Multi-Objective Optimization to Support the Design of a Sustainable Supply Chain for the Generation of Biofuels from Forest Waste

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Abstract: The production and supply chain management of biofuels from organic waste as raw material has been identified as a promising strategy in the field of renewable energies and circular economy initiatives. This industry involves complex tasks such as strategic land use, feedstock purchasing, production plant location, production capacity strategy, and material flows, which can be solved by mathematical modeling. The study proposed a multi-objective mixed-integer linear programming model to design a sustainable supply chain of biofuels with forest residues from its triple function: economic, environmental, and social. The trade-offs between the proposed objectives were determined with computational results. The proposed objectives were profit maximization, CO$_2$ minimization, and employment generation maximization. Thus, the proposed model serves as a tool for decision-making, allowing the projection of a long-term structure of the biofuel supply chains and contribute to the United Nations Sustainable Development Goals.

Keywords: biofuels; bioethanol; lignocellulose; forest waste; sustainability; multi-objective optimization; waste management; circular economy; renewable energies; sustainable development goals

1. Introduction

The production of first-generation biofuels from biomass-derived from food, such as corn and sugar cane, has led to a discussion in the industry, government, and academia over the regulation of prices between the food and fuel industries. [1]. Consequently, a necessity has been identified to support the use of new alternatives in raw materials, which are uneatable, for the production of biofuels. These raw materials must not generate conflicts of interest with the primary products of the family food basket. Those materials should be an alternative solution for products that may currently be considered waste [2]. Therefore, a second-generation biofuel derived from lignocellulosic biomass is recognized as a future renewable energy source [3]. Agricultural wastes such as corn, energy crops such as grass, short-rotation woody crops, secondary residues from sawmills, urban woody wastes such as those used in construction, and forest biomass are among the lignocellulosic biomass raw materials. In particular, the production of biofuels from agricultural waste has been identified as a good energy source [4]. The technologies used to convert lignocellulosic biomass into bioethanol can be biochemical like hydrolysis and fermentation or thermochemical like gasification and catalytic synthesis [5].
On the other hand, the environmental impacts caused by large-scale lignocellulosic biomass production and the economic impacts of inefficient bioenergy production from low-energy biomass feedstocks are among the limiting factors for the successful development of the bioenergy sector [6,7]. Therefore, efficient management of the lignocellulosic biomass supply chain (BBSC) is essential for second-generation biofuel development projects [1]. In this context, the efficient planning and management of lignocellulosic biomass agro-industrial activities are becoming a central issue for renewables’ future, as they can critically affect human welfare and environmental conservation through productivity, quality, and sustainability of the biofuel supply chain [8,9]. Biorefineries provide opportunities to improve production systems’ economic, environmental, and social performance [10]. However, careful planning of plant configuration, harvesting, production and field, and plant locations have a significant value in obtaining the maximum benefits from these systems. Likewise, feedstock availability and spatial distribution, product demand, and biofuel supply chain costs affect the overall economics of the plants, requiring proper strategy preparation to direct and promote investments over time [11].

Another critical challenge in biofuel supply chains (BSC) is uncertainty related to supply conditions, like lead times, raw material availability, changes in capacity, demand, economic environment, and regulations. More specifically, these uncertainties include the yield, the harvest rate, the biomass quality [12,13], demand, the dependence on biofuel price, the variation in the availability of resources needed for biomass production [12,14–18], the transportation conditions, the operation capacities, fluctuating market prices, and policies related to biofuels [13]. Furthermore, unpredictable climatic conditions that cause environmental impacts, which, consequently, affect the production and harvesting behavior, can be a consequence of errors related to environmental impact assessment methods [19]. Externalities that affect the demand and supply of these products, unstable economic situations, policies, and regulations are associated with the definition of technical conditions of biomass-to-fuel conversion rates [14,20,21]. Similarly, the evolution of biofuel production technologies is among the factors that can cause various sources of uncertainty [22]. Therefore, considering deterministic assumptions for technical and environmental conditions in mathematical tools to support the planning and strategy to operate the industry can significantly improve the design and the decision-making process, surpassing suboptimal solutions [6,23].

Authors in [24–26] indicate that high BBSC logistics costs motivate researchers to optimize supply chain decisions. Some studies based on BBSC optimization are interested in strategic aspects, including the location of a bio-refinery plants [25,27–31], the location of raw material collection centers [24,30,32], the network design for multi-product supply chains [8,33–35], and the location of storage facilities [31,34,36]. Some studies also propose mathematical models considering tactical and operational decisions, such as biomass and biofuel flows between BBSC facilities [37,38].

The challenge of distributing lignocellulosic-biomass-refining products includes high transportation costs for distant destinations and allocating the number of products to be distributed to consumers [38]. Studies have found that biomass collection, storage, pre-processing, and transportation from feedstock collection centers to the bioenergy plant accounts for 35% to 65% of the total cost of biofuel production [39]. Similarly, integrating strategies to facilitate the commercialization of economically viable lignocellulosic biofuels are needed [7]. In addition, feedstock characteristics have a significant influence on the sustainable biofuel supply chain design [3]. For the case of lignocellulosic biomass, its performance depends on feedstock perishability, seasonality, availability, pretreatment conditions, and storage requirements [4].

Among other important aspects to be considered are the environmental and social impacts generated by logistic operations such as transportation, storage, and production in this industry. The sustainable supply chain of biofuels and the circular economy (CE) schemes, such as recovery, recycling, regeneration, and reuse, that promote carbon reduction and economic attractiveness have become the subject of considerable inter-
est in the literature [3,19,32,40]. This work proposes the use of post-harvest and post-agricultural waste stream. In order to implement CE initiatives and contribute to the United Nations Sustainable Development Goals. Therefore, achieving the right balance between the different conflicting dimensions of sustainability (economic, environmental, and social objectives) needs to be addressed in designing the sustainable supply chain of lignocellulosic-based biofuels.

Although many contributions are available in BSC modeling, there is still an opportunity for more research. Mathematical models have been addressing sustainable biofuel supply chain designs [7,8,11]. However, the trade-off between different management objectives like social, environmental, and economic impacts analysis is scarce. Based on the above, we have identified the following research gaps that were the conceptual base for our hypothesis:

- The sustainable supply chain design can use various forest residues, considering the particularities of the supply of these raw materials, and it may affect the strategic and tactical decisions (i.e., the definition of flows for raw material and finished products between facilities and to serve the demand).
- The effects of capacity strategy (expansion and reduction) on other supply chain decisions such as the location of facilities, transportation, and material flows by fluctuating demand and raw material constraints should be considered for synchronization between resources, material, and industry necessities.
- The sustainable supply chain system’s performance should be based on financial, environmental, and social aspects, providing a more realistic analysis to support decision-making. The composition of location (strategic) resources of transportation, inventory planning, capacity utilization (tactical), and transformation and distribution (operational) decisions in a multi-period problem should ensure better overall system performance.

Consequently, we proposed this research, which handles the above gaps for our hypothesis throughout the design of a forest biomass supply chain—Eucalyptus and pine—under the conditions of one of the primary producers of biofuels globally, Colombia, which has a high potential. In detail, this research sought to answer which benefits can be obtained by using multi-objective mathematical programming to search for optimal BSC designs. Particularly, configurations, where sustainable objectives would be immersed in a conflictive environment for the biofuel production from forest waste based on lignocellulose, were used. In this country, bioethanol is only produced from raw material or food waste (mainly from sugarcane) [41,42]. Hence, the need arises to propose a sustainable supply chain design for biofuels (ethanol), which can be obtained from forest waste [42,43]. Biofuel production from forest waste will impact the country’s social and economic development path [44], especially regarding Sustainable Development Goals (SDG) 7, 8, and 12, which seek affordable and non-polluting energy, generating formal work. Additionally, SDG 13, which aims to reduce total greenhouse gas emissions, is relevant. The impact includes designing a sustainable supply chain using forest waste as a raw material source. Given its availability, lignocellulose-based biomass could play an important role in increasing renewable energy generation. Furthermore, it can be relevant in decreasing the use of fossil fuels when transformed into ethanol. For the Colombian case, the Ministry of Mines and Energy has estimated that the ethanol blend for gasoline is 10% [44].

This research aimed to examine the conditions under which the operation of a supply chain for biofuel production from forest waste lignocellulose is economically, environmentally, and socially attractive. Section 2 presents the characteristics of a mixed-integer linear programming (MILP) model for the CS design. Details of the model are presented in Appendix A. Next, the mathematical model, which considered different types of lignocellulosic biomass collection (packaging methods) in production and collection centers, is presented. Then, in Section 3, we present our analysis of the results of a case study. Finally, the main findings and scenarios are presented in Section 4.
2. Materials and Methods

This study considered a four-echelon supply chain network composed of raw materials suppliers, centers for storage and pelletizing, biorefineries, and biofuel consumption centers (see Figure 1). The locations of each of the above facilities were based on the work of [45]. The present model was developed as an estimating system that can guarantee the desired state of the bioethanol supply chain (obtained from lignocellulosic biomass). Furthermore, the model was formulated in an environment where profit and employment costs are maximized while environmental impact is minimized.

Figure 1. Supply chain network.

The model determines the material flows (multi-product) through the supply chain and inventory level maintained in storage centers to meet plant requirements.

The proposed model considered the following assumptions:

1. Four echelons (supply centers, collection centers, biorefineries, and consumption centers).
2. The model includes decision variables to open the plants and collection centers or not, considering the yearly ethanol supply for all periods. Once a plant or collection center is open, it will not be closed for the rest of the planning period.
3. Capacity and storage limitations of residues and finished products are considered.
4. Two types of raw materials (pine and eucalyptus) are included.
5. The main characteristics of the residues (raw materials) are known (e.g., waste rate and yield per unit weight).

2.1. Mathematical Model

The mathematical model details, formulation and description of equations are presented in Appendix A and Table A1. This section depicts the main physical components of the supply chain that are represented throughout sets in the mathematical model and the solution approach. As was discussed, this model was aimed to support decisions for the design of operations in the BBSC.

Sets:
2.2. Solution Approach

The multi-objective model was solved using the $\epsilon$-constraint method. This method consists of optimizing a single objective, while the others are formulated as constraints. For this study, the maximization of objective $F_1$ was maintained. At the same time, Objectives $F_2$ and $F_3$ were reformulated through Equations (1) and (2). The additional parameters, Epsilon 1 ($\epsilon_1$) and Epsilon 2 ($\epsilon_2$), the limited amount of cost per generated employment, and the maximum allowed amount of emissions were previously defined.

Equations (1) and (2) fulfill the function of restricting CO$_2$ and employment costs.

\[
F_2 \leq \epsilon_1 \quad (1)
\]

\[
F_3 \geq \epsilon_2 \quad (2)
\]

Additionally, the following equations can be used as performance measures to evaluate supply chain design: plant utilization (3) and collection center utilization (4).

\[
\sum_{\forall q} XR_{qj} / \sum_{\forall q} CAPXR_{qj} \cdot QP_j \quad \forall j, t \quad (3)
\]

\[
\sum_{\forall q} XH_{ahkt} / CCD_{akt} \cdot ACA_k \quad \forall a, k, t \quad (4)
\]

Equations (5)–(7) indicate the utilization rate of the three types of trucks used in the proposed model. The units are in weight and volume.

\[
\sum_a \sum_h \sum_k XH_{ahkt} \cdot PEH_a / NMAXVH_l \cdot CCTH_l \cdot CAPCHT_l \quad \forall l, t \quad (5)
\]

\[
\sum_a \sum_k \sum_j XTCDC_{akjt} \cdot PEH_a / NMAXVCD_o \cdot CCTCD_o \cdot CAPCCD_o \quad \forall o, t \quad (6)
\]

\[
\sum_i \sum_j \sum_n XTEDC_{ijnmt} \cdot PEP_i / NMAXV_m \cdot CCT_m \cdot CAPCP_m \quad \forall m, t \quad (7)
\]

3. Case Study

The case was based on the actual characteristics of lignocellulose-based ethanol production from two types of raw materials: pine and eucalyptus. Geographical conditions were based on Colombia. Figure 2 indicates the areas with the most significant extension of forests in the country and the current locations of the current biorefineries. The feasible locations of the collection centers and production plants are also indicated. In Colombia, the national biofuel policy allowed the ethanol and biodiesel industries to form around the sugar and palm sectors, respectively (National Council for Economic and Social Policy & National Planning Department, 2008) [46]. These productive chains have generated a direct interaction between biofuels and the agri-food industry [8]. Thus, this work sought
to analyze sustainable alternatives to biofuel policy through alternatives other than the sugar or palm sector in Colombia, which was sufficiently explored in the 2008–2021 period.

According to the current location, areas, and feasible location alternatives identified in Figure 2, the distances in km between the offering departments of raw material (especially those with the most significant forests) and the feasible locations of collection centers within the same department were established. Since the Colombian Government participated in the United Nations Climate Change Conference and signed the Paris Agreement, several initiatives were implemented or promoted to reduce carbon dioxide emissions by 20% by 2030. As a result, the most recent increase in the percentage of ethanol in the gasoline mixture [47] increased from 8% to 10%. According to the Ministry of Mines, the adjustment, which came into force in March 2018, governs for Bogota, Medellin, Cali, Barranquilla, Cartagena, Monteria, Bucaramanga, Barrancabermeja, Orito, Floreña, Villavicencio, Pereira, Manizales, Ibague, and Pasto. The location of the plants was carried out in four potentially feasible points concerning demand and supply; their distance and points were measured for the location of the collection centers (Table 1). The amount of biomass based on pine and eucalyptus depends on the yield of residues from forestry as a potential for biofuel production. According to literature reports, ethanol yields from various lignocellulosic biomass feedstock are estimated to average 0.374 for cellulose, providing ethanol yield ranges between 66 and 71 (gal/dt) [16]. Besides, it was considered that particularly cellulosic biomass has a high moisture content, which affects costs because of pretreatment processes (pre-drying).
Table 1. Distance in km between supply centers to collection centers.

|               | Cáceres | Barbosa | Espinal |
|---------------|---------|---------|---------|
| Planeta Rica  | 130.1   | 318.4   | 705.3   |
| Santa Rosa    | 154.6   | 56.4    | 474.2   |
| Plato         | 357.9   | 559.7   | 921.4   |
| Suesca        | 642.6   | 474.7   | 220.2   |
| Puerto Gaitán | 918.2   | 734.5   | 433.6   |
| Charta        | 551.9   | 393.1   | 556.6   |

The location of the plants was established. At four potentially feasible points concerning demand and supply, its distance from the location of collection centers was measured (Table 2).

Table 2. Distance in km from the collection center to plants.

|               | Duitama | Puerto Berrio | Florencia | Piedecuesta |
|---------------|---------|---------------|-----------|-------------|
| Cáceres       | 585.5   | 305.1         | 1014.1    | 523.7       |
| Barbosa       | 112.1   | 142.9         | 829.9     | 363.8       |
| Espinal       | 345.9   | 343.7         | 394       | 528.9       |

Once the plants were located, it was necessary to measure their distance from existing consumption centers (Table 3).

Table 3. Distance in km from plants to consumption centers.

|               | Barrancabermeja | Orito  | Cartagena | Floreña |
|---------------|-----------------|-------|-----------|---------|
| Duitama       | 318.7           | 943.2 | 957.1     | 177.9   |
| Puerto Berrio | 122.9           | 933.7 | 761.6     | 455.2   |
| Florencia     | 820             | 362.3 | 1458.7    | 911.9   |
| Piedecuesta   | 126.4           | 1125.9| 664.8     | 476.9   |

Finally, the distance between production plants was determined; this path was required for vertical integration between plants (Table 4).

Table 4. Distance in km between plants.

|               | Duitama | Puerto Berrio | Florencia | Piedecuesta |
|---------------|---------|---------------|-----------|-------------|
| Duitama       | 276.4   | 744.5         | 301.5     |
| Puerto Berrio |         | 733.8         | 220.6     |
| Florencia     |         |               | 920.1     |

Once the suitable forest waste was selected, the waste was placed in the packing machine producing cylindrical wooden bales of approximately 1.2 m long, 0.9 m high, and 0.9 m wide (0.972 m³). Its approximate weight was 0.729 tons. Different vehicles were used to transport the raw material, pallets, and finished product between supply centers, collection centers, plants, and consumption centers. According to Ayala [48], it is recommended to use large-capacity vehicles to avoid a more significant number of trips in the transport of products. Below are different types of trucks that can be used for supply chain design. The CO₂ emissions generated by vehicles when transporting raw material—pine and eucalyptus—or ethanol was calculated based on the distance traveled and the weight transported. Table 5 presents the emission factors (CO₂ g per ton/km) of the different vehicle types.
In the ethanol supply chain of this case study, the biorefineries had production capacity limitations with uniformly distributed losses because of conversion factors in each process. Their minimum and maximum loss values were known in each production process for each biorefinery. Following these assumptions, a spatially explicit mixed-integer linear programming (MILP) modeling framework was designed to optimize the design and planning of biofuel supply networks by considering the uncertainty in biofuel production capacity losses and the demand of the consumption centers as random variables with known parameters.

### 4. Results and Analysis

The model was developed using the solver CPLEX with the algebraic modeling system GAMS 22.5. The executions were performed on an AMD dual-core processor E1—2500 computer with a CPU at 1.4 GHz and 4 GB of ram. On average, the solutions were obtained in 750 s of CPU, with a minimum time of 300 s of CPU and a maximum time of 1200 s of CPU. The validation provided complete and realistic information according to the Colombian landscape. To this end, a set of strategic and tactical decisions was made to correctly address the analysis of the operations involved in the supply chain. According to potential waste generation, forests were grouped into six supply centers. In addition, three possible locations were selected for collection centers and four for ethanol production plants. Demand for mixing plants was obtained to supply four consumption centers. The parameters were obtained from the sources of information presented in the initial design of the logistics chain and biofuel production. The planning horizon was in an initial period of four years. The framework developed in this work addresses the complexity of the interactions of all the related resources within the nexus of a supply chain that is not present in the country. Practical solutions for a decision-making process, from the amount of biomass to be collected and the type of biorefineries to the supply and distribution strategies of bioethanol, to meet the stipulated demand of 10% blended at a national level were provided.

Figure 3 shows the relationship between the three objective functions proposed in the biofuels model from pine and eucalyptus forest wastes. The different points represent optimal solutions under the e-constraint method. Marginal progress along the axes of the three-dimensional space generates optimal solutions and image values for each objective. In this case, all points had the same size. The color of each point in the solution space represents the magnitude of CO\(_2\) emissions (tons/year), with red representing the highest number of emissions. In general, the best solutions were in the upper points of the graph, at the right front corner. That is, where the employment cost and profits are higher and emissions are lower.
For all cases in this study, the critical points correspond to solutions in the Pareto frontier. Specifically, they are points of promising non-dominated solutions in the analysis and the case study. The procedure to select the critical points starts by reviewing the set of non-dominated solutions, then evaluating the linear distance between each point and the intersection between the extreme values of each objective. (e.g., the intersection between min CO$_2$ emissions and max employment cost—see Figure 4). Finally, the sustainability-oriented problem’s context allowed us to suggest a subset of critical points to feed the analysis and discussion.

Figures 4–6 can be interpreted as follows: each compares the relationship between two objectives in two dimensions. The size of the bubble always represents the missing objective. For example, Figure 4 presents a two-dimensional graph in which the CO$_2$ emissions are located on the abscissa axis and the employment cost on the ordinate axis. At the same time, the size of the bubble represents the total profit. The color of the bubbles can also be considered a generality, which describes in more intense colors the higher levels of CO$_2$ emissions.

The relationship between the employment cost (EC) and CO$_2$ emissions are shown in Figure 4.

Table 6 shows the behavior of the critical points (A) to (E) critical points that correspond to the best benefits and trade-offs between the objectives and determine the pareto frontier are drawn in Figure 4 and discussed in Table 6. Point A represents a network configuration in which the CO$_2$ emissions are minimal (min CO$_2$ emissions) and the employment cost (sub opt EC3) is 32% away from its maximum value (max EC). In A, the total profit is low and is represented by the size of the bubble. Point B associates a network characterized by a low level of CO$_2$ emissions (CO$_2$ sub opt 1), which is 20% away from the minimum, while the employment cost is only 13% away from its maximum. In B, the total profit is only 25.7% of its maximum value.
Figure 4. Pareto frontier comparing employment cost (EC) and CO\textsubscript{2} emissions (circle size represents the total profit and letters A-E show critical points).

| Emissions | Total Profit | Employment Cost | Use of Plants | Use of Collection Centers | Use of Trucks |
|-----------|--------------|-----------------|---------------|-------------------------|--------------|
| A | Min CO\textsubscript{2} Emissions Sub opt EC3 | 10,096.7 | 1530.58 | 1182.5 | 0.4 | 0.61 | 0.39 |
| B | CO\textsubscript{2} sub opt 1 Sub opt EC2 | 12,181.93 | 1976.69 | 1633.5 | 0.42 | 0.59 | 0.35 |
| C | CO\textsubscript{2} sub opt 2 Max EC | 14,267.17 | 2274.09 | 1484.3 | 0.37 | 0.54 | 0.29 |
| D | CO\textsubscript{2} sub opt 3 Max EC | 16,352.407 | 2274.09 | 2522.9 | 0.865 | 0.95 | 0.6 |
| E | CO\textsubscript{2} sub opt 4 Max EC | 18,437.64 | 2274.09 | 3359.2 | 0.87 | 0.966 | 0.654 |

At points C, D, and E, the supply chain configurations always allow for maximum benefit to employees since the employment cost function remains at its maximum value. However, CO\textsubscript{2} emissions deviate from their minimum by 41.3%, 62%, 82.6% for C, D, and E, respectively. On the other hand, total profits increase as CO\textsubscript{2} emissions move away from the minimum value. What can be seen in the different critical points identified is a correlation between the increase in CO\textsubscript{2} emissions and the increase in the level of utilization of the plants, collection centers, and use of vehicles. However, point C's configuration shows poor utilization of fixed resources, while the employment cost is at a maximum and CO\textsubscript{2} emissions are only 41.3% away from the minimum.

From another perspective, when comparing the behavior of the economic function with the environmental function, a marked conflict between CO\textsubscript{2} emissions and total profits can be identified. This is a typical case in the industry.

Figure 5. Pareto frontier comparing CO\textsubscript{2} emissions and total profit (circle size represents the employment cost and letters F-K show critical points).

| Emissions | Total Profit | Employment Cost | Use of Plants | Use of Collection Centers | Use of Trucks |
|-----------|--------------|-----------------|---------------|-------------------------|--------------|
| F | Min CO\textsubscript{2} Emissions Sub opt profit 1 | 10,096.7 | 1969.7 | 1233.17 | 0.37 | 0.54 | 0.29 |
| G | CO\textsubscript{2} sub opt 1 Sub opt profit 2 | 12,181.9 | 4566.2 | 192.25 | 0.457 | 0.61 | 0.31 |
| H | CO\textsubscript{2} sub opt 2 Sub opt profit 3 | 14,267.2 | 5371.7 | 787.06 | 0.52 | 0.724 | 0.36 |
| I | CO\textsubscript{2} sub opt 3 Sub opt profit 4 | 16,352.407 | 2274.09 | 2522.9 | 0.865 | 0.95 | 0.6 |
| J | CO\textsubscript{2} sub opt 4 Max profit | 18,437.64 | 2274.09 | 3359.2 | 0.87 | 0.966 | 0.654 |

The behavior shown in Figure 5 and Table 7 demonstrates that at the minimum value of contamination by CO\textsubscript{2} emissions, there is a low total profit (Point F). This means a profit (sub opt profit 1) representing 31% of the best possible value in the study (max profit). In contrast, point K represents a design with maximum total profit, while CO\textsubscript{2} emissions reach 26,778.6 tons/year (this is 2.65 times the min CO\textsubscript{2} emissions value). Critical points G, H, I and J, linearly deviate from min CO\textsubscript{2} emissions by 20%, 41%, 62%, and 82%, respectively, above. In parallel, the best values below the maximum profit are represented by configurations J and I, which deviate from the maximum possible by only 3.1% and 7.2%, respectively.
from this perspective, as shown in figure 5, there was no clear trend regarding the impact on employment cost. it was only identified that, in the maximum profit configuration (point k), the employment cost represents about 60% of its maximum value (max EC). at this point, the utilization of plants and collection centers was significantly high, whereas the use of vehicles remained at half of their capacity. another particular case is evidenced by a low-capacity utilization of the vehicles in configuration F, contributing to achieving the minimum CO₂ emission value for the case study. at the same time, design F showed an exceptional value for the employment cost since it only departed from its maximum by 45.7%. the above may indicate that the environmental and social objectives do not conflict as strongly as in the economic vs. the environmental.

under the perspective that compares the objectives of maximizing total profit and employment cost, five configurations can be identified for analysis (Table 8). for example, point L represents the design that maximizes the EC and generates a total profit representing 82% of the maximum (max profit). nevertheless, in that configuration, the emissions were 3.9 times higher than the minimum possible. on the other hand, points M, N, and O showed a linear increase in total profit. for instance, between these three points, the average increase was 334 (mill COP). likewise, these three configurations were very close to the maximum profit, evidenced by deviations below 12.3%, 7%, and 2%.

![Pareto frontier](image)

**Figure 6.** Pareto frontiers comparing total profit and employment cost (circle size represents CO₂ emissions and letters L-P show critical points).

| Emissions                  | Employment Cost | Total Profit | Use of Plants | Use of Collection Centers | Use of Trucks |
|---------------------------|----------------|--------------|---------------|---------------------------|---------------|
| A  Min CO₂ Emissions      | Sub opt EC3    | 1182.5       | 0.4           | 0.61                      | 0.39          |
| B  CO₂ sub opt 1          | Sub opt EC2    | 1484.3       | 0.37          | 0.54                      | 0.29          |
| C  CO₂ sub opt 2          | Max EC         | 2522.9       | 0.865         | 0.95                      | 0.6           |
| D  CO₂ sub opt 3          | Max EC         | 3359.2       | 0.87          | 0.966                     | 0.654         |
| E  CO₂ sub opt 4          | Max EC         | 14,267.17    | 0.42          | 0.59                      | 0.35          |

At points C, D, and E, the supply chain configurations always allow for maximum benefit to employees since the employment cost function remains at its maximum value. However, CO₂ emissions deviate from their minimum by 41.3%, 62%, 82.6% for C, D, and E, respectively. On the other hand, total profits increase as CO₂ emissions move away from the minimum value. What can be seen in the different critical points identified is a correlation between the increase in CO₂ emissions and the increase in the level of utilization of the plants, collection centers, and use of vehicles. However, point C’s configuration shows poor utilization of fixed resources, while the employment cost is at a maximum and CO₂ emissions are only 41.3% away from the minimum.
From another perspective, when comparing the behavior of the economic function with the environmental function, a marked conflict between CO$_2$ emissions and total profits can be identified. This is a typical case in the industry.

The behavior shown in Figure 5 and Table 7 demonstrates that at the minimum value of contamination by CO$_2$ emissions, there is a low total profit (Point F). This means a profit (sub opt profit 1) representing 31% of the best possible value in the study (max profit). In contrast, point K represents a design with maximum total profit, while CO$_2$ emissions reach 26,778.6 tons/year (this is 2.65 times the min CO$_2$ emissions value). Critical points G, H, I and J, linearly deviate from min CO$_2$ emissions by 20%, 41%, 62%, and 82%, respectively, above. In parallel, the best values below the maximum profit are represented by configurations J and I, which deviate from the maximum possible by only 3.1% and 7.2%, respectively.

| Emissions       | Total Profit       | Employment Cost | Use of Plants | Use of Collection Centers | Use of Trucks |
|-----------------|--------------------|-----------------|---------------|---------------------------|---------------|
| F               | Min CO$_2$ Emissions 10,096.7 | Sub opt profit 1 1969.7 | 1233.17       | 0.37                      | 0.54          | 0.29          |
| G               | CO$_2$ sub opt 1 12,181.9 | Sub opt profit 2 4566.2 | 192.25        | 0.457                     | 0.61          | 0.31          |
| H               | CO$_2$ sub opt 2 14,267.2 | Sub opt profit 3 5317.1 | 787.06        | 0.52                      | 0.724         | 0.36          |
| I               | CO$_2$ sub opt 3 16,352.4 | Sub opt profit 4 5879.4 | 787.06        | 0.63                      | 0.86          | 0.4           |
| J               | CO$_2$ sub opt 4 18,437.6 | Sub opt profit 5 6139.3 | 1084.47       | 0.75                      | 0.91          | 0.45          |
| K               | CO$_2$ sub opt 5 26,778.6 | Max profit       | 6336.8        | 1381.87                   | 0.965         | 0.49          |

From this perspective, as shown in Figure 5, there was no clear trend regarding the impact on employment cost. It was only identified that, in the maximum profit configuration (Point K), the employment cost represents about 60% of its maximum value (max EC). At this point, the utilization of plants and collection centers was significantly high, whereas the use of vehicles remained at half of their capacity. Another particular case is evidenced by a low-capacity utilization of the vehicles in configuration F, contributing to achieving the minimum CO$_2$ emission value for the case study. At the same time, design F showed an exceptional value for the employment cost since it only departed from its maximum by 45.7%. The above may indicate that the environmental and social objectives do not conflict as strongly as in the economic vs. the environmental.

Under the perspective that compares the objectives of maximizing total profit and employment cost, five configurations can be identified for analysis (Table 8). For example, point L represents the design that maximizes the EC and generates a total profit representing 82% of the maximum (max profit). Nevertheless, in that configuration, the emissions were 3.9 times higher than the minimum possible. On the other hand, points M, N, and O showed a linear increase in total profit. For instance, between these three points, the average increase was 334 (mill COP). Likewise, these three configurations were very close to the maximum profit, evidenced by deviations below 12.3%, 7%, and 2%.
Table 8. Critical solution points and use of resources (employment cost vs. total profit).

| Employment Cost | Total Profit | Emissions | Use of Plants | Use of Collection Centers | Use of Trucks |
|-----------------|--------------|-----------|---------------|--------------------------|--------------|
| L Max EC 2274.1 | Sub opt profit 4 5203.2 | 39,296.0 | 0.37 | 0.54 | 0.29 |
| M Sub opt EC 1 2125.4 | Sub opt profit 3 5555.6 | 30,955.05 | 0.63 | 0.86 | 0.4 |
| N Sub opt EC 2 1976.7 | Sub opt profit 2 5890.0 | 39,289.9 | 0.75 | 0.91 | 0.45 |
| O Sub opt EC 3 1827.9 | Sub opt profit 1 6205.5 | 28,868.8 | 0.85 | 0.96 | 0.475 |
| P Sub opt EC 4 1381.8 | Max profit 6336.8 | 26,778.58 | 0.865 | 0.8625 | 0.491 |

The network design represented by the extreme Point P denotes a maximum profit and an employment cost that is 40% away from its maximum. However, at Point P, the environmental cost is too high, which correlates with high utilization rates of fixed resources such as plants and collection centers. In summary, after analyzing the critical points identified in the different perspectives, comparisons, and Pareto fronts, we were able to identify promising designs for the case study. Furthermore, the emerging complexity of the conflict between economic, environmental, and social functions was also demonstrated.

Under the three proposed objectives, three proposed collection centers were selected regardless of the region with the highest biomass supply because of their low operating costs and capacity. However, different supply chain configurations were required for each objective solved regarding the number of biorefineries and the opening of transport routes. This consideration was due to differences in transport costs by distance, CO₂ reduction, and biorefinery costs.

Optimal profit supply chain analyses (OF1) suggest using all three collection centers and centralizing production in two plants (Figure 7). In this sense, centralized facilities for large-scale bioethanol production were selected to take advantage of economies of scale to reduce the cost of biorefineries. Furthermore, the locations of all the selected biorefinery facilities were close to the consumption centers. This condition was for those with the highest demand, such as Cartagena and Barrancabermeja.

![Figure 7. First configuration supply chain maximizing FO.](image-url)
The supply chain configuration selected for the F3 emission reduction approach opened a new plant, demonstrating that the system is more sensitive to changes in biomass transport costs and emission reductions (Figure 8). The opening corresponds to the biorefinery located in Florence, in the country’s south, and close to the third-largest bioethanol consumption center, Orito. This proximity drives low biomass transportation costs and shorter trips from the country’s center, reducing emissions caused by such long transports from biorefineries only to the north. In addition, the optimal design of the supply chain configuration to minimize emissions indicates that the Florence biorefinery emits fewer greenhouse gases in its production processes. The Florence biorefinery is suitable for incorporation into the bioethanol-based supply network lignocellulosic biomass.

Figure 7. First configuration supply chain maximizing FO.

The configuration of the supply chain under the social dimension, which is to seek the maximization of the number of workers, was F2. This showed an opening of all plants or biorefineries and possible transport routes. This solution is not convenient from the point of view of greenhouse gas (GHG) emissions because of the more significant number of transportation routes and the opening of all the plants, generating the maximum quantity of emissions. For the objective of profit maximization, the increase in fixed costs of opening all biorefineries and the increase in costs reduces profits to the point of generating losses, as demonstrated in the Pareto frontier analysis [49].

The solution of the problem employing the third objective function, F3, is the most respectful way with the environment with a GHG emission of 101 Tn CO₂/week, followed by the objective function F1 with 392.9 Tn CO₂/week.

Biomass production represents a significant proportion of GHG emissions for the three options because of the use of all the supply centers to meet the minimum demand requirements in the consumption centers. In contrast, GHG emissions related to transportation to consumption centers only represent a tiny fraction of the total emitted. Therefore, the collection centers are expected to pre-process biomass locally to reduce transport-related GHG emissions.

In particular, the GHG emissions related to biorefineries represent the most significant component of F3, because of new revenue, compared to the F1 approach. The three approaches to solve the lignocellulose-based biofuel supply chain design problem have different units of GHG emissions for biomass production and transportation because of their different optimal supply chain configurations, such as the number of facilities and locations.

Figure 8. Supply chain design minimizing CO₂.
The design impact of the biofuel chain is significant and has different economic, environmental, and social consequences. For instance, centralizing bioethanol production for the lignocellulose-based biofuel supply chain in two biorefineries has some expected economic benefits. However, this strategy will increase the risks of supply chain vulnerability in the event of disruption by counting with few primary network roads with two lanes [50] and long and mountainous routes, especially towards the country’s south [51]. Therefore, the overall performance of the supply chain will be influenced by the decentralization of biorefineries and the introduction of a new biorefinery to the south of the country, thus mitigating the risk of disruption.

The strategy of increasing biorefineries adequately reduces the centralization of facilities in each region. Consequently, supply vulnerability can be reduced when a disruption occurs in a geographic region of the country. Contrary to expectations, fewer refineries centralizing bioethanol production in the country do not reduce GHG emissions [52]. The great distances and mountainous terrain through which the road network unfolds in the south of the country cause emissions to increase.

5. Conclusions

The operational, environmental, and social actions of a supply chain are interrelated. In the present investigation, the inherent trade-off between earnings, CO₂ emissions, and employment generation capacity was analyzed for a lignocellulose-based biofuel supply chain. The supply chain’s responsiveness in these three actions was analyzed using a mixed-integer linear programming mathematical model to design the supply chain network. The model is characterized by simultaneously considering multiple stages of the supply chain and presents the internal processes in bioethanol production to determine the response capacity of the supply chain. Multiple numerical analyses were carried out to demonstrate the relevance of the proposed compensations and to illustrate the managerial decisions that the model allowed us to infer.

The numerical analysis helped to understand the implications that bioethanol supply chain design decisions have on profits, GHG emissions, and job creation for a developing country like Colombia. Companies interested in boosting the economy by diversifying biofuels from biomass from different foods can use the approach presented and adjust it to their specific parameters to define strategies for reducing carbon and generating employment and profits for the partners. In addition, decision-makers in these projects can assess how the different options for the supply chain design are affected, particularly by the decisions to reduce GHG emissions and employment generation. Confirmation of the use of optimization models to support decision-making for the planning of a lignocellulosic-based ethanol supply chain included meeting the constraints from both mathematical modeling, industry, and, of course, the operation. As argued by Tong et al. in [20], this type of model determines future actions, which can only be observed after its implementation. Model validation ensured that logical relationships, as well as parameter values, accurately reflect the represented system. The analysis of results evaluated the quality of the model solution, especially concerning possible deviations from the numerical values used for the parameters.

The analysis of trade-offs showed that the distances between different locations in the supply chain strongly affect the design. Therefore, the locations of biorefineries close to the largest consumption centers in the country were presented as the best alternative for generating employment and reducing GHG. The analysis for reducing GHGs in the supply chain revealed an increase in transport combinations. However, the analysis also revealed decreasing distances to consumption centers, which corroborates the importance of using mathematical models for the problem addressed. Pareto-optimal curves showed that profits do not decline sharply at low levels of GHG emissions. This indicates that the economic performance of the supply chain is not sensitive to the restriction of GHG emissions. The opposite case is evidenced with the profit curve when an increase in job
creation is involved. Thus, the economic performance of the chain is sensitive to the restriction of job creation.

When comparing the imposition of a CO\(_2\) generation limit in the design of the supply chain for bioethanol with the maximization of profits, it was concluded that a design with maximum profits becomes more restrictive, increasing the risks of the vulnerability of the supply chain. If there were interruptions, this occurs because of the country’s geographical conditions and its road infrastructure. In addition, it was observed that reducing GHGs does not generate losses for companies or the chain in general, but it can significantly impact the design of the network. Comparable levels of GHG reduction and gains can be achieved with both evaluation criteria of the mathematical model. Unfortunately, a single solution criterion for job creation significantly hurts the chain’s profits, leading to economic losses and increased CO\(_2\) emissions.

Finally, this research is expected to contribute to a better understanding of the interactions between economic, environmental, and social sustainability approaches and their implications in the supply chain network design. For example, stochastic scheduling models would be helpful to study changes in GHG emission reductions by incurring significant variations in the demand for bioethanol in the largest refineries in the country. Furthermore, deriving robust configurations where the effects of different policies are combined could be helpful in strategic decisions. Finally, more efforts are needed to merge existing knowledge in environmental economics and the environmental supply chain to boost a developing country like Colombia.

Author Contributions: Conceptualization, writing of the original draft, software, A.P.; writing, investigation, methodology, review, editing, formal analysis, A.P.; N.C.-B.; E.G.-F.; L.R.; supervision, funding acquisition, project administration, L.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Article processing charges were provided in part by the UCF College of Graduate Studies Open Access Publishing Fund.

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

Appendix A

Appendix A.1. Parameters

| Parameter | Description | Units |
|-----------|-------------|-------|
| CFP\(_{jt}\) | Operating fixed cost of plant j per period t | COP/year |
| CFCD\(_{kt}\) | Operating fixed cost of collection center k per period t | COP/year |
| CAPCH\(_{t}\) | Load capacity of trucks type l | Ton |
| CAPCP\(_{m}\) | Load capacity of trucks type m | Ton |
| CAPCCD\(_{o}\) | Load capacity of trucks type o | Ton |
| PEP\(_{a}\) | Weight per bale of forest biomass type a | Ton |
| PEP\(_{i}\) | Weight of the product i | Ton |
| CAPCH\(_{t}\) | Volumetric load capacity of the truck type l | m\(^3\) |
| CCV\(_{m}\) | Volumetric load capacity of the truck type m | m\(^3\) |
| CCVCD\(_{o}\) | Volumetric load capacity of the truck type o | m\(^3\) |
| VEH\(_{a}\) | Volume per bale of raw material type a | m\(^3\) |
| VP\(_{i}\) | Volume of the product i | m\(^3\) |
| NMAXVH\(_{t}\) | Maximum number of trips of truck type l | - |
| NMAXV\(_{m}\) | Maximum number of trips of truck type m | - |
| Parameter          | Description                                                                 | Units          |
|--------------------|-----------------------------------------------------------------------------|----------------|
| $N_{MAXVCD}$       | Maximum number of trips of truck type o                                     |                |
| $CCTH_l$           | Number of available trucks type l                                           |                |
| $CCT_m$            | Number of available trucks type m                                           |                |
| $CCTCD_o$          | Number of available trucks type o                                           |                |
| $ECO2P_{ijl}$      | CO₂ emissions generated by plant j in period t in production of product i   | Kg             |
| $ECO2CA_{akt}$     | CO₂ emissions generated by the storage of product type a, in collection k   | Kg             |
| $ECO2CAM_l$        | CO₂ emissions by truck type l                                               | gr CO₂ *ton/km |
| $ECO2CAMS_m$       | CO₂ emissions by truck type m                                               | gr CO₂ *ton/km |
| $ECO2CAMO_o$       | CO₂ emissions by truck type o                                               | gr CO₂ *ton/km |
| $EPP_{ij}$         | Jobs generated by plants j                                                  | Employment     |
| $EPK_{akt}$        | Jobs generated by collection centers k                                      | Employment     |
| $CCPLH_{ahl}$      | Purchase price of raw material type a, at supply center h in period t       | COP/year       |
| $INC_l$            | Revenues from sales of product type i in period t                           | COP/trip       |
| $CACH_{nt}$        | Setup cost of truck type l in period t                                       | COP/trip       |
| $CAC_m$            | Setup cost of truck type m in period t                                       | COP/trip       |
| $CACCD_o$          | Setup cost of truck type o in period t                                       | COP/trip       |
| $CTCDC_{iknt}$     | Unit transportation cost of product i from collection center k to consumption center n in period t | COP/trip |
| $DPCDH_{hak}$      | Distance between supply centers h to collection centers k                   | Km             |
| $DPCD_{ijn}$       | Distance between plant j and consumption center n                          | Km             |
| $DCDC_{kj}$        | Distance from collection center k to plant j                                | Km             |
| $DCPP_l$           | Distance between plants j                                                  | Km             |
| $CCDC_{akt}$       | Capacity of collection center k of product a in period t                    | m³             |
| $LEADO_{akt}$      | Lead time of truck type l                                                  |                |
| $LEAD1_{klo}$      | Lead time of truck type m                                                  |                |
| $LEAD2_{kno}$      | Lead time of truck type o                                                  |                |
| $CVH_{hakt}$       | Trip cost of truck type l from supply center h to collection center k in period t | COP/trip |
| $CV_{min}$         | Trip cost of truck type m from plant j to consumption center n in period t | COP/trip       |
| $CVCCD_{akt}$      | Trip cost of truck type o from collection center k to plant j in period t   | COP/trip       |
| $CAPXR_{aj}$       | Production capacity in regular-time of process q at plant j                 | m³             |
| $CAPXE_{aqj}$      | Production capacity in over-time of process q at plant j                    | m³             |
| $MAXSUB_{ij}$      | Maximum quantity of product i that can be subcontracted at plant j per period t | m³/year |
| $CAPSB_{ij}$       | Inventory capacity of product a at plant j in period t                      | m³/year        |
| $INVL_{aj}$        | Initial biomass pellet inventory a of week zero at plant j                  | Ton            |
| $INVP_{ij}$        | Initial inventory of product a at plant j in week zero                       | Ton            |
| $MAXI_{aj}$        | Maximum allowable inventory level for raw material a, at plant j in period j | Ton            |
| $InvIni_{a}$       | Initial biomass inventory at collection center k at week zero               | Ton            |
| $COSTORE_{aj}$     | Production cost in regular-time per m³ produced in process q at plant j     | COP/m³         |
| $COSTEX_{aj}$      | Production cost in over-time per m³ produced in process q at plant j        | COP/m³         |
| $COSTINVPC_{aj}$   | Inventory cost of product a at plant j                                      | COP/ton        |
| $COSINCA_{a}$      | Inventory cost of product a at collection centers k                         | COP/ton        |
| $CTPC_{jnt}$       | Transportation cost of product i from plant j to consumption center n in period t | COP/year |
| $COSTPP_a$         | Cost of inter-process shipment of raw materials a                          | COP/ton        |
| $COSINVP_{aj}$     | Inventory cost of in-process product a, at plant j in process q            |                |
| $COSTINVPT_{ij}$   | Inventory cost of finished product i at plant j                             | COP/ton        |
| $INVINPRT_{j}$     | Initial inventory of pre-treatment process at plant j                       | m³             |
| $INVINHIIDR_{j}$   | Initial inventory of the hydrolysis process at plant j                      | m³             |
| $INVINIFERM_{j}$   | Initial inventory of the fermentation process at plant j                    | m³             |
| $INVINIDEST_{j}$   | Initial inventory of the distillation process at plant j                    | m³             |
| $MAXINV_{qij}$     | Maximum inventory level of product q allowed in plant j in each period t    |                |
| $\epsilon_1$      | CO₂ constraint value                                                        |                |
| $\epsilon_2$      | Employment constraint value                                                 |                |
Parameters to be generated with uncertainty.

Because of the uncertainty conditions in the BSC, the following parameters can be calculated following random values ranging between minimal and maximum values explained by probability distributions.

| Parameter | Description | Units |
|-----------|-------------|-------|
| DESP_{pretjt} | Waste coefficient of pre-treatment process at plant j in period t | - |
| DESP_{hidrojt} | Waste coefficient of hydrolysis process in plant j in period t | - |
| DESP_{fermjt} | Waste coefficient of fermentation process at plant j in period t | - |
| DESP_{destjt} | Waste coefficient of distillation process in plant j in period t | - |
| OFH_{hat} | Supply of raw material type a, in supply plant h in period t | m$^3$/month |
| Dem_{int} | Demand for product i at consumption center n in period t | m$^3$/month |

Appendix A.2. Decision Variables

| Variable | Description | Units |
|----------|-------------|-------|
| XH_{ahklt} | Quantity of bales of waste type a, to be transported from supply center h to collection center k in transport l in period t | Ton |
| X_{aqkjt} | Quantity of raw material type a, to be sent to process type q, from collection center k to plant j in period t | Ton |
| XTECD_{ijnmt} | Quantity shipped of product i from plant j to consumption center n in transport m in week t | m$^3$ |
| XCTDC_{akjot} | Quantity of pellets a, shipped from collection center k to plant j by truck type o, in period t | Ton |
| PAP_{aqjt} | Shipment of products i between production units q at plant j in period t | m$^3$ |
| XR_{aqjit} | Quantity of product i produced in regular-time in production unit q at plant j for period t | m$^3$ |
| XE_{aqjit} | Quantity of product i produced in over-time in production unit q at plant j for period t | m$^3$ |
| XPF_{ijt} | Total quantity of final product i produced at plant j in period t | m$^3$ |
| XS_{ijt} | Quantity of product i to be subcontracted at plant j in period t | m$^3$ |
| INVPA_{aqjt} | Inventory of bales type a, at plant j for period t | Ton |
| INVPT_{ijt} | Finished inventory of finished product I, in plant j in period t | m$^3$ |
| Inv_{akt} | Final inventory of bales type a at collection center k in period t | Ton |
| InventPP_{aqjit} | Inventory of units type a produced at production unit q of plant j in period t | m$^3$ |
| NVCH_{lhkt} | Number of trips of truck l from supply center h to collection center k in period t | - |
| NVC_{mijn} | Number of trips of truck m from plant j to consumption centers n in period t | - |
| NVCC_{okjt} | Number of trips of truck o, from collection center k to plant j in period t | - |
| COSMP | Raw material cost | $ |
| COSEMP | Total employment cost in supply chain | $ |
| COSEAC | Cost of jobs at collection centers | $ |
| COSEPL | Cost of jobs at plants | $ |
| Variable     | Description                                      | Units |
|--------------|--------------------------------------------------|-------|
| COSETRANL    | Cost of jobs for trucks type l                   | $     |
| COSETRANM    | Cost of jobs for trucks type m                   | $     |
| COSETRANO    | Cost of jobs for trucks type o                   | $     |
| COSSB        | Cost of subcontracting                           | $     |
| COSPR        | Production cost                                  | $     |
| COSINVT      | Inventory cost                                   | $     |
| COSTRAS      | Transport cost                                   | $     |
| COSTFIJ      | Fixed cost                                       | $     |
| INGRESOS     | Total revenues                                   | $     |
| Hper         | Losses                                           | $     |
| GNt          | Net profit per period t                          | $/year|
| COSEMPLEO    | Employment cost                                  | $     |
| EMCO2        | $CO_2$ emissions                                 | gr    |
| EMISIONTOTAL | $CO_2$ emissions per period                      | gr    |
| CO2          | $CO_2$ emissions by transport                    | gr    |
| Zjiht        | Products i shipped from supply center h to plant j per period t | Ton   |
| Vint         | Sales of products i, in consumption center n per period t | $     |
| Pjiht        | Products type i purchased at supply center h to be processed at plant j in period t | $     |

Binary variables

\[
Q_P = \begin{cases} 
1, & \text{If plant } j \text{ is opened} \\
0, & \text{otherwise}
\end{cases}
\]

\[
ACA_k = \begin{cases} 
1, & \text{If collection center } k \text{ is opened} \\
0, & \text{otherwise}
\end{cases}
\]

The objective of the model is to maximize the supply chain profit (F1). This value is the difference between the expected revenue and the total cost. The total cost is divided into the cost of raw material purchases, Equation (A1); production costs, Equation (A2); inventory costs, Equation (A3); transportation costs, Equation (A4); and fixed operating costs, Equation (A5). Finally, the objective function is provided in Equation (A6).

\[
COSMP = \sum_{\forall a} \sum_{\forall h} \sum_{\forall k} \sum_{\forall t} X_{Habkl} * CCLH_{ahlt} \tag{A1}
\]

\[
COSPR = \sum_{\forall q} \sum_{\forall j} \sum_{\forall t} X_{Rqjt} * COSTORE_{aqj} + \sum_{\forall q} \sum_{\forall j} \sum_{\forall t} X_{Eqjt} * COSTOEX_{aqj} \tag{A2}
\]

\[
COSINVT = \sum_{\forall a} \sum_{\forall j} \sum_{\forall t} COSTINVPAC_{aqj} * INVPAC_{aqjt} + \sum_{\forall a} \sum_{\forall k} \sum_{\forall t} COSINCD_{ak} * INV_{akt} + \sum_{\forall q} \sum_{\forall j} \sum_{\forall t} COSINVPP_{aqj} * InventPP_{aqjt} + \sum_{\forall v} \sum_{\forall j} \sum_{\forall t} COSTINVPT_{ij} * INVPT_{ijt} \tag{A3}
\]
OSTRAS = \sum_{\forall m} \sum_{\forall j} \sum_{\forall n} \sum_{\forall t} CVC_{mjnt} \ast NVC_{mjnt} \\
+ \sum_{\forall l} \sum_{\forall h} \sum_{\forall k} \sum_{\forall t} CVH_{lhkt} \ast NVCH_{lhkt} \\
+ \sum_{\forall o} \sum_{\forall k} \sum_{\forall j} \sum_{\forall n} \sum_{\forall t} CVCCD_{okjt} \ast NVCC_{okjt} \\
+ \sum_{\forall q} \sum_{\forall n} \sum_{\forall j} \sum_{\forall m} \sum_{\forall t} PAP_{qnjt} \ast COSTPP \\
+ \sum_{\forall i} \sum_{\forall j} \sum_{\forall n} \sum_{\forall m} \sum_{\forall t} XTECD_{ijnmt} \ast CTPCD_{ijnmt} \\
\text{(A4)}
\]

\[
COSTFIJ = \sum_{\forall j} \sum_{\forall t} CFP_{jt} \ast QP_{j} \\
+ \sum_{\forall k} \sum_{\forall t} CVH_{kt} \ast NVCH_{kt} \\
\text{(A5)}
\]

\[
F1 = \sum_{\forall i} \sum_{\forall j} \sum_{\forall n} \sum_{\forall m} \sum_{\forall t} ING_{ilt} \ast XTECD_{ijmnt} \\
- (COSMP + COSPR + COSSB + COSINVT + COSTRAS + COSTFIJ + COSEMPLEO) \text{(A6)}
\]

The objective function F2 (Equation (A12)) aims to maximize the employment cost considering jobs generated in the shipment between links, Equations (A9)–(A11); collection centers, Equation (A7); and plants, Equation (A8).

\[
COSEAC = \sum_{\forall k} \sum_{\forall t} EPCA_{kt} \ast CPEP \ast ACA_{k} \text{(A7)}
\]

\[
COSEPL = \sum_{\forall j} \sum_{\forall t} EPP_{jt} \ast CPEP \ast QP_{j} \text{(A8)}
\]

\[
COSETRANL = \sum_{\forall l} \sum_{\forall h} \sum_{\forall k} \sum_{\forall t} CEPL_{k} \ast NVCH_{hkt} \ast CPEP \text{(A9)}
\]

\[
COSETRANM = \sum_{\forall m} \sum_{\forall j} \sum_{\forall n} \sum_{\forall t} CEPM_{m} \ast NVCC_{mjnt} \ast CPEP \text{(A10)}
\]

\[
COSETRANO = \sum_{\forall o} \sum_{\forall k} \sum_{\forall j} \sum_{\forall n} \sum_{\forall o} \sum_{\forall t} CEPO_{o} \ast NVCC_{okjt} \ast CPEP \text{(A11)}
\]

\[
F2 = COSEMP = COSEAC + COSEPL + COSETRANL + COSETRANM + COSETRANO \text{(A12)}
\]

The objective function F3 (Equation (A15)) aims to minimize CO₂ emissions by considering carbon footprint generated in plants, collection centers (A13), and transportation in each link of the supply chain (A14):

\[
EMCO2 = \sum_{\forall i} \sum_{\forall j} \sum_{\forall t} ECO2P_{ijt} \ast QP_{j} + \sum_{\forall m} \sum_{\forall k} \sum_{\forall t} ECO2CA_{akt} \ast ACA_{k} \text{(A13)}
\]

\[
CO2 = \sum_{\forall a} \sum_{\forall h} \sum_{\forall k} \sum_{\forall l} \sum_{\forall t} PEH_{a} \ast XHC_{ahlkl} \ast DPCDH_{hk} \ast ECO2CAML_{l} \\
+ \sum_{\forall d} \sum_{\forall v} \sum_{\forall k} \sum_{\forall t} \sum_{\forall q} \sum_{\forall n} \sum_{\forall j} \sum_{\forall m} \sum_{\forall t} PEH_{a} \ast XTCDC_{akjt} \ast DPCD_{jn} \ast ECO2CAMO_{o} \\
+ \sum_{\forall i} \sum_{\forall j} \sum_{\forall n} \sum_{\forall m} \sum_{\forall t} PEP_{i} \ast XTECD_{ijmnt} \ast DCDC_{kj} \ast ECO2CAMM_{m} \text{(A14)}
\]

\[
\text{Total Emissions} = CO2 + EMCO2 \text{(A15)}
\]

The model is subject to 43 types of constraints: capacity, inventory, production, lead time, and transportation constraints, among others. These constraints are explained below.

Constraint (A16) allows limiting the maximum of primary raw material collected in the different collection centers, according to each offer of the supply centers. Constraint
(A17) allows balancing the input of material to the collection centers with the capacity of the biorefineries.

\[ \sum_k \sum_l X_{ahlkt} \leq OFH_{hat} \quad \forall a, h, t \]  \quad (A16)

\[ \sum_h \sum_l X_{ahlkt} \leq CCD_{akt} \ast ACA_k \quad \forall a, h, t \]  \quad (A17)

Constraint (A18) allows balancing the inventory of bales and pellets entering and leaving the collection centers.

\[ \sum_h \sum_l X_{ahlkt} + INV_{akt-1} = \sum_j \sum_o X_{TCDC_{akjot}} + INV_{akt} \quad \forall a, h, t \]  \quad (A18)

Restrictions (A19)–(A22) limit the production capacity per process in plants considering the number of products shipped and the opening of new plants.

\[ PAP_{pre-treatment} \ast Hydrolysis \ast j \leq CAPXR_{pre-treatment} \ast j \ast Q_p^j \quad \forall q, j, t \]  \quad (A19)

\[ PAP_{Hydrolysis} \ast fermentation \ast j \leq CAPXR_{Hydrolysis} \ast j \ast Q_p^j \quad \forall q, j, t \]  \quad (A20)

\[ PAP_{fermentation} \ast destilation \ast j \leq CAPXR_{fermentation} \ast j \ast Q_p^j \quad \forall q, j, t \]  \quad (A21)

\[ PAP_{Ethanol} \ast destilation \ast j \leq CAPXR_{destilation} \ast j \ast Q_p^j \quad \forall q, j, t \]  \quad (A22)

Constraint (A23) allows the balancing of pellets shipped between collection centers to plants.

\[ \sum_o X_{TCDC_{akjot}} = \sum_q X_{aqkj} \quad \forall a, k, j, t \]  \quad (A23)

Constraint (A24) allows balancing the number of pellets sent from the collection center to the pre-treatment process at the plant, considering the inventory of bales per period.

\[ \sum_o X_{TCDC_{akjot}} + INV_{PAC_{ajt-1}} = X_{apre-treatment_{ktj}} + INV_{PAC_{ajt}} \quad \forall a, k, j, t \]  \quad (A24)

Constraint (A25) allows balancing the demand from consumption centers with the amount of product shipped from plants.

\[ \sum_j \sum_m X_{TIEC_{ijm}} = Dem_{int} \quad \forall i, m, t \]  \quad (A25)

Constraint (A26) allows limiting the bale capacity of the collection center.

\[ INV_{akt} \leq CCD_{akt} \ast ACA_k \quad \forall a, k, t \]  \quad (A26)

Equation (A27) allows balancing the total quantity of final product in the plants and the quantity to be shipped to consumption centers.

\[ X_{PF_{ij}} + INV_{PIT_{ij}} = \sum_n \sum_m X_{TEC_{ijm}} + INV_{PIT_{ij}} \quad \forall i, j, t \]  \quad (A27)

Restrictions (A28)–(A42) allow restricting some elements during the transportation of the material in the different links of the supply chain, taking into account the type of vehicle, the number of vehicles available, the maximum number of trips possible per period, and the maximum transport capacity of the vehicle in terms of weight and volume. Constraints (A28), (A33), and (A38) restrict the maximum number of trips allowed per type of vehicle used for trips from supply centers to collection centers, from collection centers to production plants, and from production plants to consumption centers. In addition, constraints (A29), (A34), and (A39) indicate the availability of transport by vehicle type.
Likewise, constraints (A28), (A35), and (A40) restrict the quantities (measured in kg) that can be shipped in each vehicle, as well as the availability of trucks for shipment. In parallel, constraints (A29), (A36), and (A41) restrict the amount of product that can be transported in volumetric terms between links. Besides, constraints (A30), (A37), and (A42) restrict the amount of product to be transported in terms of delivery times for each type of vehicle.

\[
\sum_{\forall a} \sum_{\forall k} NVCH_{ijklt} \leq CCTH_{l} \times NMAXVH_{l} \quad \forall l, t \quad (A28)
\]

\[
NVCH_{ijklt} \leq NMAXVH_{l} \times CCTH_{l} \quad \forall l, h, k, u, t \quad (A29)
\]

\[
XH_{ijklt} \times PEH_{a} \leq CAPCHT_{l} \times NVCH_{ijklt} \times CCTH_{l} \quad \forall a, h, k, l, t \quad (A30)
\]

\[
XH_{ijklt} \times PEV_{a} \leq CAPCHT_{l} \times NVCH_{ijklt} \times CCTH_{l} \quad \forall a, h, k, l, t \quad (A31)
\]

\[
PEH_{a} \times XH_{ijklt} \leq CAPCHT_{l} \times NVCH_{ijklt} \quad \forall a, h, k, l, t, u \quad (A32)
\]

\[
\sum_{\forall v} \sum_{\forall k} NVCC_{okjt} \leq CCTCD_{o} \times NMAXVCD_{o} \quad \forall v, o, t \quad (A33)
\]

\[
NVCC_{okjt} \leq NMAXVCD_{o} \times CCTCD_{o} \quad \forall v, o, k, j, t \quad (A34)
\]

\[
\sum_{\forall v} XTCDC_{akjot} \times PEH_{a} \leq CAPCCD_{o} \times NVCC_{akjot} \times CCTCD_{o} \quad \forall v, k, j, o, t \quad (A35)
\]

\[
\sum_{\forall v} XTCDC_{akjot} \times VEH_{a} \leq CCTCD_{o} \times CCVCD_{o} \times NMAXVCD_{o} \quad \forall v, k, j, o, t \quad (A36)
\]

\[
PEH_{a} \times XTCDC_{akjot} \leq CAPCCD_{o} \times NVCC_{akjot} \quad \forall k, j, o, t \quad (A37)
\]

\[
\sum_{\forall v} \sum_{\forall m} NVC_{mjnt} \leq CCT_{m} \times NMAXV_{m} \quad \forall v, m, t \quad (A38)
\]

\[
NVC_{mjnt} \leq NMAXV_{m} \times CCT_{m} \quad \forall v, j, n, m, u \quad (A39)
\]

\[
\sum_{\forall v} XTECD_{ijmnt} \times PEP_{i} \leq CAPCP_{m} \times NVC_{mjnt} \times CCT_{m} \quad \forall v, j, n, m, t \quad (A40)
\]

\[
\sum_{\forall v} XTECD_{ijmnt} \times VP_{i} \leq CCT_{m} \times CCV_{m} \times NMAXV_{m} \quad \forall v, j, n, m, t \quad (A41)
\]

\[
\sum_{\forall v} PEP_{i} \times XTECD_{ijmnt} \leq CAPCP_{m} \times NVC_{mjnt} \quad \forall v, j, n, m, t \quad (A42)
\]

The constraints (A43)–(A46) allow carrying out the raw material balancing between processes in the plants.

\[
\sum_{\forall v} \sum_{\forall k} X_{pre\text{-}treatment,kj} + InventPP_{pre\text{-}treatment,jt} - 1 = XR_{pre\text{-}treatment,jt} +XE_{pre\text{-}treatment,jt} + InventPP_{pre\text{-}treatment,jt} - 1 \quad \forall q, j, t \quad (A43)
\]

\[
PAP_{\text{pre\text{-}treatment,hydrolysis,jt}} + InventPP_{\text{hydrolysis,jt}} - 1 = XR_{\text{hydrolysis,jt}} +XE_{\text{hydrolysis,jt}} + InventPP_{\text{hydrolysis,jt}} - 1 \quad \forall q, j, t \quad (A44)
\]

\[
PAP_{\text{hydrolysis,Fermentation,jt}} + InventPP_{\text{Fermentation,jt}} - 1 = XR_{\text{Fermentation,jt}} +XE_{\text{Fermentation,jt}} + InventPP_{\text{Fermentation,jt}} - 1 \quad \forall q, j, t \quad (A45)
\]

\[
PAP_{\text{Fermentation,Distilation,jt}} + InventPP_{\text{Distilation,jt}} - 1 = XR_{\text{Distilation,jt}} +XE_{\text{Distilation,jt}} + InventPP_{\text{Distilation,jt}} - 1 \quad \forall q, j, t \quad (A46)
\]
The constraint (A47) allows determining the waste generated by plant processes. The value 0.99 was set as the waste coefficient.

\[
0.99 \sum_{k} X_{a}^{pre-treatment}_{kj} + \text{INVLEC}_{ajt} + \text{INVFACT}_{2jt} = X_{Destilation}^{pre-treatment}_{jt} + X_{Destilation}^{pre-treatment}_{jt} + \text{INVLEC}_{ajt} + \text{INVFACT}_{2jt} \quad \forall a, q, j, t
\] (A47)

To calculate the total production in the plants, constraints (A48)–(A51) consider the production in regular and overtime for each product for each process.

\[
X_{Pre-treatment}^{pre-treatment}_{jt} + X_{Pre-treatment}^{pre-treatment}_{jt} - \text{InventPP}_{Pre-treatment}^{pre-treatment}_{jt} = PAP_{Pre-treatment}^{pre-treatment}, \forall q, j, t
\] (A48)

\[
X_{hydrolysis}^{hydrolysis}_{jt} + X_{hydrolysis}^{hydrolysis}_{jt} - \text{InventPP}_{hydrolysis}^{hydrolysis}_{jt} = PAP_{hydrolysis}^{hydrolysis} - \text{fermentation}_{jt}^{fermentation}, \forall q, j, t
\] (A49)

\[
X_{fermentation}^{fermentation}_{jt} + X_{fermentation}^{fermentation}_{jt} - \text{InventPP}_{fermentation}^{fermentation}_{jt} = PAP_{fermentation}^{fermentation} - \text{destilation}\_jt, \forall q, j, t
\] (A50)

\[
X_{Destilation}^{Destilation}_{jt} + X_{Destilation}^{Destilation}_{jt} - \text{InventPP}_{Destilation}^{Destilation}_{jt} = XPF_{Ethanol}^{Destilation}_{jt}, \forall q, j, t
\] (A51)

On the other hand, constraint (A52) allows restricting the inventory of finished products in the inventory of production plants.

\[
\text{INVPT}_{ijt} \leq \text{CAPSB}_{ijt} \quad \forall i, j, t
\] (A52)

Through constraints (A53)–(A56), it is possible to restrict the inventories of products in the intermediate processes in the plants for each period.

\[
\text{InventPP}_{aqjt} \leq \text{MAXINVI}_{qjt} \quad \forall a, j, t
\] (A53)

By means of constraint (A54), it is possible to restrict the final inventory of bales in the plants and storage centers for each period.

\[
\text{INVPAC}_{ajt} \leq \text{MAXP}_{ajt} \quad \forall a, k, t
\] (A54)

Using constraints (A55) and (A56), the quantity produced in regular and overtime is restricted. On the other hand, Equation (A57) seeks to limit the maximum amount of finished product that can be subcontracted in each plant per period.

\[
X_{R_{qjt}} \leq \text{CAPXR}_{qj} * Q_{P_{j}} \quad \forall q, j, t
\] (A55)

\[
X_{E_{qjt}} \leq \text{CAPXE}_{aqj} * Q_{P_{j}} \quad \forall q, j, t
\] (A56)

\[
X_{S_{ijt}} \leq \text{MAXSUB}_{aqj} \quad \forall i, j, t
\] (A57)

Equations (A58)–(A60) restrict the use of truck capacity in tons to at least 80%.

\[
XH_{ahlkt} * \text{PEH}_{a} \geq 0.8 * \text{NVCH}_{ihlkt} * \text{CAPCHT}_{l} \quad \forall l, t
\] (A58)

\[
XTDC_{akjot} * \text{PEH}_{a} \geq 0.8 * \text{NVCC}_{akjot} * \text{CAPCCD}_{o} \quad \forall o, t
\] (A59)

\[
XTECD_{ijnmt} * \text{PEP}_{i} \geq 0.8 * \text{NVC}_{ijnmt} * \text{CAPCP}_{m} \quad \forall m, t
\] (A60)
Table A1. The following table describes the parameter values of the mathematical model. Values are reported from years 2019–2020 [53–56].

| Parameter Description | Values:                                      |
|-----------------------|----------------------------------------------|
| **CFP**<sub>j</sub><sup>t</sup> | Operating fixed cost of plant j per period t | Values from COP 70,000.00/year depending on the capacity |
| **CFCD**<sub>k</sub><sup>t</sup> | Operating fixed cost of collection center k per period t | Values from COP 25,000.00/year depending on the capacity |
| **CAPCH**<sub>T</sub><sup>i</sup> | Load capacity of trucks type I | See Table 5. (Ton.) |
| **CAPCP**<sub>m</sub><sup>t</sup> | Load capacity of trucks type m | See Table 5. (Ton.) |
| **CAPCCD**<sub>o</sub><sup>t</sup> | Load capacity of trucks type o | See Table 5. (Ton.) |
| **PEH**<sub>a</sub> | Weight per bale of forest biomass type a | 0.957 ton |
| **PEP**<sub>i</sub> | Weight of the product i | 0.789 ton/m³ |
| **CAPCH**<sub>L</sub><sup>i</sup> | Volumetric load capacity of the truck type l | Values from 70 m³ depending on the capacity |
| **CCV**<sub>m</sub><sup|i</sup> | Volumetric load capacity of the truck type m | Values from 32 m³ depending on the capacity |
| **CCVCD**<sub>o</sub><sup>i</sup> | Volumetric load capacity of the truck type o | Values from 42 m³ depending on the capacity |
| **VEH**<sub>a</sub> | Volume per bale of raw material type a | Scalar value 0.972 m³ |
| **VP**<sub>i</sub> | Volume of the product i | Scalar value 1 m³ |
| **ECO2P**<sub>ijt</sub> | CO₂ emissions generated by plant j in period t | Values from 6.098 ton/period |
| **ECO2CA**<substinence</sub><sup>L</sup><sub>a</sub><sup>t</sup> | CO₂ emissions generated by the storage of product type a, in collection center k in period t | Values from 2.698 ton/period |
| **ECO2CAM**<sub>L</sub><sup>i</sup> | CO₂ emissions by truck type l | Values from 68 gr CO₂ *ton/km |
| **ECO2CAMM**<sub>m</sub><sup>i</sup> | CO₂ emissions by truck type m | Values from 48 gr CO₂ *ton/km |
| **ECO2CAMO**<sub>O</sub><sup>i</sup> | CO₂ emissions by truck type o | Values from 52 gr CO₂ *ton/km |
| **EP**<sub>j</sub><sup>j</sup> | Jobs generated by plants j | Values between 15 and 24 jobs depending on the capacity |
| **EPKAK**<sub>k</sub><sup|i</sup> | Jobs generated by collection centers k | Values between 6 and 14 jobs depending on the capacity |
| **CPEP** | Average employment cost per person | 1,802,000 COP/employment that will increase based on the Colombia’s salary increment |
| **CCLH**<sub>ah</sub> | Purchase price of raw material type a, at supply center h | 5,000 COP/tale that will increase based on the CPI |
| **ING**<sub>i</sub> | Revenues from sales of product type i | 2,323,000 COP/m³ that will increase based on the CPI |
| **CACH**<sub>L</sub><sup>i</sup> | Setup cost of truck type l | Values from 75,000 COP/trip that will increase based on the CPI |
| **CAC**<sub>m</sub><sup>i</sup> | Setup cost of truck type m | Values from 75,000 COP/trip that will increase based on the CPI |
| **CACCD**<sub>o</sub><sup>i</sup> | Setup cost of truck type o | Values from 75,000 COP/trip that will increase based on the CPI |
| **CTC**<sub>d</sub><sup>k</sub><sub>a</sub><sup>i</sup> | Unit transportation cost of product i from collection center k to consumption center n | Values from 25 COP/trip that will increase based on the CPI |
| **DPCDH**<sub>h</sub><sup>k</sup> | Distance between supply centers h to collection centers k | See Table 1 |
| **DPCD**<sub>j</sub><sup>n</sup> | Distance between plant j and consumption center n | See Table 2 |
| **DCDC**<sub>k</sub><sup>j</sup> | Distance from collection center k to plant j | See Table 3 |
| **DCPP**<sub>j</sub><sup>i</sup> | Distance between plants j | See Table 4 |
| **CCD**<sub>k</sub><sup>a</sup><sup>i</sup> | Capacity of collection center k of product a in period t | Values from 20.500 m³/year that will increase based on the CPI |
| **CVH**<sub>hk</sub> | Trip cost of truck type l from supply center h to collection center k | Values from 5.100 COP/km that will increase based on the CPI |
| **CVC**<sub>m</sub><sup>i</sup><sup>j</sup><sup>n</sup> | Trip cost of truck type m from plant j to consumption center n | Values from 4.250 COP/trip that will increase based on the CPI |
Table A1. Cont.

| Parameter Description | Values: |
|-----------------------|---------|
| $CVCDD_{aqj}$ | Trip cost of truck type o from collection center k to plant j Values from 4.870 COP/trip that will increase based on the CPI |
| $CAPXR_{qj}$ | Production capacity in regular-time of process q at plant j Values from 25.000 m$^3$/year depending on the capacity |
| $CAPXE_{qj}$ | Production capacity in over-time of process q at plant j Values from 6.250 m$^3$/year depending on the capacity |
| $MAXSUB_{ij}$ | Maximum quantity of product i that can be subcontracted at plant j per period t Values from 1000 m$^3$/year depending on the capacity |
| $CAPSB_{ij}$ | Inventory capacity of product i at plant j in period t Values from 1200 m$^3$/year depending on the capacity |
| $COSTORE_{qij}$ | Production cost in regular-time per m$^3$ produced in process q at plant j Values from 480.000 COP/m$^3$ depending on the capacity that will increase based on the CPI |
| $COSTEX_{qij}$ | Production cost in over-time per m$^3$ produced in process q at plant j Values from 120.000 COP/m$^3$ that will increase based on the CPI |
| $COSTINVPAC_{aqj}$ | Inventory cost of product a at plant j Values from 2.000 COP/ton that will increase based on the CPI |
| $COSINCA_{aK}$ | Inventory cost of product a at collection centers k Values from 2.500 COP/ton that will increase based on the CPI |
| $COSTPP_a$ | Cost of inter-process shipment of raw materials a Values from 2.800 COP/ton that will increase based on the CPI |
| $COSINVPP_{qij}$ | Inventory cost of in-process product a, at plant j in process q Values from 1500 COP/ton that will increase based on the CPI |
| $COSTINVPT_{qij}$ | Inventory cost of finished product i at plant j 2.500 COP/ton that will increase based on the CPI |
| $DESP_{prejt}$ | Waste coefficient of pre-treatment process at plant j in period t Uniform between 0.01 and 0.05 |
| $DESPדברjt$ | Waste coefficient of hydrolysis process in plant j in period t Uniform between 0.01 and 0.05 |
| $DESP_{fermj}$ | Waste coefficient of fermentation process at plant j in period t Uniform between 0.01 and 0.05 |
| $DESP_{destjt}$ | Waste coefficient of distillation process in plant j in period t Uniform between 0.01 and 0.05 |
| $OFH_{hat}$ | Supply of raw material type a, in supply plant h in period t Values from 120.000 COP/m$^3$ Values from 120.000 COP/m$^3$ that will increase based on the CPI |
| $Dem_{nat}$ | Demand for product i at consumption center n in period t Normal with mean 12.500 and standard deviation 1.500 m$^3$/year |

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