cases of interregional transport, the average between the individual values of the areas involved in the displacement was considered. As in Brazil, these totals were also adjusted to represent the reference base adopted by the study when divided by the average truck load (220 bags/truck $\times$ 60 kg coffee/bag).

Along with the equations designed to determine (EI) and $(\$I)$, restrictions were also proposed to guide the application of those models. The first of them (Equation (4)) establishes that the amount of roasted coffee distributed in each consumer center in the United States must never be less than the minimum demand in the region (d_p). A correction factor (f = 0.746) was applied to this total to discount regular coffee losses during roasting. The value of (f) was determined from the data collected by Giraldi-Díaz et al. [20].

$$\sum_{n}^{7} k_{np} \geq 0.746 d_p \tag{4}$$

The restrictions described by Equations (5)–(7) seek to ensure that the distribution of coffee among roasters is proportional to the markets they will serve. The normalization of market shares was performed considering that the American coffee demand was served by its three leading brands (Section 2.1) [28]. Because of this assumption, Folgers handles 52.3% of the total coffee received in the country, while Starbucks (considering the production of its five plants—Augusta, GA; Carson Valley, NV; Gaston, SC; Kent, WA; and York, PA)—and Maxwell accumulate 25.8% and 21.9% of the transactions that occur in the same segment, respectively.

$$\sum_{p}^{15} k_{Folgers,p} \geq 0.523 \sum_{n}^{7} \sum_{p}^{15} k_{np} \quad (5)$$

$$\sum_{p}^{15} k_{Stb-Augusta,p} + \sum_{p}^{15} k_{Stb-C.Valley,p} + \sum_{p}^{15} k_{Stb-Gaston,p} + \sum_{p}^{15} k_{Stb-Kent,p} + \sum_{p}^{15} k_{Stb-York,p} \geq 0.258 \sum_{n}^{7} \sum_{p}^{15} k_{np} \quad (6)$$

$$\sum_{p}^{15} k_{Maxwell,p} \geq 0.219 \sum_{n}^{7} \sum_{p}^{15} k_{np} \quad (7)$$

The following restriction determines that the absolute losses generated by the roasting process are proportional to the amount of input distributed to that unit. The modeling of this condition was described by Equation (8), based on the relation between the total coffee produced by a roaster (n) and the amount of natural material delivered to it, multiplied by the correction factor (Equation (4)).

$$0.746 \sum_{m}^{4} w_{mn} - \sum_{p}^{15} k_{np} = 0 \quad (8)$$

Equation (9) specifies the same concept for each port in the United States (m). This restriction ensures that the coffee loaded in Brazilian ports is fully distributed to American roasters.

$$\sum_{j}^{3} z_{jm} - \sum_{n}^{7} w_{mn} = 0 \quad (9)$$

Another restriction uses the same approach to describe the behavior of the coffee that transits in each port of Brazil (j). For this case, Equation (10) presents a mass balance, without losses, between the sum of the quantities of coffee from the different national producers and the total of the same input that arrives at North American ports.

$$\sum_{j}^{6} y_{ij} - \sum_{m}^{4} z_{jm} = 0 \quad (10)$$

The restriction depicted by Equation (11) establishes that the calculation base adopted by the study, which corresponds to the total amount of green coffee produced in Brazil, has a reference value of $C_{BR} = 1000$ kg. This calculation base was used since the actual coffee flow has a magnitude of millions of tons. Conversely, the application of smaller quantities (e.g., 1.0 kg) could generate some inaccuracies due to rounding operations.

$$\sum_{i}^{6} \sum_{j}^{3} y_{ij} = 1000 \quad (11)$$

Statistics prepared by the National Supply Company (CONAB) [26] report that in the states of Bahia and Espírito Santo, there is a division between the production of Arabica (BA_A, ES_A) and Robusta (BA_R, ES_R) coffee. These relationships are expressed concerning the distribution ports (Santos: St, Rio de Janeiro: RJ, and Salvador: Sv) through the restrictions represented by Equations (12) and (13).

$$y_{BA_{A,St}} + y_{BA_{A,RJ}} + y_{BA_{A,Sv}} - 0.6270 \times \left(y_{BA_{R,St}} + y_{BA_{R,RJ}} + y_{BA_{R,Sv}} \right) = 0 \quad (12)$$

$$y_{ES_{A,St}} + y_{ES_{A,RJ}} + y_{ES_{A,Sv}} - 0.4085 \times \left(y_{ES_{R,St}} + y_{ES_{R,RJ}} + y_{ES_{R,Sv}} \right) = 0 \quad (13)$$

Coffee production in each state was also subject to restrictions established according to the local average agricultural productivity. This occurred by setting lower and upper limits for those performances (Equations (14)–(17)). These data were also obtained from Conab [26] for 2017 to 2021.

$$66.1 \leq \sum_{j}^{3}\left(y_{BA_{A,j}} + y_{BA_{R,j}}\right) \leq 81.7 \quad (14)$$

$$216 \leq \sum_{j}^{3}\left(y_{ES_{A,j}} + y_{ES_{R,j}}\right) \leq 324 \quad (15)$$

$$506 \leq \sum_{j}^{3} y_{MG_j} \leq 595 \quad (16)$$

$$91.5 \leq \sum_{j}^{3} y_{SP_j} \leq 109 \quad (17)$$

The (x_{ij}) distances were defined based on identifying the shortest routes between the coffee-producing areas and the ports of origin used for transoceanic transfers. For the roads that were already known beforehand not being used for the transport of coffee (i.e., MG—Port of Salvador; SP—Port of Rio de Janeiro; SP—Port of Salvador; BA—Port of Rio de Janeiro; and ES—Port of Salvador), we applied an initial value of distance $L = 10,000$ km, without establishing a range of variation. As a result, these trajectories were no longer considered by the model. The same strategy was used to consider costs associated with transporting coffee in the United States: the longest distribution routes (and for that very reason, less likely), which connect US ports–roasters–consumer centers, had an associated cost of US$1000.00/kg coffee, while the amounts adopted for regular routes varied: US$0.004–0.665/kg [49].

The association of all the equations were presented before generating an optimization problem with 174 variables and 48 restrictions. As such, we chose to model it in the Google Colab environment, using the Pyomo optimization package as a support resource [50,51]. The presence of non-linear constraints led to the inclusion of the Ipopt solver [52] to handle the problem.

3. Results and Discussion

3.1. Environmental Analysis: Life Cycle Assessment Results

Table 2 presents the LCA results obtained for the supply of 1.0 kg of Brazilian coffee to the 15 main consumption centers of the beverage in the United States. A preliminary analysis of the values revealed little variability between the performances of the routes under study for many impact categories selected during life cycle modeling. Because of this, only the impacts that showed significant differences between results—i.e., those with a ratio between the standard deviation and the mean $\left(\frac{s}{\bar{x}}\right) > 1.0\%$—were considered for diagnostic purposes. This limitation meant that the effects of acidification (terrestrial), ecotoxicity (freshwater), eutrophication (fresh and marine water), human non-carcinogenic toxicity, ionizing radiation, land use, stratospheric ozone depletion, and water consumption were no longer included in the analysis.

Considering the other impacts, the arrangements with the best environmental results culminated in the distribution of coffee in the northeast region of the United States—in Washington DC and Philadelphia—and the state of Texas, in the cities of Austin, Dallas, and Houston. At the other extreme, accumulating the most significant environmental impacts of the series are the American northwest—Seattle and Portland—consumption centers, followed by the California markets: San Francisco, San Jose, San Diego, and Los Angeles.

Table 2. Environmental performance results associated with the distribution of 1.0 kg of roasted and ground Brazilian coffee to the main centers of consumption in the United States.

Consumption Center	GWP (kg CO_{2eq})	O_3F, HH (g NO $_{xeq}$)	FPMF (g $PM2.5_{eq}$)	O_3F, TE (g NO $_{xeq}$)	TEcoT (kg 1,4-DB)	MEcoT (g 1,4-DB)	HCTox (g 1,4-DB)	MRS (g Cu $_{eq}$)	FRS (kg oil $_{eq}$)
Austin	6.19	26.3	17.0	27.1	20.8	535	424	29.1	0.89
Chicago	6.25	26.5	17.1	27.3	21.7	538	428	29.2	0.91
Dallas	6.17	26.3	17.0	27.1	20.5	535	423	29.1	0.89
Denver	6.37	27.1	17.2	27.9	23.2	542	436	29.5	0.95
Houston	6.14	26.2	17.0	27.0	20.0	533	420	29.0	0.87
Los Angeles	6.48	27.4	17.3	28.2	24.8	546	443	29.7	0.99
New York	6.19	26.3	17.0	27.1	20.8	535	424	29.1	0.89
Philadelphia	6.17	26.2	17.0	27.0	20.5	534	422	29.1	0.88
Phoenix	6.41	27.2	17.3	28.0	23.8	544	439	29.6	0.97
Portland	6.56	27.7	17.4	28.6	25.8	549	448	29.9	1.02
San Diego	6.47	27.3	17.3	28.2	24.6	546	442	29.7	0.99
San Francisco	6.55	27.6	17.4	28.4	25.7	549	448	29.8	1.01
San Jose	6.54	27.5	17.4	28.4	25.6	548	447	29.8	1.01
Seattle	6.56	27.7	17.5	28.6	25.9	549	449	29.9	1.02
Washington DC	6.13	26.1	16.9	26.9	19.9	533	420	29.0	0.87

Legend: GW—global warming; O_3F, HH—ozone formation, human health; FPMF—fine particulate matter formation; O_3F, TE—ozone formation, terrestrial ecosystems; TEcoT—terrestrial ecotoxicity; MEcoT—marine ecotoxicity; HCTox—human carcinogenic toxicity; MRS—mineral resource scarcity; FRS—Fossil Resource Scarcity.

Neither the origin of Brazilian coffee (cultivation zone and respective agricultural productivity) nor the variety (Arabica or Robusta) brought significant contributions to the analyzed categories. The roasting of green coffee also had little contribution. However, the finished product's distribution logistics were the main source of impact. In this field, the composition of the American roasting market and the location of the companies that dominate the sector were determinants of the environmental results of each arrangement. Folgers, Starbucks, and Maxwell House have factories close to each other and to the state of Texas, which justifies the favorable results obtained by Austin, Dallas, and Houston. Likewise, the existence of a Starbucks unit in York was decisive in cushioning the effects of coffee distribution to New York, Philadelphia, and Washington, DC, since the products marketed by Folgers and Maxwell in these centers travel relatively long routes.

Conversely, although Starbucks process coffee in Carson Valley and Kent, the environmental metrics of California and the northwest zone of the US are harmed because Folgers and Maxwell coffees must cross the country by road to supply their markets.

When checking the results for global warming potential, the category selected to describe the environmental domain during the optimization exercise, expressive participation of agricultural coffee processing in the global impact of the analyzed arrangements was noticed. The sum of the installments referring to the practice of these activities in the Brazilian producing regions (BA, ES, MG, and SP) resulted in 5.31 kg CO_{2eq}/RF, that is, between 81% and 87% of the total GWP of the scenarios. This result corroborates records available in the literature [20,23,53].

The practices and technical recommendations exercised in Brazil for coffee cultivation resulted in 1.34 kg CO_{2eq}/RF originating from CO_2 and N_2O releases due to the manufacture and application of lime (soil acidity correction) and urea (nitrogen source) and the use of agricultural machinery to optimize planting, fertilization, coffee plantation, and product harvesting [54]. The biowaste (stem, leaves, roots, and plant remains) generated due to the periodic cleaning of the orchard is another relevant impact focus. Each kilogram of coffee supplied to the American consumer brings together 781 g CO_{2eq} because of the incineration of these wastes, which emits biogenic CH_4 because it is carried out under inadequate conditions [34].

The other stages of the coffee supply chain contribute in small amounts to GWP. The transport of green grains from rural areas to the outlet ports brings an accumulated impact of 210 g CO_{2eq}/RF (152 g CO_{2eq} to the Port of Santos, 52.2 g CO_{2eq} to the Port of Rio de Janeiro, and 5.75 g CO_{2eq} to the Port of Salvador). Given the tanking volume of the freighters, the contributions caused by transoceanic locomotion were negligible; the same phenomenon occurred with roasting. These findings also align with literature reports [22,53]. The effects of coffee distribution by road from destination ports to roasters added up to 349 g CO_{2eq}/RF of accumulated impact. These portions are common to products supplied to consumer markets, regardless of location. Conversely, the final stage of logistics, referring to road transport of roasted and ground coffee to the center of consumption, imposed contributions that ranged from 5.5% to 12% of the total impact for GWP.

3.2. Optimization Results

The optimization exercise used the export of 1,000 kg of Brazilian coffee to the United States as a calculation basis. Therefore, the demands of each consumer center were calculated based on this reference and considering mass losses that occurred during roasting.

At first, single-objective economic and environmental optimizations were carried out separately. In this case, the economic optimum obtained was $f^0_{\$I}$ = US$ 4189.64, while the environmental optimum reached f^0_{EI} = 4371.30 $kgCO_{2eq}$. Based on those results, a multiobjective optimization was carried out for the problem under study. Figure 3 presents the results of this development in the form of a surface constituted of the variation in weights of each objective. As one could expect in advance, an increase in the weight of the environmental domain causes the points to concentrate in the lower-right region of the graph. On the other hand, the increase in the weight of the economic dimension causes the points to cluster in the upper-left area of the diagram. Within this spectrum, attention is drawn to the concentration of points in the region of values US$ 4190.00 and 4372.50 kg $CO_{2\ eq}$, obtained for weights w = 0.60, 0.50, 0.40, 0.30, 0.20, 0.19, 0.18, and 0.17.

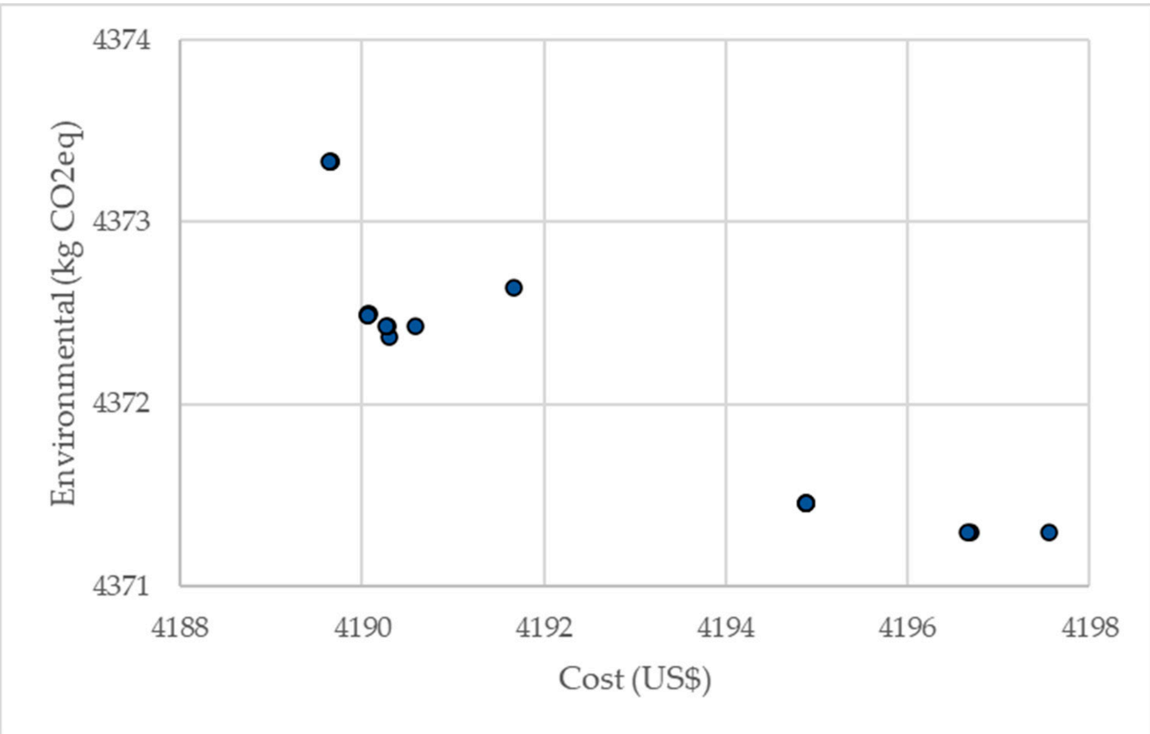

Figure 3. Multiobjective optimization results for exporting 1.0 ton of Brazilian coffee to the United States.

During the calculations, we observed that the interval between w = 0.10 (US$4196.69; 4371.30 kg $CO_{2\ eq}$) and w = 0.20 (US$4190.27; 4372.43kg $CO_{2\ eq}$) had some difference in terms of trends of results. Because of this, we decided to test the interval of $0.11 \leq w \leq 0.19$

in more detail using a step increase of $\Delta w = 0.01$. From this verification, we perceived a concentration of points in the region of US$4194.89 for $w = 0.12$, 0.13, 0.14 and 0.16, another in the region of US$4190.00 for $w = 0.17$, 0.18 and 0.19, in addition to a point with abnormal behavior—$w = 0.15$ (US$4191.67 and 4372.64 kg $CO_{2\ eq}$).

This is due to the non-convex behavior of the objective function (Equations (2) and (3)). Although the weighted sum method is unable to detect such a feature [55], the use of the Ipopt package enabled the Pareto Front plotting based on an interior point method [52].

After analyzing the results from Figure 3, we note there was low variability in values for both dimensions. The variation in weight reverted to a variation slightly more significant than 2.0 kg CO_{2eq} and approximately US$8.00 per ton of exported coffee. However, when projecting these values to the actual scale of production in the country, almost 51 million bags in 2022 alone [56], a saving of US$24 million is obtained, in addition to avoiding close to 6.0 kt of impact from GWP. The composition of the weights that define the relative importance between the environmental and economic perspectives depends on the decision-maker, e.g., coffee producers, retailers, importers, and others listed in Byrnes et al. [57], or even a composition of these actors.

Changes in supply chain behavior from oscillations in weights resulted in (i) changes in some of the average distances between growing zones and export ports and the amounts of coffee shipped from these routes; (ii) variations, sometimes significant, in the quantities transported from Brazil to the United States; and (iii) marginal changes in the supply of roasted coffee to some of the consumer centers. Conversely, fluctuations in (w) did not modify the volumes of green coffee distributed for roasting.

As for the flow of coffee through the Brazilian territory, it was noted that as the environmental variable prevails over the economic dimension $(w \to 0)$, production from Minas Gerais should no longer be shipped through the Port of Santos (16.35 kg), but to do it only for the Port of Rio de Janeiro. On the other hand, coffee grown in Espírito Santo—both Arabica (93.82 kg) and Robusta (229.7 kg)—no longer leaves through the Port of Rio de Janeiro to be exported through the Port of Santos, even though this municipality is farther away from that production center than the previous one. The changes that occurred in the others were of little significance.

The most significant changes occurred in the amount of coffee transported from port to port. With the increase in environmental importance, the coffee that arrives in America through New Orleans, coming almost entirely from the Port of Rio de Janeiro (730.4 kg, against 11.6 kg coming from the Port of Salvador), is now also distributed through the Port of Santos. In the limit condition, this partition would be 400.5 kg via the Port of Rio de Janeiro, 310.3 kg via Santos, and 31.2 kg from Salvador. It is worth mentioning that New Orleans is the American port that receives the most Brazilian coffee. When the destination is the Port of Los Angeles, the search for better environmental performance reduces the participation of the Port of Santos from 107.8 kg to 43.6 kg, and the difference is distributed between the Ports of Rio de Janeiro (45.2 kg) and Salvador (19.2 kg). New York is another direction that starts to receive coffee in a more harmonized way than it currently does as the weight of the environmental dimension intensifies: the 57.7 kg arriving exclusively from Salvador would be reduced to 13.5 kg, with the Ports of Rio de Janeiro and Santos starting to be responsible for shipping 22.3 kg and 21.9 kg of grains, respectively. Finally, Seattle would follow the same trend, moving from a ratio between Rio de Janeiro and Salvador of (82.3 + 10.0) kg to another, which now involves Santos, whose distribution would be (37.8 + 17.8 + 36.7) kg in this order.

The model adopted to address the problem meant that several US cities needed to be supplied with coffee from all brands. This was the case for San Francisco, Seattle, Portland, and San Jose, for which Folgers ceased to be a supplier. In addition, an increase in the environmental weight would redistribute the Philadelphia and Washington scenarios, which would also begin to receive coffee from this supplier, albeit in reduced proportions (0.23 kg and 0.26 kg) compared to competitors. Maxwell House, in turn, would supply coffee only to New York, Philadelphia, and Washington. In the case of Starbucks, the York plant would be dedicated to serving New York, while the Carson Valley unit would supply San Francisco and San Jose and the Kent facility would serve Seattle and Portland. Finally, the group's roasters located in Gaston and Augusta did not contribute relevantly to coffee distribution, regardless of weight distribution.

These results may prove unrealistic at first. It is neither reasonable nor healthy for the market that the leading American coffee brands cease to be represented in competitive consumption centers but start to hold a monopoly in other regions. On the other hand, this result is relevant when it gives the dimension of the influence of the environmental variable on central elements of the supply chains under study. In the current context, in which retail management will no longer be restricted to the economic dimension or logistical ease, optimization exercises that include the environmental domain are helpful to demonstrate that considering this component can lead to unexpected and even trivial (re)arrangements [14].

4. Conclusions

The realization of multiobjective optimization involving the environmental and economic dimensions and from the perspective of the life cycle of the US market supply only from the Brazilian commodity provided the following conclusions:

- Confirming reports available in the literature by pointing out coffee cultivation as the stage that concentrates the most significant contributions to the Global Warming Potential of the entire arrangement.
- The transport of the product by road also plays an essential role in the same context, especially if the distances to be covered during the journey port–roaster–consumer center in the United States are extensive.

The multiobjective optimization considering economic and environmental variables showed differences in the order of 2.0 kg CO_{2eq} and US$8.00 between the best and worst arrangements for the environmental and economic domains, which can be considered quite significant when projected to the country's annual coffee exports scale. How coffee distribution behaves in the face of oscillations in the weights attributed to the environmental and economic dimensions denotes two aspects:

- These are competing objectives.
- Considering environmental aspects for supply chain management can bring non-trivial results, with the boundary condition of a monopoly ensuring the possible environmental performance.

This prospective background research allows future investigations regarding modifications in the mathematical model.

- One of these possibilities comprises modifying specific variables and restrictions that make up the current MOO model to consider uncertainties related to them. One way of approaching the issue is to proceed as Torabzadeh et al. [11] and model part of the data using fuzzy logic. In this way, vital parameters for the model, such as the demand for coffee in the United States, agricultural productivity in Brazil, and the price of green coffee quoted on the stock exchange, could be contemplated more realistically.
- Expanding coffee production and consumption markets and incorporating other regions of the planet would be another natural outcome of this study. Acting in this way opens the prospect, for example, of verifying the influence between these centers in the case of excess supply or demand. Another variant of the current issue consists of identifying the installation location of a roaster capable of absorbing the variations in coffee demand that occur in the United States. A sensitivity analysis involving the loss resulting from the roasting process could also highlight the importance of having more efficient industries in the global SC scenario.
- Investigating the environmental and economic validity of scenarios in which coffee grinding and roasting occurs in Brazil instead of in America. Morita et al. [58] had already used this approach to evaluate the environmental performance of jeans com-

mercialized in the Brazilian market but produced with inputs imported from the United States. This approach would serve to verify if the environmental impacts could be reduced. Additionally, and maybe with more relevance, the analysis would help create a value chain capable of raising economic income in a developing country.

- In the context of carbon taxation, it would be possible to evaluate the impact of this policy, considering that agricultural cultivation and industrial activity can have positive and negative effects on the cost of coffee. Chaudhari et al. [59] followed this direction when exploring such a variant.
- Finally, it would still be possible to integrate the social variable with the present model of MOO, converting the exercise of GSCM into an SSCM.

This study met its original objective of proposing a multiobjective optimization model based on the principles of the GSC so that coffee produced in Brazil could fully supply the North American market with lower environmental impacts and costs. We hope that the findings reached by this research can guide future actions in this segment to make its activities even more sustainable.

Author Contributions: Conceptualization, H.S., L.T.B., L.K. and A.Y.; methodology, H.S., L.K. and A.Y.; software, H.S.; validation, H.S., L.K. and A.Y.; formal analysis, H.S., L.T.B., L.K. and A.Y.; investigation, H.S.; writing—original draft preparation, H.S.; writing—review and editing, L.K.; visualization, H.S. and L.K.; supervision, L.K. and A.Y.; project administration, L.K. and A.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brazil (CAPES)—Finance Code 001.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Glossary

i	Coffee-producing regions in Brazil: Bahia (BA): Arabica and Robusta varieties; Espírito Santo (ES): Arabica and Robusta; São Paulo (SP): Arabica; and Minas Gerais (MG): Arabica
j	Port of origin in Brazil: Santos (SP); Rio de Janeiro (RJ); and Salvador (BA)
m	Port of destination in the United States: New York (NJ); New Orleans (LA); Los Angeles (CA); and Seattle (WA)
n	Coffee roasters in the United States: Folgers; Maxwell; Starbucks Augusta; Starbucks Gaston; Starbucks Carson Valley; Starbucks Kent; and Starbucks York
p	Coffee-consuming cities in the United States: New York (NJ); Los Angeles (CA); Chicago (IL); San Francisco (CA); Seattle (WA); San Diego (CA); Houston (TX); Philadelphia (PA); Portland (OR); Washington (DC); San Jose (CA); Phoenix (AZ); Austin (TX); Denver (CO); and Dallas (TX)

Variables

x_{ij}	Average distance traveled between the coffee growing area and the port of origin (km)
y_{ij}	Amount of coffee shipped from the producer to the port of origin (kg)
z_{jm}	Amount of coffee shipped from the port of origin (Brazil) to the port of destination (US) (kg)
w_{mn}	Quantity of coffee shipped from the American port to the roasting company (kg)
k_{np}	Amount of coffee shipped from the roaster to the consumer center (kg)

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