logistics

Article

Economic Justice in the Design of a Sugarcane-Derived Biofuel Supply Chain: A Fair Profit Distribution Approach

Jimmy Carvajal [1], William Sarache [2] and Yasel Costa [3,4,*]

[1] Tecnologico de Monterrey, Escuela de Ingeniería y Ciencias, Monterrey 64700, Mexico; jimmy.carvajal@tec.mx
[2] Universidad Nacional de Colombia, Facultad de Ingeniería y Arquitectura, Departamento de Ingeniería Industrial, Campus La Nubia, Manizales 170001, Colombia; wasarachec@unal.edu.co
[3] MIT-Zaragoza Logistics Center (ZLC), 50018 Zaragoza, Spain
[4] Universidad de Manizales, College of Economics and Accounting, Manizales 170001, Colombia
* Correspondence: ycosta@zlc.edu.es

Abstract: *Background*: In agricultural supply chains, unequal bargaining power often leads to economic inequality, particularly for farmers. The fair profit distribution (FPD) approach offers a solution by optimizing supply chain flows (materials, information, and money) to promote economic equity among members. However, our literature review highlights a gap in applying the FPD approach to the facility location-allocation problem in supply chain network design (SCND), particularly in sugarcane-derived biofuel supply chains. *Methods*: Consequently, we propose a multi-period optimization model based on FPD to design a sugarcane biofuel supply chain. The methodology involves four steps: constructing a conceptual model, developing a mathematical model, designing a solution strategy, and generating insights. This model considers both investment (crop development, biorefinery construction) and operational phases over a long-term planning horizon, focusing on farm location and crop allocation. *Results*: By comparing the FPD model to a traditional centralized planning supply chain (CSC) approach, we examine the impact of the planning horizon, number of farms, and sugarcane prices paid by biorefineries on financial performance. While the FPD model results in lower overall system profits, it fosters a fairer economic scenario for farmers. *Conclusions*: This study contributes to economic justice in supply chains and offers insights to promote fair trade among stakeholders.

Keywords: fair profit distribution; economic justice; social sustainability; biofuel supply chains optimization; location-allocation problem

check for updates

Citation: Carvajal, J.; Sarache, W.; Costa, Y. Economic Justice in the Design of a Sugarcane-Derived Biofuel Supply Chain: A Fair Profit Distribution Approach. *Logistics* **2024**, *8*, 122. https://doi.org/10.3390/logistics8040122

Academic Editor: Robert Handfield

Received: 5 September 2024
Revised: 26 October 2024
Accepted: 8 November 2024
Published: 18 November 2024

1. Introduction

Food and energy security, poverty reduction, and global warming are challenges that require the deployment of sustainable strategies in agricultural systems. Biofuel production is a feasible alternative for addressing these challenges, not only to reduce the consumption of fossil fuels, but also to increase growers' incomes [1]. Biofuels can be obtained from first-, second-, third-, and fourth-generation technologies [2,3]. Due to its high biomass yields, first-generation technology has proven advantages for biofuel production. In particular, sugarcane has been identified as one of the raw materials with the highest potential for bioethanol obtention [4]. As a result, large-scale bioethanol production projects based on sugarcane have been carried out in several countries to improve their energy matrices [5]. However, new challenges have emerged relating to the negative effects of sugarcane-based biofuel production on the environment, food security, and specific social issues [6,7].

A sugarcane biofuel supply chain involves various operations, such as agricultural production, transportation, processing, and distribution. Several contributions from the so-called centralized planning supply chain (CSC) optimization approach have addressed the sugarcane supply chain design problem, seeking an optimum solution in terms of cost reduction or profit maximization throughout the entire supply chain [8–10]. In real-life scenarios, supply chain actors (farmers, producers, transporters, and marketers) normally act independently to privilege their individual economic interests [11,12]. This approach seems self-evident, given that the primary objective of a for-profit organization is to generate and enhance economic gains by effectively marketing its goods and services [13]. However, due to information asymmetries and differences in bargaining power in sugarcane supply chains, a CSC approach can lead to member dissatisfaction due to unfair profit distribution, especially among small farmers.

In contrast, a parallel strand of research proposes the fair profit distribution (FPD) approach to support supply chain decisions [14]. FPD aims to improve fair individual benefits by seeking supply chain flow optimization (materials, information, and cash) to guarantee economic equity among its members. In the context of agricultural supply chains, fairness is a matter of global concern and a relevant issue in the declaration of the Sustainable Development Goals (SDGs) of the United Nations [15]. Studies by [14,16,17] have pointed out notable differences between FPD and other approaches that seek global supply chain optimization while ignoring the problem of asymmetric information and bargaining power imbalances.

The FPD approach contributes to the social dimension of sustainable supply chains. According to [18], social considerations are a growing trend in the field of supply chain network management and design that "make companies more socially responsible, despite the fact that it imposes more costs on them". From this perspective, the FPD approach seeks to promote economic justice among the supply chain members, contributing to distributive justice [19,20]. In this way, the FPD approach aligns with the concept of fair trade, which "...promotes sustainable farming by helping producers in developing countries improve trading conditions and their own livelihoods" [21]. The Fairtrade movement "...is based on the need to provide farmers–growers and their rural communities with adequate rewards for their production in cross-continental supply chains" [22].

Although the FPD approach has been applied in various fields such as welfare economics, telecommunications, and supply chain contracting, among others [17], our literature review reveals a significant gap regarding its application to the facility location-allocation problem in supply chain network design (SCND). Specifically, no studies have been found that apply this approach considering the particularities of a sugarcane-derived biofuel SCND. Consequently, the research question addressed in this work is as follows: How should a biofuel supply chain from sugarcane be structured in terms of farm location and crop allocation, considering the development of a biorefinery, in such a way that a fair distribution of benefits is achieved in the long term?

Therefore, this paper proposes a multi-objective optimization model based on the FPD approach to support strategic decision-making in sugarcane biofuel supply chains. From an operations research perspective, the proposed methodology involves four steps: constructing a conceptual model, developing a mathematical model, designing a solution strategy, and interpreting and generating insights. The commercial optimizer GUROBI was used to solve the mathematical model and compare the FPD model with a traditional centralized planning supply chain (CSC) approach under various scenarios to assess the financial performance of the supply chain members. Several managerial insights suggest the importance of establishing collaboration and negotiation agreements among supply chain members to achieve equitable financial performance. This approach not only ensures the long-term financial sustainability of the biorefinery, but also supports the development of farm crops in accordance with long-term strategic planning.

The contributions of this paper can be summarized as follows:

- The proposed model maximizes and balances the profits of the supply chain members (farmers and biorefineries) using the FPD approach. It addresses the problem of facility location and allocation for biofuel-SCND, based on sugarcane, over a long-term horizon (multi-period), considering both the investment stage (crop development and biorefinery construction) and the operation stage.

- To provide more realistic results, the model considers relevant agricultural aspects, such as crop yields, operational day availability due to weather conditions, and limitations of agricultural machinery, among others.
- The proposed FPD model is compared with a traditional CSC approach, and various supply chain configurations are analyzed to improve economic justice among supply chain members. The computational outcomes derived from the proposed optimization model provide quantitative information to facilitate fair trade among farmers and biorefineries.
- An output-oriented data envelopment analysis (DEA) model is proposed to establish relative efficiencies between selected farms, considering their attributes vs. allocated land area, economic performance, and investment.

The subsequent sections of this paper are structured as follows: Section 2 presents a literature review. Section 3 offers a comprehensive description of the FDP-based optimization model. In Section 4, to evaluate the effectiveness of the proposed model, a set of instances is generated and presented; furthermore, the computational results obtained from the FDP-based model are compared with those obtained using the CSC model. Finally, Section 5 delves into the discussion and outlines the main conclusions.

2. Literature Review

A supply chain is a complex network of organizations involved in producing a particular product or service. The objective of supply chain members, including raw providers, service providers, manufacturers, and traders, is to add economic value for both customers and stakeholders. Supply chain network design (SCND) focuses on strategic decisions such as facility location and capacity allocation, supplier selection, and transport mode selection, among others [23].

Sugar production is part of agricultural supply chains (ASCs) [15,24]. Unlike industrial supply chains, in ASCs, numerous farmers typically participate as providers of commodities, owing to their restricted capacity to produce a given good [24]. ASCs pose numerous challenges due to their operations' complexity and multiple influencing factors, such as yield variability, perishability, climate conditions, transport infrastructure, and long production cycle times, among others, which affect the performance of this kind of supply chains [25,26].

Sugarcane is an excellent feedstock, used not only in the food industry but also for biofuel production, fertilizers, and bioelectricity [27]. A typical sugarcane supply chain involves several players related to growth, harvest, transport, mill processing, and distribution [9,28]. As part of ASCs, the sugarcane supply chain is also a complex system that can be affected by factors such as crop yield variability, harvested cane perishability, climate conditions, and long production cycle times [26,29]. These influential factors generate operational and financial risks that mostly affect the agricultural echelon (farmers) [29,30]. Therefore, in the biofuel SCND, proper synchronization is required between farmers, transport, and biorefineries to achieve supply chain goals [10,31]. However, it is not an easy task due to the multiple interests in design and planning decisions [12,17].

According to [22,32], proper interaction among supply chain members is essential for creating value for the entire system. Notwithstanding, this interaction can be seriously affected by asymmetries in available information and bargaining power. These asymmetries contribute to heightened supply costs, impacting shareholder investments. From a social standpoint, numerous authors concur that information asymmetries among ASCs members play a substantial role in the wastage of agricultural products and result in unfair pricing for farmers [22,30,33,34].

To identify the most relevant publications that link the FPD approach with SCND in general, and particularly in the field of biofuels from sugarcane, a bibliographic review methodology like that applied in [35,36] was used. This methodology consists of the following stages: (1) definition of the purpose and objectives of the review; (2) location, selection, and evaluation of scientific articles; (3) analysis of results; (4) identification of knowledge gaps. For this purpose, the following search equations were established:

Equation (1): "Fair profit" OR "fairness profit distribution" OR "economic justice" AND Supply chain" OR "supply chain network design".

Equation (2): "Fair profit" OR "fairness profit distribution" OR "economic justice" AND Supply chain" OR "supply chain network design" AND sustainability OR sustainable OR social concerns.

Equation (3): "Fair profit" OR "fairness profit distribution" OR "economic justice" AND Supply chain" OR "supply chain network design" AND bioenergy OR biofuel OR ethanol OR sugarcane OR "biofuels-based biomass".

Equation (4): "Fair profit" OR "fairness profit distribution" OR "economic justice" AND Supply chain" OR "supply chain network design" AND sustainability OR sustainable OR social concerns AND bioenergy OR biofuel OR ethanol OR sugarcane OR "biofuels-based biomass".

Using the SCOPUS database (period 2000–2024), 29 articles were identified with Equation (1), 5 articles with Equation (2), and 2 articles with Equation (3); no articles were found with Equation (4). After reviewing the abstracts and keywords, duplicate works or those not directly related to the subject under study were eliminated, resulting in a final selection of 26 articles. The literature analysis reveals that the FPD approach has been applied in various fields such as welfare economics, telecommunications, supply chain contracting and collaboration, and supply chain network design, among others. Although ref. [15] conducted an extensive literature review focusing on fairness-enabling practices and existing business applications in ASCs, the study falls short in providing practical contributions, particularly from the perspective of mathematical modeling of supply chains under the FPD approach. Therefore, contributions to SCND in the field of ASCs and biofuel production from biomass remain an open field, offering multiple opportunities for research, given its particularities and influencing factors previously described.

In the work of [17], a mixed-integer nonlinear programming model (MINLP) is proposed to determine the optimal production, distribution, and capacity planning of a multi-echelon supply chain using transfer prices. To define FPD, they analyzed the proportional and max–min fairness criteria, considering the bargaining power of supply chain members. Computational results showed that both FPD approaches achieved fairer profit distributions than the maximization of total profit approach. In [37], a profit distribution model was proposed under centralized decision-making, considering the secondary ASC. The results indicated that the distribution, based on an optimal profit distribution coefficient, maximizes the profit of each supply chain actor. In turn, ref. [38] investigated the interaction between peer-induced fairness and distributional fairness in price contract design, within the context of a supply chain consisting of one supplier and two retailers. The results showed that both types of fairness affect economic outcomes in the supply chain, but peer-induced fairness had a stronger impact than distributional fairness. Ref. [39] studied how firm concerns about fairness affect the nature of optimal contracts in the marketing channel; the analysis shows that, in a fair channel, retailers tend to achieve an equitable outcome in channel interactions, and the maximum channel utility can be achieved when the manufacturer considers a constant wholesale pricing policy.

To help textile fiber producers and buyers achieve fair profits by eliminating intermediaries in the supply chain, ref. [40] developed an online blockchain-based sustainable logistics management system (OBSLMS). This system enables direct communication between supply chain members, enhancing efficiency, reducing fraud, strengthening security, and promoting transparency. To explore the impact of horizontal collaboration on the structure of distribution networks, transportation planning, and revenue sharing, ref. [41] proposed a location routing problem (LRP) model within collaborative initiatives for sustainable urban freight transportation in Morocco's dry food products sector. The model evaluates individual shippers' benefits through a profit allocation problem, considering their contributions and level of collaboration within the supply chain.

Later, ref. [42] proposed a mathematical model to evaluate the impact of quality decisions under two scenarios: (i) buyer dominance, and (ii) coordination between buyer and seller. The model demonstrates that under a coordination scenario, total supply chain profitability increases, prices decrease, and quality levels improve. In the work of [43], a fair profit-sharing strategy is developed for a two-echelon supply chain model to coordinate the retailer's safety stock level with the distributor's visit interval and replenishment policy. The results indicate that coordinating the visit interval and safety stock leads to better performance for supply chain agents in terms of customer service levels and profits.

The author of [44] developed a model for a two-echelon supply chain comprising a single manufacturer and a single retailer, with a particular emphasis on an imperfect production system. The numerical findings highlight the effectiveness of coordination mechanisms and defect management policy. To guarantee the success and acceptance of local energy markets (LEMs), ref. [45] suggests a cooperative game-theoretic framework designed to encourage prosumer participation and equitable profit distribution. The findings underscore the advantages of a consumer-focused LEM, such as enhanced local trading dynamics, equitable profit sharing, and increased grid stability.

The author of [46] proposed an optimization framework for a SCND focused on repurposing retired electric vehicle (EV) batteries within distributed energy systems (DES) to promote resource circularity. By integrating a supply chain profit allocation model with a DES model, the framework maximizes overall supply chain profit while ensuring fair distribution of profits among the EV sector, DES operators, and the dismantling and recycling (D&R) sector. A MINLP model to optimize operational decisions and profit allocation mechanisms in a cellulosic bioethanol supply chain in Illinois was proposed by [47]. A game-theory-based Nash bargaining solution approach is employed to ensure a fair distribution of profits among gathering facilities, biorefineries, and distribution centers. In the context of supply chain collaboration, ref. [48] designed an integrated vendor-managed inventory model, structured with a single capacitated manufacturer at the first level and multiple retailers at the second level. Since a bi-objective model is proposed, the lexicographic max–min approach is employed to obtain a fair, non-dominated solution.

To ensure FPD, ref. [49] developed a multi-objective mixed-integer nonlinear programming (MOMINLP) framework for the production and distribution planning problem in a supply chain system. The model achieves a balanced profit distribution among all members, while also considering customer service levels and inventory management. In a similar study, ref. [50] presented a multi-product, multi-stage, and multi-period scheduling model for an uncertain multi-echelon supply chain network. The model accounted for uncertain market demands and product prices, as well as multiple conflicting objectives such as FPD, inventory levels, customer service levels, and decision robustness in the face of uncertain product demands. A compromised solution was demonstrated through a numerical example.

The author of [51] proposed a framework to coordinate the operational decisions between pipeline carriers and oil shippers, along with a bi-level programming model to characterize the decentralized decision-making process of the stakeholders. To achieve coordination, a negotiation mechanism based on FPD was introduced. The method was tested on a large-scale refined products logistics system in China, obtaining a fairer profit distribution compared to centralized decision-making. Using the concept of fair entropy, ref. [37] solved for the optimal profit distribution coefficient in a two-tier ASC composed of a single cooperative and a single wholesaler. The model considered both resources and risk as factors to determine the importance weights of each supply chain actor.

In the work of [52], a model for fair profit allocation in the sugarcane agro-industry supply chain was developed, considering uncertain risks and value-added contributions. The profits were distributed based on the marginal contribution, risk potential, and value-added contribution of each supply chain actor. In a similar paper, ref. [53] formulated a risk and value-added balancing model to determine the ideal and fair product price at each supply chain echelon. The results indicate that upstream companies face higher risks, while downstream companies capture more value-added and profit. Therefore, based on a proper balance between risk and value-added, the model determines both prices and an FPD.

Using cooperative game theory, ref. [54] studied the stable and fair allocation of profits under vertical integration between manufacturers and retailers, considering an ex-post change in the leadership position. Their findings demonstrate that vertical integration is stable when all members are pessimistic, in the sense that they are certain they will not become the contracting leader if they deviate from the grand coalition. It was also shown that the benefits of the grand coalition should be allocated to a greater extent to retailers and higher-cost members. Under a business collaboration scheme, ref. [55] proposes a model for the design of a delivery service network, considering a multi-time horizon. The model defines which company in the network should handle the delivery of certain products in designated regions, using the infrastructure (vehicles and facilities) of the other companies. The fair profit distribution among the companies is found through a numerical example.

Considering the diseconomies of scale and network externalities in the e-commerce supply chain (ECSC), ref. [56] proposed a benchmark model led by an e-platform that generates optimal decisions. By comparing the benchmark model with other extended models, imbalances (prices vs. service) caused by network externalities and diseconomies of scale are detected. It was demonstrated that improving network externalities promotes a fair profit distribution in the ECSC. To study the impacts of implementing and promoting blockchain on decision-making and coordination in the secondary supply chain under the retailer's fairness concerns towards the manufacturer, ref. [57] demonstrated that, under coordination with the two-part tariff contract, the manufacturer's blockchain level shows the most significant growth, while the retailer's publicity efforts and system profits also increase significantly, and the product gains a greater price advantage.

A multi-product, multi-stage, and multi-period production and distribution planning model formulated by [58] achieved a proper balance between multiple objectives such as maximizing the profits of each company, maximizing the level of customer service, and ensuring FPD. Using cooperative game analysis, ref. [59] studied a two-echelon closed-loop supply chain comprising a risk-neutral manufacturer, a fairness-neutral, risk-averse retailer, and a risk-neutral retailer with fairness concerns. The numerical study reveals that the impact of the risk aversion and fairness concern parameters is dynamic, varying in influence and not consistently positive or negative.

Although the previously mentioned articles make significant contributions, there is a clear gap in the literature regarding the use of the FPD approach to address the facility location-allocation problem in SCND. Although we have identified three studies that relate the FPD approach to ASCs, specific aspects that affect this type of supply chain, e.g., crop particularities, have not been studied. As highlighted by [26], concerns related to ASCs are rarely explored, underscoring the pressing need for further investigation into how agricultural specificities influence biomass production. Notably, no studies have been found that apply an FPD approach to biofuel SCND involving sugarcane biomass. This gap is particularly critical, as deeper analysis is required to achieve economic fairness. From a mathematical standpoint, especially in sugarcane-based SCND, the asymmetry of information and power imbalances between farmers and biorefineries introduce significant obstacles to advancing economic justice, especially for the farmers involved.

3. Problem Statement

3.1. Problem Description

The analyzed supply chain comprises two components: the agricultural echelon (sugarcane crops) and the industrial echelon (biofuel production). In the agricultural echelon, a group of farms grows sugarcane to supply a biorefinery where bioethanol, energy and bio-fertilizer are produced. Cane stems are also produced on farms to be used as seed. This seed can be consumed by the farm itself or sold to other farms. The planning horizon consists of two stages: investment and operation (see Figure 1). During the investment stage, crops are developed and a biorefinery is built simultaneously. At this stage, it is important to synchronize these two activities so that the sugarcane achieves the appropriate ripeness level to supply the biorefinery. During the operational phase, the biorefinery enters its production stage, while sugarcane cultivation must continue on the farms. During this stage, initial incomes are generated, which permits the financial leverage of operations.

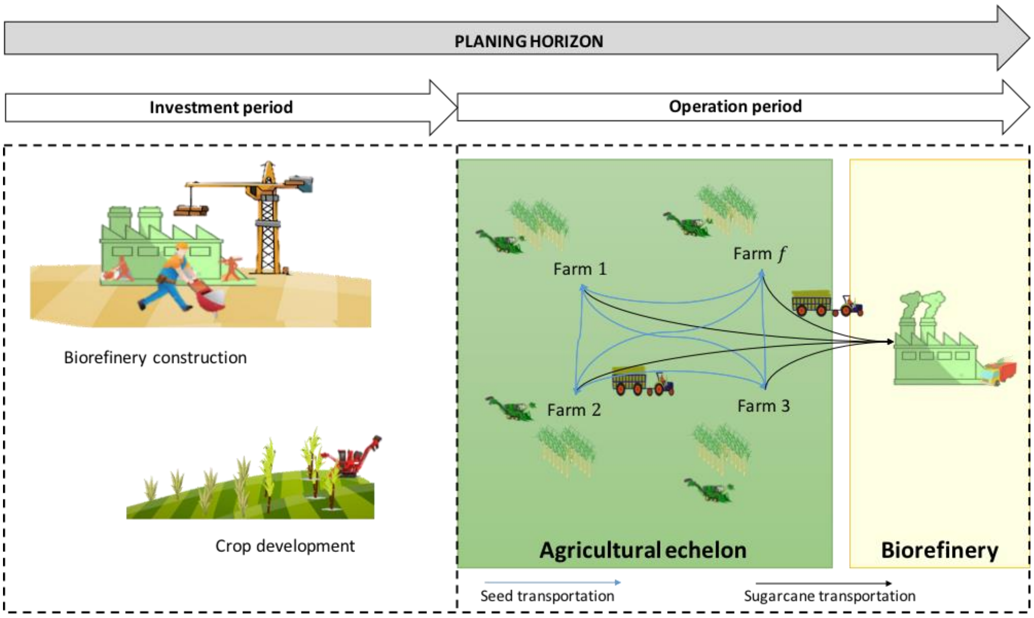

Figure 1. Stages of supply chain development.

For the two mentioned stages, the model addresses the problem of facility location and allocation by synchronizing the operation planning between farms and biorefineries. In this case, it starts from a finite set of farms, on which the sugarcane crops are grown. Each farm has a maximum available area for sugarcane cultivation. On the other hand, there is a biorefinery that demands sugarcane stems during all time periods. Depending on biorefinery requirements, the model assigns a crop area to be planted for each of the located farms. It is also assumed that the sugarcane yield (crop productivity) depends on its age: the older the crop the lower its yield. This adds greater complexity and realism to the model.

Typically, the problem of facility location and allocation focuses on minimizing operating costs and maximizing benefits, considering the supply chain as a whole (here called the centralized planning supply chain, CSC), which could be unrealistic in agri-industrial contexts [60]. Under a CSC approach it is assumed that all supply chain members belong to the same organization and, therefore, a unique decision center is in charge of optimizing costs and profits [12]. Nevertheless, in real-world scenarios, where most supply chain members operate as independent companies, decisions made under this approach may lead to inequities and negotiation conflicts [17].

Our proposed model is grounded in an FPD approach that integrates max–min fairness [61] within a long-term planning horizon. The objective is to identify optimal farm locations through selection and allocate an optimal capacity level for crop growth to each selected farm. This is done with the goal of maximizing the minimum profit attained by both the agricultural (selected farms) and industrial echelons (biorefinery).

3.2. Assumptions and Notations

Sugarcane is a perennial crop, meaning it is initially planted, grown, harvested, and then regrown. This regrowth process is called ratooning. For agro-industrial purposes, the models typically consider only five ratoon cycles to account for performance decline over time. The first index introduced is $r \in R$ representing a set of ratoons in the crop life cycle (1, 2, 3, 4, 5). The sugarcane crop is cultivated on one of the potential farms that can be selected for development, $f \in F$. At the industrial level, a set of potential products can be obtained from sugarcane processing (ethanol, energy from cogeneration, and bio-fertilizer as a by-product), $j \in P$. The final index introduced is the time horizon for project assessment, represented as a set of discrete periods *N*, where $t \in TH$.

Parameter's information is classified into three groups: investment information, operating income and costs, and production rates. First, the investment parameters include: AMI, agricultural machinery investment over a five-year period ($/ha); BPI, biofuel plant investment ($); CAC, biorefinery construction auditing cost ($); CFI, investment in complementary industrial facilities ($); ITI, information and communication technology (IT) investment ($); PPEI, property, plant, and equipment investment made during the agricultural investment stage ($); PPEII, property, plant, and equipment investment made during the industrial investment stage ($); and SCC, sowing cost during the investment period ($/ha). Additionally, during the investment stage, the investments in the biorefinery and farm development are subject to an execution percentage (EP), defined as follows: BID_t, EP of the investment plan in the biorefinery for each period *t* during the investment stage (%); CAD_t, EP of the construction auditing cost for each period *t* during the investment stage (%); CFD_t, EP of the investment plan in complementary facilities for each period *t* during the investment stage (%); ITD_t, EP of the investment plan in IT for each year t during the investment stage (%); and finally, $\mathrm{CTN}_{t,f}$, land investment cost during period *t* for each farm *f* ($/ha).

Another set of parameters pertains to operational costs and incomes from sales, as outlined below: ACS, crop amortization rate for each harvested ratoon ($/ha); AE, administrative expenses for agricultural operations ($/ha); DLC, direct workforce cost of agricultural operations ($/ha); EPEC^j, sale price for each product j ($/und); HC, standard transportation cost, $/(ton-km); $\mathrm{inputCost}_j$, cost of input needed to process a product j ($/und); MCO, crop maintenance cost ($/ha); OHC, operating harvest cost ($/ha); and WHC, operating harvest cost for discarded sugarcane ($/ha). The last set of parameters related to operational rates includes: BioCap_t, annual sugarcane milling capacity of the biorefinery during the period t (t/y); Dis_f^g, Manhattan distance measured between each potential location f and others g, including the biorefinery (km); DCom_f, maximum amount of land available for purchase at each farm f (ha); $\mathrm{HarvestingC}_t$, maximum harvesting capacity using available equipment in period t (ha/y); SCS, amount of seed required to sow sugarcane (t/ha); $\mathrm{SowingC}_t$, maximum sowing capacity considering available equipment in period t (ha/y); TCH_r, amount of sugarcane harvested at ratoon r during the cutting time (t/ha); $x_{r,f}^0$, amount of sugarcane planted at initial time by each ratoon r and each farm f (ha); μ_j, production rate of product j obtained in the biorefinery (units/t). Additional information includes: PCane, the percentage of ethanol price equivalent production based on sugarcane (%) and td, the discount rate (%) required for assessing financial flows over time.

The decision variables required for model optimization are introduced below, in relation to the agricultural echelon structure: $\mathrm{area}_{t,f}$, the area used for sugarcane cultivation at period t by farm f (ha/y); $\mathrm{Land}_{t,f}$, the amount of land acquired at each farm f at the end of each period t (ha/y); $\mathrm{Cland}_{t,f}$, the amount of purchased land available for planting a new crop in during period t at each farm f (ha); $x_{t,r,f}$, the total area sown with sugarcane, classified into different ratoons r at the end of period t at each farm f (ha/y); $Y_{t,f}$, the amount of land sown during period t for each farm f (ha/y); $\mathrm{Co}_{t,r,f}$, the area harvested during period t at farm f in ratoon r (ha/y). Regarding sugarcane performance: $\mathrm{CC}_{t,f}$, the amount of sugarcane harvested and transported to the biorefinery during period t for each farm f (t/y); $\mathrm{CV}_{t,f}$, the amount of cane discarded when ripening period is exceeded during period t at farm f (t/y); CP_t, the cane harvested but wasted because it was not sent to the biorefinery on time during the period t (t/y); CS_t, the amount of cane shortage at biorefinery during the period t (t/y); $\mathrm{CscI}_{t,f}$, the amount of cane seed produced at the farm f and transported to other farms during the period t (t/y); $\mathrm{CscO}_{t,f}$, the amount of cane seed received from other farms to be used in sowing operation at farm f during the period t (t/y);

$\text{CSC}_{t,f}^{g}$, the amount of cane seed transported from farm f to farm g for sowing operations at period t (t/y); and NPVF_f, the net present value of profit obtained by each farm f at agricultural tier over the time horizon ($).

Moreover, we set additional decision variables to model particular aspects of the biorefineries, such as: SugarCan_t, the amount of sugarcane received in the biorefinery from all farms during the period t (t/y); Supply_t, the amount of sugarcane to be processed in the biorefinery during the period t (t/y); $\text{Production}_{t,j}$, the amount of final product j produced in the biorefinery process during the period t (Und/y); and NPVI, the net present value of profit obtained by the biorefinery over the time horizon ($). Finally, the variable $K^{+/-}$ is included to represent the minimum NPV of profit obtained by each tier of supply chain (agricultural echelon, biorefinery), This is part of the max–min modeling approach, which reflects the FPD framework.

4. Mathematical Modeling

4.1. Methodology

This paper addresses the identified problem from the perspective of operations research, which is characterized by an axiomatic and normative process [62]. The proposed methodology follows a series of steps aimed at solving the scientific problem: constructing a conceptual model, developing a mathematical model, designing a solution strategy, and finally, interpreting and generating insights [62–64]. The conceptual model is based on a literature review and the development of a conceptual framework that considers FPD as a strategy for achieving economic justice. A mathematical model is then introduced to operationalize the conceptual model by identifying its key elements (sets, parameters, and decision variables), as well as the logical relationships resulting from the interaction of the system components, represented by constraints and performance measures. The next phase focuses on the solution strategy, using commercial optimizers (GUROBI) to solve the mathematical models and search for an optimal solution, while using multi-objective optimization to explore the trade-offs between the two approaches presented. Finally, in the interpretation and knowledge generation phase, the results and key factors influencing the ASC design are analyzed and discussed.

4.2. Objective Function

Based on the above, the objective function (see Equation (1)) maximizes the minimum net present value (NPV) of profits obtained by each supply chain player (farmers and biorefinery). To find a configuration that allocates profits fairly, the variable $\boldsymbol{k}^{+/-}$ establishes a minimum threshold of economic performance for each set of supply chain members. Positive and negative values fall within the domain of the objective function. Positive values reflect favorable economic performance for the supply chain, whereas negative values indicate undesirable economic performance at one of the chain's echelons.

$$\text{Maximize} : Z = K^{+/-} \tag{1}$$

4.3. Model Constraints

The objective function has two auxiliary constraints, through which a lower performance bound is established for supply chain echelons (biorefinery and farms) (Equations (2) and (3)). As shown in Equation (3), the minimum profit depends on both the biorefinery's profits (Equation (2)) and the aggregated profit of farms. The information about sets, parameters, and decision variables are declared in Appendix A.

$$K^{+/-} \leq \text{NPVI} \tag{2}$$

$$K^{+/-} \leq \sum_{f \in F} \text{NPVF}_f \tag{3}$$

Agricultural decisions are modeled from Equations (4)–(16). Initially, the profits for each farmer are calculated using Equation (4). Farm incomes are composed of the sales of fresh sugarcane and the salvage value of the purchased land at the end of the time horizon. The farm costs are determined by investment and operating costs. The former includes crop investments, land, and equipment purchase, while the latter is composed of harvest, crop renewal, seed purchasing, and waste costs. The mass balance is set by Equation (5), where the total sown area is updated based on the new sown area (crop renewal) and the harvested area; in the first period $(\mathrm{t}=1)$, $\mathrm{X}^0_{\mathrm{r,f}}$ is included as a parameter that indicates the initial value of available land at farm f and the area sown for every ratoon ***r***. In Equation (6), the harvesting capacity is established for each ratoon during the entire planning horizon. Using Equation (7), the sowing capacity is limited by the availability of seed, which can be purchased from other farms or produced by the farms' own crops.

$$\mathrm{NPVF_f} = \sum_{\mathrm{t\in TH}} \begin{bmatrix} \mathrm{CC_{t,f} * EPEC^1 * PCane} - \\ \mathrm{Y_{t,f} * (SCS * OHC - MCO)} + \\ \mathrm{area_{t,f} * (DLC + AE + MCO)} + \\ \mathrm{CC_{t,f}OHC + CV_{t,f}WHC} + \\ \mathrm{CscI_{t,f} * 1.1(EPEC^1 * PCane)} + \\ \mathrm{Y_{t,f}SCC + Cland_{t,f}CTN_t + area_{t,f}PPEI} \end{bmatrix} (1+\mathrm{td})^{-\mathrm{t}} + \sum_{\mathrm{t\in TH}} \mathrm{Cland_{t,f}\,CTN_0} * (1+\mathrm{td})^{-\mathrm{N}} \qquad \forall \mathrm{f} \in \mathrm{F} \tag{4}$$

$$\begin{aligned} \mathbf{x_{t,r,f}} &= \{\mathbf{Y_{t,f}\ if\ r = 1\ else\ 0}\} + \{\mathbf{Co_{t-1,r-1f}\ \ if\ (t > 1 \wedge\ r > 1)\ else\ 0}\} \\ &+ \{\mathbf{X^0_{r,f}\ if\ t = 1\ else\ 0}\} + \{\mathbf{x_{t-1,r,f} - Co_{t-1,r,f}\ if\ t > 1\ else\ 0}\} \end{aligned} \qquad \begin{gathered} \forall \mathbf{f} \in \mathbf{F} \\ \forall \mathbf{t} \in \mathbf{TH} \\ \forall \mathrm{r} \in \mathrm{R} \end{gathered} \tag{5}$$

$$\mathrm{x_{t,,r,f} - Co_{t,,r,f}} \geq 0 \qquad \begin{gathered} \forall \mathbf{f} \in \mathbf{F} \\ \forall \mathbf{t} \in \mathbf{TH} \\ \forall \mathrm{r} \in \mathrm{R} \end{gathered} \tag{6}$$

$$\begin{gathered} \mathbf{CscI_{t,f}} + \left(\mathbf{x_{t-1,1,f} - Co_{t-1,1,f}}\right) * \mathbf{TCH_1} + \\ \left(\mathbf{Co_{t-1,1,f} + x_{t-1,2,f} - Co_{t-1,2,f}}\right) * \mathbf{TCH_2} \geq\ \mathbf{Y_{t,f}} * \mathbf{SCS} \end{gathered} \qquad \begin{gathered} \forall \mathbf{f} \in \mathbf{F} \\ \forall \mathbf{t} \in \mathbf{TH} \\ \backslash\{\mathrm{t} = 1\} \end{gathered} \tag{7}$$

Regarding crop yield, Equations (8)–(10) establish the amount of cane stems produced by farmers, as well as their possible uses, such as seed for planting, raw material to feed biorefineries, or discarded cane. Harvested cane is a perishable raw material that, like other agricultural products, poses a challenge due to the time delay between harvesting and reaching the mill location. Therefore, cane is discarded when it exceeds its ripening period, or when farms generate a certain amount of it before biorefineries are built. Equation (8) ensures the balance between the sugarcane produced and used. The equation's left-hand side establishes the total sugarcane produced by crops, while the right-hand side is composed of the total seed required, sugarcane stems transported to the biorefinery, discarded cane stems, and the seed sold to other farms. Equation (9) guarantees the sale of sugarcane seeds produced by farms' own crops, and Equation (10) ensures that all purchased seeds are used to plant new crops.

$$\sum_{\mathbf{r\in R}} \mathbf{Co_{t,r,f}} * \mathbf{TCH_r} = \mathbf{Y_{t,f}} * \mathbf{SCS} + \mathbf{CC_{t,f}} + \mathbf{CV_{t,f}} + \mathbf{CscO_{t,f}} - \mathbf{CscI_{t,f}} \qquad \begin{gathered} \forall \mathbf{f} \in \mathbf{F} \\ \forall \mathbf{t} \in \mathbf{TH} \end{gathered} \tag{8}$$

$$\sum_{\mathbf{r}\in[\mathbf{1},\mathbf{2}]} \mathbf{Co_{t,r,f} * TCH_r \geq Y_{t,f} * SCS + CscO_{t,f}} \qquad \forall \mathbf{f} \in \mathbf{F} \quad \forall \mathbf{t} \in \mathbf{TH} \tag{9}$$

$$\mathbf{Y_{t,f} * SCS \geq CscI_{t,f}} \qquad \forall \mathbf{f} \in \mathbf{F} \quad \forall \mathbf{t} \in \mathbf{TH} \tag{10}$$

Equations (11)–(14) facilitate the development of the agricultural plan. The amount of land sown is updated for each period by considering the new sown area, the harvested area at the end of a productive cycle, and the area sown in the previous period (Equation (11)). Equation (12) sets the balance of land purchased for each farmer. Equation (13) ensures that the sown area does not exceed the total available area for each farm. Moreover, 5% of additional area is allocated for alleys for each cultivated hectare. Finally, Equation (14) limits the amount of land that can be acquired by each farm.

$$\mathbf{Y_{t,f}} + \left\{\mathbf{area_{t-1,f} - Co_{t-1,5,f}\ if\ t > 1\ else\ 0}\right\} + \left\{\sum_{\mathbf{r}\in\mathbf{R}} \mathbf{x^{0}_{r,f}\ \ if\ t\ = 1\ else\ 0}\right\} = \mathbf{area_{t,f}} \qquad \forall \mathbf{f} \in \mathbf{F} \quad \forall \mathbf{t} \in \mathbf{TH} \tag{11}$$

$$\mathbf{Land_{t,f} = Land_{t-1,f}\ if\ t > 1\ else\ 0 + Cland_{t,f} + 1.1} * \left\{\sum_{\mathbf{r}\in\mathbf{R}} \mathbf{x^{0}_{r,f}\ \ if\ t = 1\ else\ 0}\right\} \qquad \forall \mathbf{f} \in \mathbf{F} \quad \forall \mathbf{t} \in \mathbf{TH} \tag{12}$$

$$\mathbf{Area_{t,f} * 1.05 \leq Land_{t,f}} \qquad \forall \mathbf{f} \in \mathbf{F} \quad \forall \mathbf{t} \in \mathbf{TH} \tag{13}$$

$$\sum_{\mathbf{t}\in\mathbf{TH}} \mathbf{Cland_{t,f} \leq DCom_f} \tag{14}$$

Using Equations (15) and (16), agricultural machinery and available workforce are assigned to sowing and harvesting operations, respectively. Equation (15) establishes the maximum sowing capacity, which depends on sowing crews and seed availability. It is assumed that five sowing crews are available, and each of these consists of one mechanical planter, two tractors, and five workers. Due to the nature of agricultural operations, the availability of these resources is often affected by weather conditions. Sowing crews are shared among all farms and are scheduled by the biorefinery, in accordance with farm requirements. Equation (16) establishes the maximum harvesting capacity. A harvesting crew is composed of mechanical harvesters, tractors, trucks, tipping trailers, and load trailers. This machinery also belongs to the biorefinery and is assigned to each farm according to the harvest schedule. Therefore, the costs of harvesting operations are deducted from the sugarcane price paid to each farm.

$$\sum_{\mathbf{f}\in\mathbf{F}} \mathbf{Y_{t,f} \leq\ SowingC_t} \qquad \forall \mathbf{t} \in \mathbf{TH} \tag{15}$$

$$\sum_{\substack{\mathbf{f}\in\mathbf{F}\\ \mathbf{r}\in\mathbf{R}}} \mathbf{Co_{t,r,f} \leq HarvestingC_t} \qquad \forall \mathbf{t} \in \mathbf{TH} \tag{16}$$

Equation (17) calculates the ***NPV*** profit of the biorefinery (income minus cost). The income is composed of the sales of bioethanol, electric power, and bio-fertilizer. The total cost is made up of investment (capital expenditures, CAPEX) and operational costs (operational expenditures, OPEX). CAPEX includes the cost of biorefinery construction and machinery acquisition, including harvesting machinery and engine repowering. OPEX is composed of the cost of sugarcane purchase, as well as transportation, workforce, indirect costs, and discarded sugarcane stems.

$$\mathbf{NPVI} = \sum_{\mathbf{t \in TH}} \left[\begin{array}{l} \sum\limits_{\mathbf{j \in P}} \mathbf{Production_t^j * EPEC^j} - \sum\limits_{\mathbf{j \in P}} \mathbf{Production_t^j * inputCost_j} - \\ \sum\limits_{\mathbf{f\ in \in F}} \mathbf{CC_{t,f} * (EPEC^1 * PCane + DLC + AE) + CP_t * WHC} - \\ \mathbf{[BPI * \left(BID_t + ITI * ITD_t + CAC * CAD_t + CFI * CFD_{ty}\right)} + \\ \mathbf{\frac{PPEII}{CpxP}\ if\ t \in CpxP\ else\ \ PPEII * \frac{Supply_t}{BioCap_t} + AMI]} - \\ \sum\limits_{\mathbf{f \in F}} \mathbf{CC_{t,f} * Dis_f^{Bio} * HC} \end{array} \right] \qquad \forall \mathbf{f \in F} \qquad (17)$$

$$\in \mathbf{F * (1 + td)^{-t}}$$

Biorefinery operations are modeled in Equations (18)–(21). Equation (18) determines the amount of sugarcane (raw material) supplied from farms. The sugarcane balance and maximum processing capacity are calculated in Equations (19) and (20), respectively. Additionally, Equation (21) establishes production planning to transform biomass into bioethanol, electrical energy, and bio-fertilizer.

$$\mathbf{SugarCan_t} = \sum_{\mathbf{f \in F}} \mathbf{CC_{t,f}} \qquad \forall \mathbf{t \in TH} \qquad (18)$$

$$\mathbf{SugarCan_t = Supply_t + CP_t} \qquad \forall \mathbf{t \in TH} \qquad (19)$$

$$\mathbf{Supply_t + CS_t = BioCap_t} \qquad \forall \mathbf{t \in TH} \qquad (20)$$

$$\mathbf{Supply_t * \mu_j = Production_{t,j}} \qquad \begin{array}{c} \forall \mathbf{t \in TH} \\ \forall \mathbf{j \in P} \end{array} \qquad (21)$$

To develop new crops, Equation (22) guarantees the amount of seed to be supplied from farm **f** to other farms, and Equation (23) guarantees that the seed produced on farm **f** can be transported to other farms.

$$\sum_{\mathbf{g \in F, f \neq g}} \mathbf{CSC_{t,f}^g = CscI_{t,f}} \qquad \begin{array}{c} \forall \mathbf{t \in TH} \\ \forall \mathbf{f \in F} \end{array} \qquad (22)$$

$$\mathbf{CscO_{t,f}} = \sum_{\mathbf{g \in F, f \neq g}} \mathbf{CSC_{t,g}^f} \qquad \begin{array}{c} \forall \mathbf{t \in TH} \\ \forall \mathbf{f \in F} \end{array} \qquad (23)$$

Finally, all decision variables must be greater than or equal to zero (see Equation (24)).

$$\begin{array}{l} \mathbf{area_{t,f}, CC_{t,f}, Co_{t,rf}, CP_t, CS_t, CSC_{t,g}^f, CscI_{t,f}, CscO_{t,f}, Ctierra_{t,f},} \\ \mathbf{CV_{t,f}, NPVI, NPVF_f, Production_t^j, SugarCa, Supply_t, x_{t,r,f}, Y_{t,f}} \end{array} \qquad \geq \mathbf{0} \qquad (24)$$

4.4. Sub Model to Analyse Agricultural Echelon Efficiency

As each farm selected by the FPD model has specific attributes, such as distance to biorefineries, available versus allocated land area, economic performance, and investment, it is exceedingly challenging to rank them in terms of overall efficiency. To conduct an impartial comparison (with data envelopment analysis, DEA) of farms, an output-oriented DEA-CCR model [65] is proposed to determine the relative efficiencies among the selected farms. DEA methods have been widely applied in the development of decision-making tools. Specifically, in the field of supply chain network design (SCND) and biofuel production, the works of [66–69] are particularly notable.

In the work of [66], a common weight data envelopment analysis (CWDEA) method is proposed for optimizing the location of feedstock cultivation within a biodiesel supply chain. The model incorporates a comprehensive set of sustainability criteria to evaluate potential locations. In a case study conducted in Iran, the model identifies optimal locations for biomass cultivation, aiming to balance socioeconomic development with environmental benefits in marginal and largely underdeveloped lands. To support the policymakers to make strategic and tactical level decisions related to biodiesel supply chain planning in Iran, ref. [67] proposed an integrated hybrid approach based on a data envelopment analysis (DEA) and mathematical programming techniques for a biodiesel SCND from Jatropha Curcas L. (JCL) and waste cooking oil (WCO). In the first phase, the model assesses JCL cultivation areas using a unified DEA (UDEA) model, with locations achieving better efficiency scores considered as candidate locations for JCL cultivation.

The author of [68] developed a transformed TSN (T-TSN) DEA method by applying a multi-criteria DEA model to address inconsistencies in assigning overall efficiency scores to the DMUs under evaluation. The proposed approach was validated in a biomass-biofuel logistics network through a case study in South Carolina, USA, demonstrating its superiority over the traditional TSN-DEA model. In the research work developed by [69], a methodological framework is proposed to define, assess, and prioritize strategies aimed at minimizing social life-cycle impacts across the supply chain of energy products. The framework integrates social life cycle assessment (S-LCA) with multi-criteria decision analysis (MCDA). The weighted sum method (WSM) and data envelopment analysis (DEA) were employed as MCDA tools to evaluate fifteen strategies within the specific supply chains of oil and fertilizers, assessing their suitability in a case study conducted in Portugal.

The DEA model is presented in Equations (25)–(29). The sets are as follows: DMU is the set of selected farms (decision-making units); I is the set of used resources, including distance, exploited area, and investment; and O is the set of performance measures, represented by the NPV of farms. Regarding the parameters introduced: $Y_{j,k}$ indicates the level of utilization of resource $j \in I$ by the farms $k \in DMU$; $X_{j,k}$ indicates the performance measure $j \in O$ obtained by each farm $k \in DMU$; and $\in$ expresses the efficiency penalty due to excessive resource consumption or poor performance. Finally, the decision variables used in the model include: $\lambda_{k,l}$, which represents the weight assigned to each farm $k \in DMU$, forming a linear combination with all the other farms $l \in DMU$; $S^{+}_{j,i}$, indicating the NPV surplus of the farms for each performance measure $j \in O_j$ and farm $i \in DMU$; $S^{-}_{i,j}$, the slack variable related to the used resources $i \in I$ for each farm $j \in DMU$; and most importantly, θ_i, representing the relative efficiency of farm $i \in DMU$.

$$\text{Minimize } f = \sum_{i \in DMU} \left[\theta_i - \in * \left(\sum_{j \in I} S^{+}_{j,i} + \sum_{j \in O} S^{-}_{j,i} \right) \right] \tag{25}$$

$$\text{Subject to} \sum_{k \in DMU} Y_{j,k} * \lambda_{k,l} - S^{+}_{l} = Y_{jl} \qquad \begin{array}{c} \forall \mathbf{l} \in \mathbf{DMU} \\ \forall j \in O \end{array} \tag{26}$$

$$\sum_{k \in DMU} X_{j,k} * \lambda_{k,l} + S^{-}_{l} = \theta_l * X_{jl} \qquad \begin{array}{c} \forall \mathbf{l} \in \mathbf{DMU} \\ \forall j \in i \end{array} \tag{27}$$

$$\sum_{k \in DMU} \lambda_{k,l} = 1 \qquad \forall l \in DMU \tag{28}$$

$$\lambda_{k,l}, \theta_l, S_l^-, S_l^+ \geq 0 \tag{29}$$

5. Results and Analysis

5.1. Preliminary Outcomes and Analysis

To assess the efficacy of the FPD model, a series of instances were generated. Drawing from the research of [4,70], a processing capacity of 5500 tons per day was assumed for the biorefinery, considering an ethanol production rate of 72.5 L per ton of processed sugarcane stems. Through analysis of various studies, as presented in Table 1, the costs, prices, and technical information pertaining to agricultural operations were generated. Furthermore, additional information regarding the number of farms, their respective areas in hectares, locations (coordinates), and distance from each farm to the biorefineries was randomly generated.

Table 1. Contributions employed in constructing the instances.

Source	Information Obtained from the Source
[70]	• Biorefinery capacity (5500 tons of cane per day) • Effect of weather on agricultural operations • Effect of weather on harvest season duration
[71]	• Crop yield per harvested ratoon
[4]	• Cane yield (72.5 liters of ethanol per ton of cane)
[72]	• Production of concentrated vinasse (bio-fertilizer)

As illustrated in Figure 2, each selected farm is positioned in relation to the biorefinery at a random length radius. To compute the distances between the biorefineries and each farm, as well as the distances between each pair of farms, the Manhattan method was employed. The climatic factor plays a significant role in ASCs, as rainfall can impact harvesting operations and, consequently, the capacity of the biorefinery. As such, to create a more realistic scenario, as outlined by [70], the projected impact of weather on the number of days available for harvest operations was considered.

In various countries, biofuel prices are regulated by national governments through price policies that establish upper and lower limits depending on international sugar prices, regional gasoline prices, and the export parity price of gasoline. Since biofuel prices are not set by the market, the proposed model uses the average price according to the study outlined by [70]. In the case of sugarcane (raw material), prices are set through contracts between biorefineries and growers and depend on the sugarcane yield (kilograms of sugar or liters of ethanol obtained per ton of cane). A yield of 116 kg of sugar per ton of cane was used as the basis for setting the price of the raw material. In this case, the price of a ton of sugarcane stems corresponds to 50% of the final sale price of 116 kg of sugar as outlined by [73].

Using the dataset described above, an initial instance was created for a planning horizon of 15 years, consisting of 10 farms distributed in the northeast quadrant. The farms had sufficient area to guarantee the supply of sugarcane stems for biorefineries, with sizes (in hectares) as follows: Farm 1 = 1730, Farm 2 = 3090, Farm 3 = 12,280, Farm 4 = 1540, Farm 5 = 5190, Farm 6 = 5630, Farm 7 = 8210, Farm 8 = 4320, Farm 9 = 2690, Farm 10 = 13,150. The biorefinery was located at coordinates (0,0). Two sugarcane seedbeds were randomly defined, one on Farm 4 (42 hectares) and another on Farm 6 (56 hectares). The sugarcane seedbeds were used to supply the farms and facilitate crop growth.

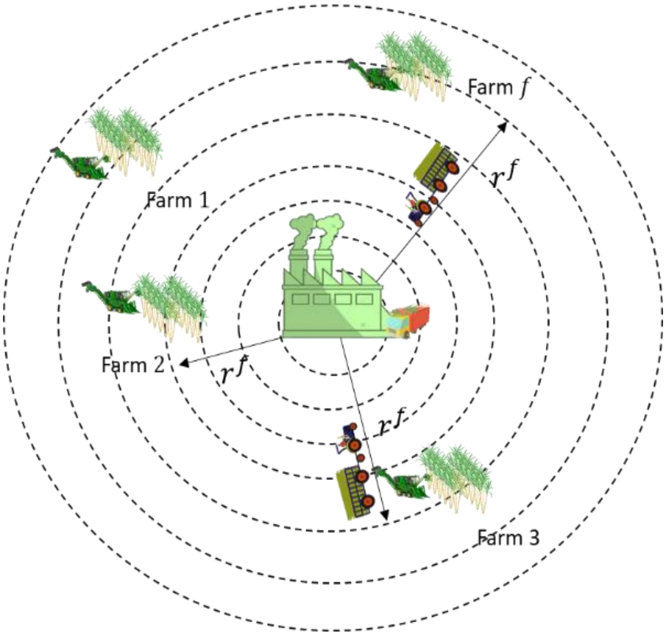

Figure 2. Locations of farms around the biorefinery.

To compare the results of the FPD model, the generated instance was used to formulate the traditional centralized supply chain (CSC) model. As mentioned before, this model aims to maximize the profits of the supply chain (using NPV formula). To implement this approach, Equations (2) and (3) were replaced by Equation (30). The two models formulated in this paper (FPD vs. CSC) were solved using the Gurobi 9.0 computational tool.

$$K^{+/-} \leq NP + \sum_{f \in F} NPVF_f \tag{30}$$

As illustrated in Figure 3, the FPD model assigns four farms (2, 4, 6, and 10), whereas the CSC model assigns five farms (1, 2, 4, 6, and 9). Although the total NPV obtained by the FPD approach ($ 324,210 = $ 143,157 + $ 181,053) was lower than that obtained by the CSC approach ($ 366,678 = $ 127,534 + $ 239,144), it is important to analyze the results from the FPD perspective. In the FPD model, the farms' share (Tier_1) of the total NPV was 44.15% ($ 143,157/$ 324,210), while in the CSC model, it was only 34.78% ($ 127,534/$ 366,678). In other words, although the CSC model generated a higher NPV for the entire supply chain ($ 366,678), most of the profits (65.21%) were obtained by the biorefinery (Tier_2).

Figure 4 displays the harvested area of each farm, as well as biorefinery productivity, over a 15-year planning horizon. As depicted, the biorefinery productivity growth in the CSC model outpaced that of the FPD model. However, this increase was achieved by allocating more farms and generating greater sugarcane waste. This, in turn, led to higher costs for the farms, thereby affecting their profitability. In contrast, the FPD model (with slower biorefinery productivity in the initial years) is better aligned with the growth of harvesting operations, which reduces sugarcane waste and enhances farmer profitability.

Table 2 displays the economic performance attained by the supply chain players in the FPD approach. It shows that farms 2, 4, and 6 utilized all their available land, while Farm 10, being the farthest, only utilized 24.4%, which directly affected its relative efficiency (93%). Using this model, the total profit for the entire supply chain was $ 324,210 ($ 143,157 + $ 181,053), and the average profitability (NPV/CAPEX) was 60.1% and 47% for farms and the biorefinery, respectively.

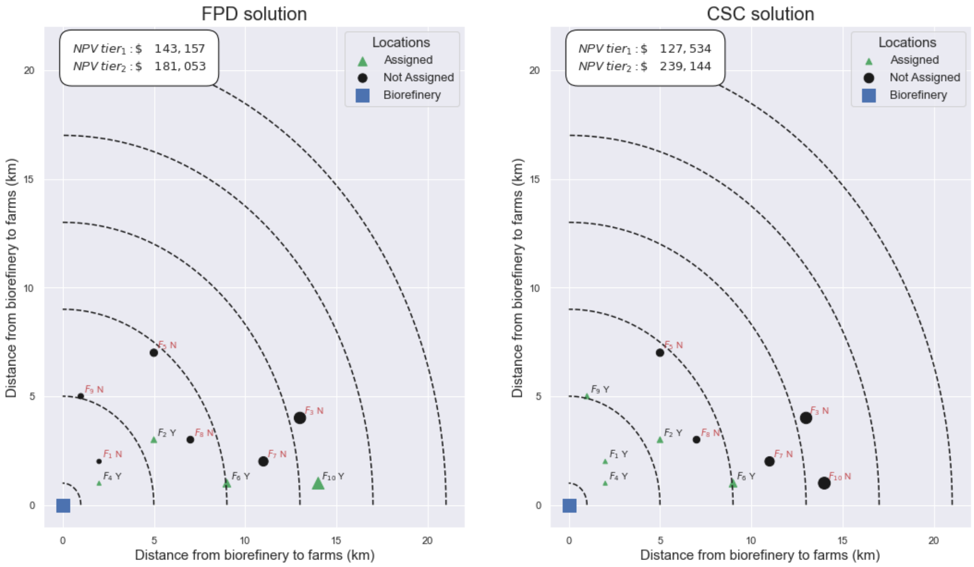

Figure 3. Farm locations and allocation using the FPD and CSC approaches.

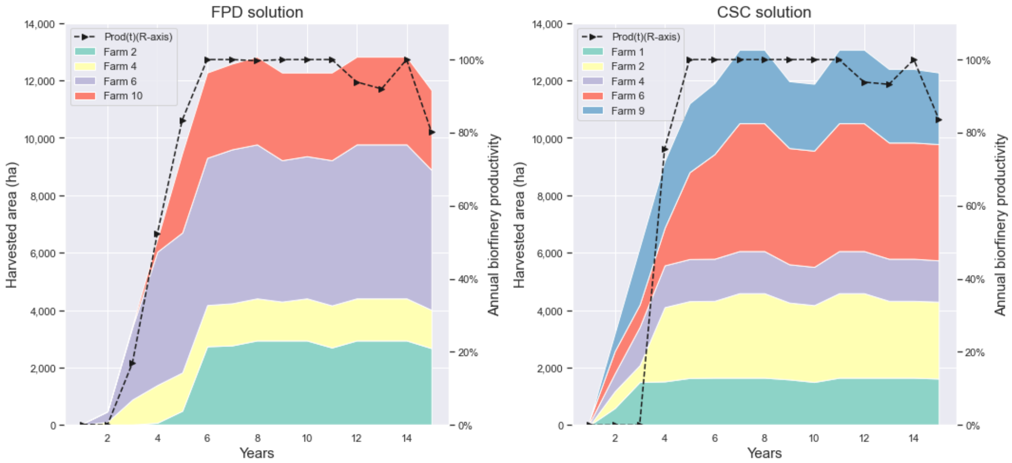

Figure 4. Harvested area for each farm and biorefinery productivity.

Table 2. Economic performance of supply chain players from the FPD approach.

Tier	Player	NPV (Million COP)	Percentage of Land Used (%)	Distance (Km)	CAPEX (Million COP)	NPV/ CAPEX (%)	Relative Efficiency (%)
1	Farm 2	31,068	100	8	47,194	66	100
	Farm 4	18,910	100	3	30,382	62	100
	Farm 6	61,259	100	10	108,038	57	100
	Farm 10	31,918	24.4	15	52,780	60	93
	Total for farms	143,157		238,394		60.1	
2	Biorefinery	181,053			384,490	47	

As discussed earlier, the CSC model improves biorefinery profitability but reduces farm benefits. According to Table 3, five farms were allocated, and four of them achieved relative efficiencies of 100%. With this model, the total profit for the entire supply chain was $366,678 (127,534 + 239,144). However, the average farmer profitability was only 50.9%, while the biorefinery achieved 61.4%.

Table 3. Economic performance of supply chain players from the CSC approach.

Tier	Player	NPV (Million COP)	Percentage of Area Used (%)	Distance (Km)	CAPEX (Million COP)	*NPV*/ CAPEX(%)	Relative Efficiency (%)
1	Farm 1	16,703	100	4	35,219	47	91
	Farm 2	25,641	100	8	53,936	48	100
	Farm 4	17,066	100	3	31,909	53	100
	Farm 6	43,377	83.03	10	76,017	57	100
	Farm 9	24,745	100	6	53,715	46	100
	Total for farms	127,534		250,796		50.9	
2	Biorefinery	239,144			389,037	61.4	

A Pareto front is generated using a multi-objective framework to compare the CSC and FPD approaches. One of the most widely used multi-objective optimization methods, the ε-constraint method, was employed. This method involves solving a series of constrained single-objective problems, allowing for the identification of a set of Pareto optimal, non-dominated solutions. The goal is to find solutions that are economically more efficient from the FPD perspective, even though these may result in a slightly less competitive aggregate economic performance compared to the base-case solution.

The synthesis problem involves solving a sequence of M problems, denoted as $(\mathrm{LP}-\mathrm{CSC})_{\mathrm{i}}$, which optimize FPD while being constrained by a single relative CSC index. Equation (31) is added, with the value of ϵ_m iteratively increasing within the range of total NPV, spanning from FPD to CSC extreme solutions. Despite the conflicting nature of these two approaches, eight non-dominated solutions provide an adequate balance between maximizing the economic benefits of the entire supply chain and ensuring a fair distribution of profits among all stakeholders involved (see Figure 5).

$$\mathrm{NPVI} + \sum_{\mathrm{f} \in \mathrm{F}} \mathrm{NPVF}_{\mathrm{f}} \geq \epsilon_{\mathrm{m}} \tag{31}$$

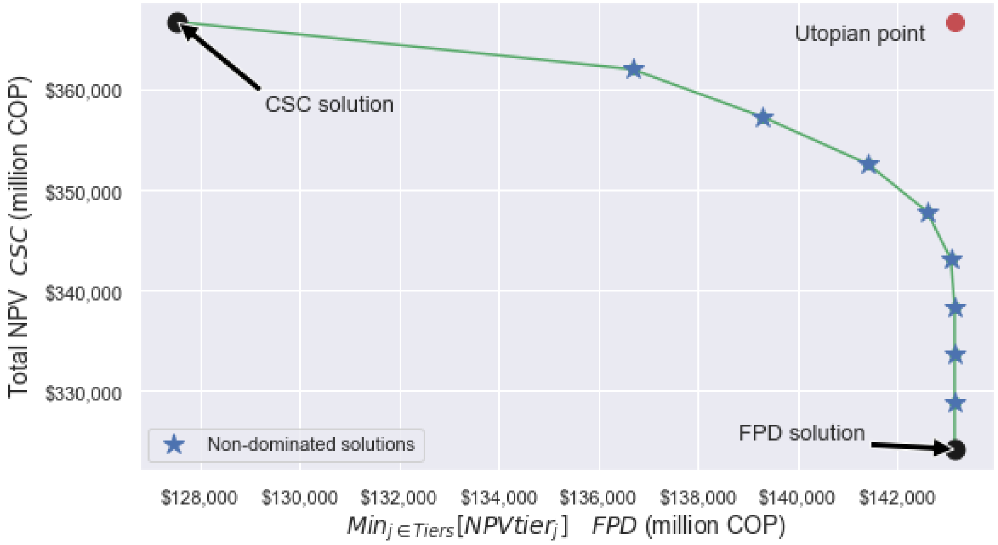

Figure 5. Pareto-optimal front using multi-objective framework.

Table 4 shows the numerical results of the two extreme solutions (FPD = solution 1, CSC = solution 10) and the eight non-dominated solutions (solutions 2 to 9). As shown, solutions 6 to 9 offer the best balance in terms of the NPV/CAPEX ratio, assigning six farms to supply the biorefinery.

Table 4. Non-dominated solutions for a multi-objective framework.

Solution	Number of Farms	Average *NPV*/CAPEX for Farms (%)	NPV/CAPEX for Biorefinery (%)	*NPV* CCS *	*NPV* FPD *
1	4	61	47	324	143
2	7	61	48	329	143
3	7	62	50	334	143
4	7	59	51	338	143
5	5	60	52	343	143
6	6	60	53	348	143
7	6	59	55	353	141
8	6	57	56	357	139
9	6	56	58	362	137
10	6	51	61	367	128

* Given in millions of COP.

5.2. Computational Experiments and Sensitivity Analysis

The proposed model was used for two computational experiments. The first experiment analyzes the effect of the planning horizon and number of farms on the financial performance of the supply chain, while the second examines the influence of sugarcane prices paid by the biorefinery on crop allocation decisions. For both experiments, a comparison was made between the CSC and FPD approaches.

5.2.1. The Influence of Time Horizon and the Number of Farms on Supply Chain Financial Performance

The influence of the time horizon (TH) and number of required farms on supply chain financial performance was analyzed to assess profitability. To generate realistic instances, farm sizes were defined in accordance with [73]. Farm sizes were established using a logistic growth model, considering the radius (km) as a rising rate, and a range of farm sizes between 100 Ha and 6000 Ha. Instances were generated using random coordinates $\left(x_f, y_f\right)$ which, on the one hand, allows for radius calculation, and on the other, derives the farm sizes and distances. Biorefinery production capacity was calculated based on the findings of [70], who assessed the effect of weather conditions (specifically, rainfall) on supply chain performance. Using a Markov chain, these authors generated random instances to determine the number of days without rainfall, or annual operative days.

The experiment considered two factors and five levels: (1) the number of farms (5, 13, 21, 29, and 37) and (2) time horizons (8, 10, 12, 14, and 16 years). The experiment was conducted by crossing the five levels for each factor. In Figure 6, the experimental results are shown for each model (FPD vs. CSC). As shown for the FPD model, a shorter TH negatively affects biorefinery NPV, regardless of the number of farms. Starting from a TH of 10 years, the biorefinery NPV becomes profitable, except for a scenario with five farms. This performance grows as the TH increases. The agricultural echelon (farms) presents a similar behavior, showing negative performance in a scenario with 37 farms and eight years of TH. Regarding the CSC model, farms are always profitable, but the biorefinery is only financially feasible for a long TH. Again, a scenario with five farms is never attractive for the biorefinery. Therefore, two relevant facts are noted in Figure 6: First, regardless of the model (FPD vs. CSC), the biorefinery is not profitable in a short planning horizon (five and eight years of TH). Second, as of year 12, biorefinery profitability rapidly grows for the CSC model, at the expense of farm profitability.

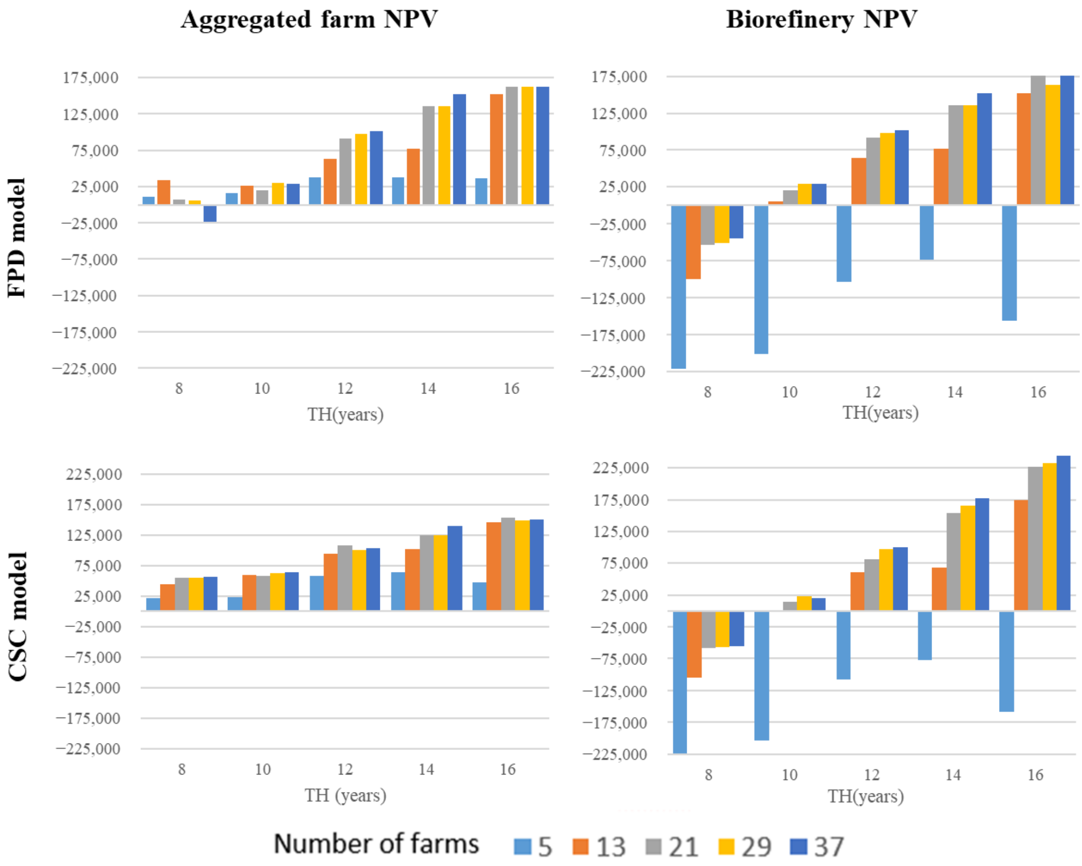

Figure 6. Effect of the number of farms and time horizon on supply chain performance.

5.2.2. The Influence of Sugarcane Prices Paid to Farmers on Crop Allocation Decisions

Based on the percentage of equivalent production as a negotiation strategy between the farmers and the biorefinery, six price levels were considered (32.5%, 36%, 39.5%, 43%, 46.5%, and 50%). In this case, it was assumed that 72.5 liters of bioethanol are obtained per ton of sugarcane. Therefore, in the worst scenario, the farmer would obtain the sale price of 23.56 liters of bioethanol (23.56/72.5 = 32.5%) per ton of sugarcane as income. In contrast, the best income is obtained in a scenario of 50% equivalent production.

As shown in Figure 7, the total NPV (TNPV) of a CSC performs consistently at all levels of sugarcane pricing. However, upon closer inspection of this model, an unfair distribution among the two supply chain echelons is clearly observed, especially when sugarcane prices are either very low or very high. Although the TNPV obtained by the FPD model sacrifices global economic efficiency, it achieves a fairer distribution profit among supply chain members, especially for 39.5% and 43% of equivalent production. In this experiment, the optimal sugarcane price (39.5%) was found when sugarcane transportation was operated by the biorefinery, and the price was paid depending on average crop yields.

A complementary experiment was conducted to analyze the level of incidence of other factors (distance between the farms and the biorefinery, farm utilization, total investment, and financial performance) on farm profits. The experiment considered 30 farms, and three different strategies were used to set the sugarcane prices as follows:

- Strategy 1: Percentage of equivalent ethanol production (BEP = 32.5%).
- Strategy 2: Percentage of equivalent sugar yield (BSY = 50%).
- Strategy 3: Best percentage found (39.5%).

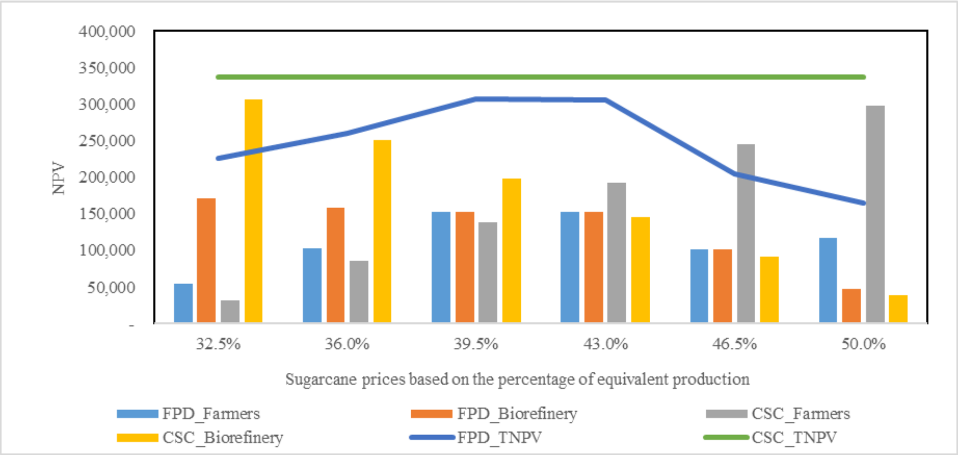

Figure 7. Effect of sugarcane prices on NPV.

Figure 8 shows the Pareto fronts for each pricing strategy. For Strategy 1, we observe a set of non-dominated solutions that achieve growth in the global financial performance of the supply chain, without significantly affecting the fair distribution of profits. However, as the NPV approaches the extreme CSC solution, the level of inequality between supply chain members increases. Although Strategy 2 generates a significant reduction (45%) in global supply chain financial performance, the minimum profit obtained by each echelon is better than that achieved by Strategy 1. Finally, Strategy 3 achieves the best result in terms of the FPD, and the gap between the two extreme solutions (CSC vs. FPD) is reduced. With this strategy, it is possible to find a reduced set of non-dominated solutions that allow for an adequate balance between the two approaches, with respect to the utopian solution (FPD*, CSC*).

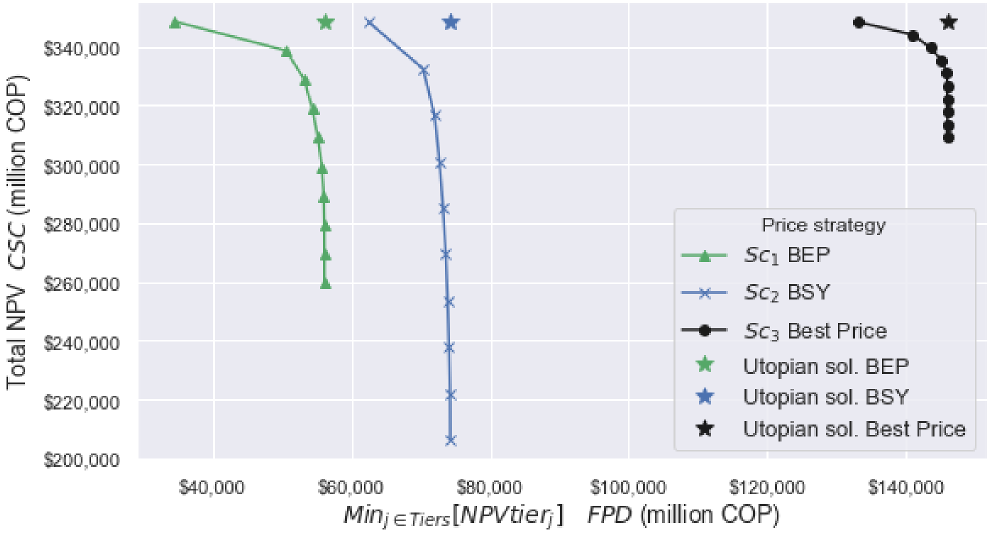

Figure 8. Pareto optimal fronts for scenarios based on price strategies.

The DEA model (Equations (24)–(28)) was applied to obtain farm efficiencies and facilitate a comparison between them. Additionally, the FPD and CSC approaches were used for contrast (see Figure 9 and Table 5). The relative efficiency of each farm represents its general performance measure, which depends on available resource utilization and economic performance obtained. In Strategy 1, the FPD model allocates 11 farms, achieving an average efficiency of 94%. On the other hand, the CSC model allocates 21 farms, but the average efficiency is reduced to 84.48%, which affects farm profit distribution. With Strategy 2, the CSC model achieves a better farm financial performance than that obtained with the FPD model. However, as previously discussed, in this scenario, biorefinery profits are affected. In Strategy 3, both models perform similarly, in terms of average efficiency and number of farms allocated.

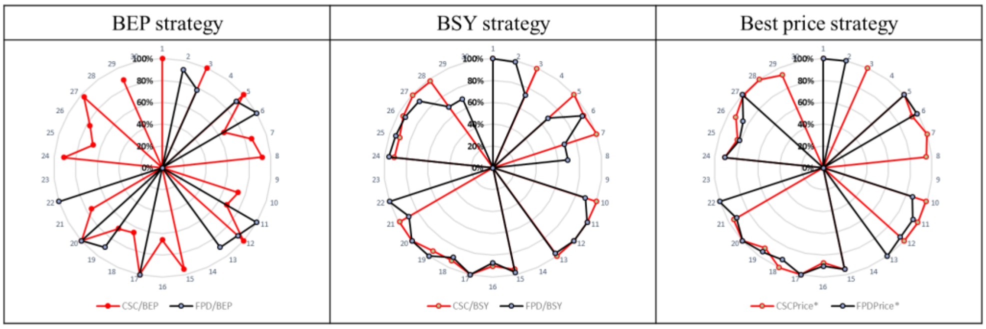

Figure 9. Farm efficiencies under three sugarcane pricing strategies.

Table 5. Farms efficiencies under three sugarcane pricing strategies.

	BEP Strategy			**BSY Strategy**			**Best Percentage Strategy**		
	NF	**ARE**	**F-NPV**	**NF**	**ARE**	**F-NPV**	**NF**	**ARE**	**F-NPV**
FPD model	11	94%	55,039	25	89.4%	116,677	20	94.8%	153,339
CSC model	21	84.5%	31,408	21	97.1%	298,127	22	96.14%	138,950

NF: number of farms, ARE: average relative efficiency, F-NPV: total farmer NPV (millions of COP).

Finally, Figure 10 illustrates the main factors that affect farm efficiency for each analyzed scenario (comprising 30 farms). In terms of farm economic performance (output), the main issue was observed in Strategy 2 (BSY) under the FPD approach, as 10 farms were affected due to poor economic performance. Regarding input values, the distance between farms and investment levels (CAPEX) are the two main aspects influencing farm efficiency. Specifically, for Strategy 1 (BEP), 19 farms were impacted by excessive CAPEX under the CSC approach. On the other hand, 14 farms were affected by their distance to the biorefinery under the FPD approach. In strategies 2 (BSY) and 3, distance was the factor that most influenced farm inefficiency. Overall, Strategy 3 (the best pricing percentage found) displayed the lowest number of inefficient farms (outputs/input).

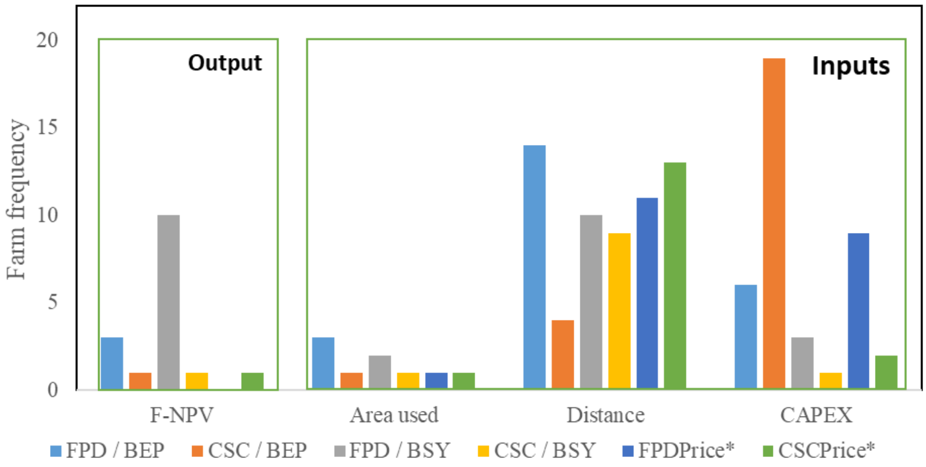

Figure 10. Inefficiencies caused by output/input farmer outcomes for sugarcane price scenarios.

6. Managerial Insights

Although the adoption of the FPD approach results in a lower total NPV for the system compared to the CSC, it allows for a more balanced financial performance (NPV/CAPEX) between the farmers and the biorefinery. This outcome highlights the need for negotiation agreements where the number of farms and the amount of land to be cultivated are aligned with the growth of biorefinery capacity. In this case, well-coordinated planning between the construction phase and the full operation of the biorefinery, as well as the growth of crops (number of farms and cultivated area), should be part of such negotiations.

It is also important to consider that, due to transportation costs, farms located farther from the biorefinery will face reduced demand. In other words, it is crucial to avoid unplanned crop growth on distant farms for which demand is not synchronized with the growth of biorefinery capacity. This necessary balance between biorefinery capacity and the number of assigned farms is clearly supported by the Pareto analysis. This balance helps to avoid losses from unused crops in biofuel production and underutilized capacity in the biorefinery, leading to a better profit distribution and greater economic fairness for the supply chain members.

Another practical implication relates to the effect of the time horizon on the financial performance of the supply chain. The sensitivity analysis indicates that, regardless of the approach used (FPD vs. CSC), there is a higher financial risk for the biorefinery due to the significant investments required during the construction phase. This highlights the need for a win-win negotiation strategy based on a planning horizon of at least 10–12 years. In this case, the results suggest that negotiations between the parties should carefully define the long-term growth of the cultivated areas (number of farms and cultivated area per farm) to ensure the feasibility of the biorefinery during the said timeframe.

The price paid by the biorefinery to the farms for sugarcane is another aspect that both parties must carefully review and negotiate. The results show that a price too low or too high, regardless of the approach (FPD vs. CSC), leads to an unfair distribution of profits. Since, in the context of ASCs, the literature typically indicates that farmers have borne the brunt due to their low bargaining power, for the biorefinery to thrive in the long term, it must offer a fair price for the sugarcane. On the other hand, farmers must also understand that a price set too high is not feasible for the biorefinery either. In this case, promoting a collaborative logistics strategy focused on reducing costs in harvesting, loading, and transportation operations could improve the price negotiation schemes between the farms and the biorefinery.

Finally, in SCND, the location of farms with respect to the biorefinery is a key factor in its financial performance. This is quite logical, as greater distances result in higher transportation costs. In this case, price negotiations between farmers and the biorefinery must consider the effect of transportation costs. The present study indicates, for instance, that when transportation is carried out by the refinery, better financial performance is achieved for both parties. However, in countries with poor road infrastructure, it is the responsibility of local and national governments to make the necessary investments to reduce freight transportation costs, thereby enabling the participation of farmers whose location is less favorable in these types of agro-industrial projects. Although the longer distance between facilities is a disadvantage, it has been proven that costs can be reduced with more efficient transportation systems.

7. Conclusions

The literature review on SCND presents various research challenges under the FPD approach. In the agricultural context, one of the biggest problems is the unfair distribution of profits among supply chain members. The present study's literature review reveals that, due to information asymmetries and differences in bargaining power, most of the profits go to industrial and commercial players in the supply chain, which affects the economic interests of farmers, especially small growers. This inequity is reflected in greater poverty conditions and negotiation conflicts, making it a highly concerning problem in sugarcane biofuel supply chains. Despite the relevance of the situation, most contributions on FPD have been applied to welfare economics, telecommunications, or supply chain contracting.

Therefore, investigations addressing the design of ASCs under an FPD approach constitute a fertile research field, especially from the standpoint of SCND optimization.

To tackle this problematic situation, the proposed FPD model supports the design decisions of an ASC for biofuel production using sugarcane, seeking to achieve a fairer profit distribution between farmers and biorefineries. By analyzing the effect of time horizons and the number of farms on financial supply chain performance, as well as the influence of different price-setting strategies on crop allocation decisions, various configuration alternatives for the supply chain were proposed. The two sensitivity analyses provide valuable quantitative information to facilitate fair sugarcane price negotiation between farmers and biorefineries.

The numerical results also allow the evaluation of various scenarios for the investment and operation decisions of the supply chain, establishing the most convenient number of farms to achieve improved profit distribution. Although the CSC approach achieves maximum profit for the supply chain as a whole, the largest portion goes to biorefineries. In contrast, with the FPD approach, although the total utility of the system is lower, a better economic scenario is observed for farmers. Thus, the present paper contributes to the field of social justice, providing insights to facilitate fair trade among the sugarcane supply chain members for biofuel production. On the other hand, via the DEA analysis, it was determined that the distance between farms and biorefineries, as well as the investment level for crop development (CAPEX), are the two factors that most affect profit distribution.

Considering the model limitations and assumptions, multiple research lines may be suggested to improve this contribution. Specifically, it is important to consider sources of uncertainty, such as the influence of climatic conditions on crop yields, harvest season length, and agricultural machinery availability, which can affect farm financial performance. Economic performance assessment, using the so-called economic value added (EVA) model, offers a holistic measure that deserves further analysis from the FPD approach. Additionally, involving the environmental dimension will allow for performance assessment from a sustainability perspective, guaranteeing an economically profitable, socially responsible, and environmentally friendly supply chain design.

Author Contributions: Conceptualization, W.S. and J.C.; methodology, J.C. and Y.C.; validation, J.C.; formal analysis, W.S. and Y.C.; investigation, J.C., W.S. and Y.C.; writing—original draft preparation, Y.C. and W.S.; writing—review and editing, W.S. and Y.C.; supervision, W.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by Minciencias (Colombia), grant "CONVOCATORIA 757".

Data Availability Statement: The data presented in this study are available on request from the first author. The data are not publicly available due to ethical restrictions.

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

Appendix A

Table A1. Subscript indices.

Sets	Description
$r \in R$	Set of ratoons in the crop life cycle $(1, 2, 3, 4, 5)$
$f \in F$	Set of potential farms to be selected for developing sugarcane crop
$t \in TH$	Time horizon for project assessment (periods) (N).
$j \in P$	Set of potential products to be obtained by sugarcane processing (Ethanol, Energy by cogeneration, bio-fertilizer as by-product)

Table A2. Parameters.

Parameter	Description	Unit
$\boldsymbol{ACS}$	Crop amortization rate for each harvested ratoon	\$/ha
$\boldsymbol{AE}$	Administrative expenses for agricultural operations	\$/ha
$\boldsymbol{AMI}$	Agricultural machine investment over a five-year period	\$/ha
$\boldsymbol{BPI}$	Biofuel plant investment	\$
$\boldsymbol{BID_t}$	Execution percentage of the investment plan in the biorefinery for each period $\boldsymbol{t}$ during the investment stage.	%
$\boldsymbol{BioCap_t}$	Annual sugarcane milling capacity of the biorefinery during the period t	t/y
$\boldsymbol{CAD_t}$	Execution percentage of the construction auditing cost for each period t during the investment stage	%
$\boldsymbol{CAC}$	Biorefinery construction auditing cost	\$
$\boldsymbol{CFD_t}$	Execution percentage of investment plan in complementary facilities for each period $\boldsymbol{t}$ during the investment stage	%
$\boldsymbol{CFI}$	Investment in complementary industrial facilities	\$
$\boldsymbol{CTN_{t,f}}$	Land investment cost during period t for each farm f	\$/ha
$\boldsymbol{Dis_f^g}$	Manhattan distance measured between each potential location f to others g including biorefinery	km
$\boldsymbol{DCom_f}$	Maximum amount of land available for purchase at each farm f	ha
$\boldsymbol{DLC}$	Direct workforce cost of agricultural operations	\$/ha
$\boldsymbol{EPEC^j}$	Sale price by each product j	\$/und
$\boldsymbol{HarvestingC_t}$	Maximum harvesting capacity using available equipment in period t	ha/y
$\boldsymbol{HC}$	Standard transportation cost	$\frac{\$}{t-km}$
$\boldsymbol{inputCost_j}$	Cost of input needed to process a product j	\$/und
$\boldsymbol{ITI}$	Information and communication technology (IT) investment	\$
$\boldsymbol{ITD_t}$	Execution percentage of the investment plan in IT for each year t during the investment stage	%
$\boldsymbol{MCO}$	Crop maintenance cost	\$/ha
$\boldsymbol{OHC}$	Operating harvest cost	\$/ha
$\boldsymbol{PCane}$	(%) percentage of ethanol price equivalent production based on sugarcane	%
$\boldsymbol{PPEI}$	Property, plant, and equipment investment executed during the investment agricultural stage.	\$
$\boldsymbol{PPEII}$	Property, plant, and equipment investment executed during the investment industrial stage.	\$
$\boldsymbol{SCS}$	Amount of seed required to sow sugarcane	t/ha
$\boldsymbol{SCC}$	Sowing cost during the investment period	\$/ha
$\boldsymbol{SowingC_t}$	Maximum sowing capacity considering the available equipment in period t	ha/y
$\boldsymbol{TCH_r}$	Amount of sugarcane harvested at ratoon r during the cutting time	t/ha
$\boldsymbol{td}$	Discount rate	%
$\boldsymbol{x_{r,f}^0}$	Amount of sugarcane planted at initial time by each ratoon r and each farm f	ha
$\boldsymbol{WHC}$	Operating harvest cost of sugarcane discarded	\$/ha
$\boldsymbol{\mu_j}$	Production rate of product j obtained in the biorefinery.	Und/t

Table A3. Decision variables.

Variable	Description	Unit
$\boldsymbol{area_{t,f}}$	Area used for sugarcane crop at period t by farm f	ha/y
$\boldsymbol{CC_{t,f}}$	Amount of sugarcane harvested and transport to biorefinery during period t for each farm f	t/y
$\boldsymbol{Cland_{t,f}}$	Amount of purchased land available to plant a new crop in during period t at each farm f	ha
$\boldsymbol{Co_{t,r,f}}$	Area harvested at period t at farm f in ratoon r	ha/y
$\boldsymbol{CscI_{t,f}}$	Amount of cane seed produced in the farm f transported to other farms during the period t.	t/y
$\boldsymbol{CscO_{t,f}}$	Amount of cane seed received from other farm, to be used in sowing operation at farm f during the period t.	t/y
$\boldsymbol{CSC_{t,f}^g}$	Amount of cane seed transported from the farm f to farm g, for sowing operations at period t.	t/y
$\boldsymbol{CV_{t,f}}$	Amount of cane discarded when ripening period is exceeded during period t in farm f	t/y
$\boldsymbol{CP_t}$	Cane harvested and wasted because it was not sent to the biorefinery on time during the period t	t/y
$\boldsymbol{CS_t}$	Amount of cane shortage at biorefinery during the period t	t/y
$\boldsymbol{K^{+/-}}$	Minimum NPV of profit obtaining by each tier of supply chain (agricultural echelon, biorefinery)	%
$\boldsymbol{NPVF_f}$	Net present value of profit obtained by each farm at agricultural tier over the time horizon	\$
$\boldsymbol{NPVI}$	Net present value of profit obtained by the biorefinery over the time horizon	\$

Table A3. *Cont.*

Variable	Description	Unit
$\boldsymbol{SugarCan_t}$	Amount of sugarcane received in the biorefinery from all farms during the period t	t/y
$\boldsymbol{Supply_t}$	Amount of sugarcane to be processed in the biorefinery during the period t	t/y
$\boldsymbol{Production_{t,j}}$	Amount of final product j produced in the biorefinery process during the period t	Und/y
$\boldsymbol{Land_{t,f}}$	Amount of land acquired at each farm at the end of each period t	ha/y
$\boldsymbol{x_{t,r,f}}$	Total area sown with sugarcane, which is classified in different ratoons r at the end of period t at each farm f	ha/y
$\boldsymbol{Y_{t,f}}$	Amount of land sown during period t for each farm f	ha/y

References

1. United Nations Sustainable Development Agenda. United Nations Sustainable Development 2017. Available online: https://www.un.org/sustainabledevelopment/development-agenda/ (accessed on 2 December 2018).
2. Moncada, J.; Cardona, C.A.; Rincón, L.E. Design and analysis of a second and third generation biorefinery: The case of castorbean and microalgae. *Bioresour. Technol.* **2015**, *198*, 836–843. [CrossRef] [PubMed]
3. Espinoza-Pérez, A.T.; Camargo, M.; Narváez-Rincón, P.C.; Alfaro-Marchant, M. Key challenges and requirements for sustainable and industrialized biorefinery supply chain design and management: A bibliographic analysis. *Renew. Sustain. Energy Rev.* **2017**, *69*, 350–359. [CrossRef]
4. van den Wall Bake, J.D.; Junginger, M.; Faaij, A.; Poot, T.; Walter, A. Explaining the experience curve: Cost reductions of Brazilian ethanol from sugarcane. *Biomass Bioenergy* **2009**, *33*, 644–658. [CrossRef]
5. Alonso-Pippo, W.; Luengo, C.A.; Alonsoamador Morales Alberteris, L.; García del Pino, G.; Duvoisin, S. Practical implementation of liquid biofuels: The transferability of the Brazilian experiences. *Energy Policy* **2013**, *60*, 70–80. [CrossRef]
6. Budzianowski, W.M.; Postawa, K. Total Chain Integration of sustainable biorefinery systems. *Appl. Energy* **2016**, *184*, 1432–1446. [CrossRef]
7. da Silva, A.F.; Marins, F.A.S.; Dias, E.X. Addressing uncertainty in sugarcane harvest planning through a revised multi-choice goal programming model. *Appl. Math. Model.* **2015**, *39*, 5540–5558. [CrossRef]
8. Florentino, H.d.O.; Jones, D.F.; Irawan, C.A.; Ouelhadj, D.; Khosravi, B.; Cantane, D.R. An optimization model for combined selecting, planting and harvesting sugarcane varieties. *Ann. Oper. Res.* **2022**, *314*, 451–469. [CrossRef]
9. Higgins, A.; Thorburn, P.; Archer, A.; Jakku, E. Opportunities for value chain research in sugar industries. *Agric. Syst.* **2007**, *94*, 611–621. [CrossRef]
10. Plà, L.M.; Sandars, D.L.; Higgins, A.J. A perspective on operational research prospects for agriculture. *J. Oper. Res. Soc.* **2014**, *65*, 1078–1089. [CrossRef]
11. Gao, J.; You, F. A stochastic game theoretic framework for decentralized optimization of multi-stakeholder supply chains under uncertainty. *Comput. Chem. Eng.* **2019**, *122*, 31–46. [CrossRef]
12. Bertsimas, L.; Parlar, M.; Zhu, S.X. Pricing and Lead Time Decisions in Decentralized Supply Chains. *Manag. Sci.* **2007**, *53*, 713–725. [CrossRef]
13. Cho, S.J.; Chung, C.Y.; Young, J. Study on the Relationship between CSR and Financial Performance. *Sustainability* **2019**, *11*, 343. [CrossRef]
14. Zheng, X.-X.; Liu, Z.; Li, K.W.; Huang, J.; Chen, J. Cooperative game approaches to coordinating a three-echelon closed-loop supply chain with fairness concerns. *Int. J. Prod. Econ.* **2019**, *212*, 92–110. [CrossRef]
15. Samoggia, A.; Beyhan, Z. Fairness-Enabling Practices in Agro-Food Chain. *Sustainability* **2022**, *14*, 6391. [CrossRef]
16. Yue, D.; You, F. Game-theoretic modeling and optimization of multi-echelon supply chain design and operation under Stackelberg game and market equilibrium. *Comput. Chem. Eng.* **2014**, *71*, 347–361. [CrossRef]
17. Liu, S.; Papageorgiou, L.G. Fair profit distribution in multi-echelon supply chains via transfer prices. *Omega* **2018**, *80*, 77–94. [CrossRef]
18. Rabbani, M.; Hosseini-Mokhallesun, S.A.A.; Ordibazar, A.H.; Farrokhi-Asl, H. A hybrid robust possibilistic approach for a sustainable supply chain location-allocation network design. *Int. J. Syst. Sci. Oper. Logist.* **2020**, *7*, 60–75. [CrossRef]
19. Alghababsheh, M.; Gallear, D.; Saikouk, T. Justice in supply chain relationships: A comprehensive review and future research directions. *Eur. Manag. Rev.* **2023**, *20*, 367–397. [CrossRef]
20. Ha, T.-S.; Moon, K.-K. Distributive Justice, Goal Clarity, and Organizational Citizenship Behavior: The Moderating Role of Transactional and Transformational Leadership. *Sustainability* **2023**, *15*, 7403. [CrossRef]
21. Dai, X.; Lin, Y.-T.; Shi, R.; Xu, D. A manufacturer's responsible sourcing strategy: Going organic or participating in fair trade? *Ann. Oper. Res.* **2020**, *291*, 195–218. [CrossRef]
22. Barling, D.; Samoggia, A.; Olafsdottir, G. Dynamics of Food Value Chains: Resilience, Fairness and Sustainability. *Agriculture* **2022**, *12*, 720. [CrossRef]
23. Melo, M.T.; Nickel, S.; Saldanha-da-Gama, F. Facility location and supply chain management—A review. *Eur. J. Oper. Res.* **2009**, *196*, 401–412. [CrossRef]

24. De Silva, L.; Jayamaha, N.; Garnevska, E. Sustainable Farmer Development for Agri-Food Supply Chains in Developing Countries. *Sustainability* **2023**, *15*, 15099. [CrossRef]
25. Goodarzian, F.; Shishebori, D.; Bahrami, F.; Abraham, A.; Appolloni, A. Hybrid meta-heuristic algorithms for optimising a sustainable agricultural supply chain network considering CO_2 emissions and water consumption. *Int. J. Syst. Sci. Oper. Logist.* **2023**, *10*, 2009932. [CrossRef]
26. Kusumastuti, R.D.; van Donk, D.P.; Teunter, R. Crop-related harvesting and processing planning: A review. *Int. J. Prod. Econ.* **2016**, *174*, 76–92. [CrossRef]
27. Medina, G.D.S.; Costa, R.B.D. Building Agro-Industrial Capabilities in the Sugarcane Supply Chain in Brazil. *Logist.* **2023**, *7*, 71. [CrossRef]
28. Kadwa, M.; Bezuidenhout, C.N. Modelling sugarcane supply consistency at a sugar mill. *Comput. Electron. Agric.* **2015**, *111*, 107–111. [CrossRef]
29. Ahumada, O.; Villalobos, J.R. Application of planning models in the agri-food supply chain: A review. *Eur. J. Oper. Res.* **2009**, *196*, 1–20. [CrossRef]
30. Soto-Silva, W.E.; Nadal-Roig, E.; González-Araya, M.C.; Pla-Aragones, L.M. Operational research models applied to the fresh fruit supply chain. *Eur. J. Oper. Res.* **2016**, *251*, 345–355. [CrossRef]
31. Matindi, R.; Masoud, M.; Hobson, P.; Kent, G.; Liu, S.Q. Harvesting and transport operations to optimise biomass supply chain and industrial biorefinery. *Int. J. Ind. Eng. Comput.* **2018**, *9*, 265–288. [CrossRef]
32. Xu, X.; Chen, X.; Jia, F.; Brown, S.; Gong, Y.; Xu, Y. Supply chain finance: A systematic literature review and bibliometric analysis. *Int. J. Prod. Econ.* **2018**, *204*, 160–173. [CrossRef]
33. Messmann, L.; Zender, V.; Thorenz, A.; Tuma, A. How to quantify social impacts in strategic supply chain optimization: State of the art. *J. Clean. Prod.* **2020**, *257*, 120459. [CrossRef]
34. Shukla, M.; Jharkharia, S. Agri-fresh produce supply chain management: A state-of-the-art literature review. *Int. J. Oper. Prod. Manag.* **2013**, *33*, 114–158. [CrossRef]
35. Oliveira, J.B.; Lima, R.S.; Montevechi, J.A.B. Perspectives and Relationships in Supply Chain Simulation: A Systematic Literature Review. *Simul. Model. Pract. Theory* **2016**, *62*, 166–191. [CrossRef]
36. Behzadi, G.; O'Sullivan, M.J.; Olsen, T.L.; Zhang, A. Agribusiness Supply Chain Risk Management: A Review of Quantitative Decision Models. *Omega* **2017**, *79*, 21–42. [CrossRef]
37. Gu, F.; Yu, X. Profit distribution mechanism of agricultural supply chain based on fair entropy. *PLoS ONE* **2022**, *17*, e0271693. [CrossRef]
38. Ho, T.-H.; Su, X.; Wu, Y. Distributional and Peer-Induced Fairness in Supply Chain Contract Design. *Prod. Oper. Manag.* **2014**, *23*, 161–175. [CrossRef]
39. Haitao, C.T.; Raju, J.S.; Zhang, Z. Fairness and chanel coordination. *Manag. Sci.* **2007**, *53*, 1303–1314. [CrossRef]
40. Bhuvaneshwarri, I.; Ilango, V. An online blockchain based sustainable logistics management system (OBSLMS) enabled by the Internet of Things for the textile industry. *Ind. Textila* **2023**, *74*, 660–666. [CrossRef]
41. Ouhader, H.; EL Kyal, M. Collaborative location routing problem for sustainable supply chain design with profit sharing. *Environ. Sci. Pollut. Res.* **2023**, *30*, 90099–90120. [CrossRef]
42. Hauck, Z.; Rabta, B.; Reiner, G. Coordinating quality decisions in a two-stage supply chain under buyer dominance. *Int. J. Prod. Econ.* **2023**, *264*, 108998. [CrossRef]
43. Nematollahi, M.; Hosseini-Motlagh, S.M.; Cárdenas-Barron, L.E.; Tiwari, S. Coordinating visit interval and safety stock decisions in a two-level supply chain with shelf-life considerations. *Comput. Oper. Res.* **2022**, *139*, 105651. [CrossRef]
44. Dash, A.; Giri, B.C.; Sarkar, A.K. Coordination and defect management strategy for a two-level supply chain under price and sales effort-sensitive demand. *Int. J. Syst. Sci. Oper. Logist.* **2023**, *10*, 2103198. [CrossRef]
45. Andriopoulos, N.; Plakas, K.; Birbas, A.; Papalexopoulos, A. Design of a Prosumer-Centric Local Energy Market: An Approach Based on Prospect Theory. *IEEE Access* **2024**, *12*, 32014–32032. [CrossRef]
46. Jing, R.; Wang, J.; Shah, L.; Guo, M. Emerging supply chain of utilising electrical vehicle retired batteries in distributed energy systems. *Adv. Appl. Energy* **2021**, *1*, 100002. [CrossRef]
47. Yue, D.; You, F. Fair Profit Allocation in Supply Chain Optimization with Transfer Price and Revenue Sharing: MINLP Model and Algorithm for Cellulosic Biofuel Supply Chains. *AIChE J.* **2014**, *60*, 3211–3229. [CrossRef]
48. Pasandideh, R.S.H.; Akhavan Niaki, S.T.; Niknamfar, A.H. Lexicographic max–min approach for an integrated vendor-managed inventory problem. *Knowl. Based Syst.* **2014**, *59*, 58–65. [CrossRef]
49. Chen, L.I.; Wang, B.W.; Lee, W.C. Multiobjective Optimization for a Multienterprise Supply Chain Network. *Ind. Eng. Chem. Res.* **2003**, *42*, 1879–1889. [CrossRef]
50. Chen, C.L.; Lee, W.C. Multi-objective optimization of multi-echelon supply chain networks with uncertain product demands and prices. *Comput. Chem. Eng.* **2004**, *28*, 1131–1144. [CrossRef]
51. Qiu, R.; Liao, Q.; Tu, R.; Jiao, Y.; Yang, A.; Guo, Z.; Liang, Y. Pipeline pricing and logistics planning in the refined product supply chain based on fair profit distribution. *Comput. Ind. Eng.* **2023**, *175*, 108840. [CrossRef]
52. Asrol, M.; Marimin; Machfud; Yani, M.; Taira, E. Supply Chain Fair Profit Allocation Based on Risk and Value Added for Sugarcane Agro-industry. *Oper. Supply Chain Manag.* **2020**, *13*, 150–165. [CrossRef]

53. Asrol, M. Risk and value-added balancing model for a sustainable industry's supply chain. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *729*, 012047. [CrossRef]
54. Kumoi, Y.; Matsubayashi, N. Vertical integration with endogenous contract leadership: Stability and fair profit allocation. *Eur. J. Oper. Res.* **2014**, *238*, 221–232. [CrossRef]
55. Makhmudov, M.; Chung, K.H.; Ko, C.S. Network design for the temporal and spatial collaboration with service class in delivery services. *Int. J. Ind. Eng.* **2023**, *30*, 246–255. [CrossRef]
56. Wang, Y.; Cui, Y.; Shen, L.; Cheng, T.E.C. Service Pricing Decision of E-Commerce Supply Chain Members Considering Diseconomies of Scale and Network Externalities. *J. Syst. Sci. Inf.* **2022**, *10*, 425–444. [CrossRef]
57. Wang, Y.; Wu, Q.; Cheng, T.C.E.; Sun, Y. Supply chain modelling considering blockchain improvement and publicity with fairness concern. *J. Intell. Manuf.* **2023**, 1–22. [CrossRef]
58. Chen, C.L.; Wang, B.W.; Lee, W.C.; Huang, H.P. The optimal profit distribution problem for a supply chain network. *Process Syst. Eng.* **2003**, *15*, 422–427.
59. Zeng, T.; Yang, T. Unfair and Risky? Profit Allocation in Closed-Loop Supply Chains by Cooperative Game Approaches. *Appl. Sci.* **2022**, *12*, 6245. [CrossRef]
60. Borodin, V.; Bourtembourg, J.; Hnaien, F.; Labadie, N. Handling uncertainty in agricultural supply chain management: A state of the art. *Eur. J. Oper. Res.* **2016**, *254*, 348–359. [CrossRef]
61. Bertsimas, D.; Farias, V.F.; Trichakis, N. The Price of Fairness. *Oper. Res.* **2011**, *59*, 17–31. [CrossRef]
62. Bertrand, J.; Fransoo, J.C. Operations Management Research Methodologies Using Quantitative Modeling. *Int. J. Oper. Prod. Manag.* **2002**, *22*, 241–264. [CrossRef]
63. Sørensen, C.G.; Bochtis, D.D. Conceptual Model of Fleet Management in Agriculture. *Biosyst. Eng.* **2010**, *105*, 41–50. [CrossRef]
64. Galal, N.M.; El-Kilany, K.S. Sustainable Agri-Food Supply Chain with Uncertain Demand and Lead Time. *Int. J. Simul. Model. (IJSIMM)* **2016**, *15*, 485–496. [CrossRef]
65. Cooper, W.W.; Seiford, L.M.; Zhu, J. *Handbook on Data Envelopment Analysis*; Springer Science and Business Media: New York, NY, USA, 2011; Volume 164, 498p.
66. Mohtashami, Z.; Bozorgi-Amiri, A.; Tavakkoli-Moghaddam, R. A data envelopment analysis model for location optimization of feedstock cultivation in a biodiesel supply chain: A case study. *Environ. Dev. Sustain.* **2024**, *26*, 0513–10532. [CrossRef]
67. Babazadeh, R.; Razmi, J.; Rabbani, M.; Pishvaee, M.S. An integrated data envelopment analysis-mathematical programming approach to strategic biodiesel supply chain network design problem. *J. Clean. Prod.* **2017**, *147*, 694–707. [CrossRef]
68. Hong, J.D. Application of Transformed Two-Stage Network DEA to Strategic Design of Biofuel Supply Chain Network. *J. Syst. Sci. Syst. Eng.* **2023**, *32*, 129–151. [CrossRef]
69. Martín-Gamboa, M.; Días, A.C.; Iribarren, D. Definition, assessment and prioritisation of strategies to mitigate social life-cycle impacts across the supply chain of bioelectricity: A case study in Portugal. *Renew. Energy* **2022**, *194*, 1110–1118. [CrossRef]
70. Carvajal, J.; Sarache, W.; Costa, Y. Addressing a robust decision in the sugarcane supply chain: Introduction of a new agricultural investment project in Colombia. *Comput. Electron. Agric.* **2019**, *157*, 77–89. [CrossRef]
71. Colin, E.C. Mathematical programming accelerates implementation of agro-industrial sugarcane complex. *Eur. J. Oper. Res.* **2009**, *199*, 232–235. [CrossRef]
72. de Souza Dias, M.O.; Maciel Filho, R.; Mantelatto, P.E.; Cavalett, O.; Rossell, C.E.V.; Bonomi, A.; Leal, M.R.L.V. Sugarcane Processing for Ethanol Sugar in Brazil. *Environ. Dev.* **2015**, *15*, 35–51. [CrossRef]
73. Procaña. Colombian Sugarcane Industry: Description. Available online: http://www.procana.org/new/quienes-somos/presentacion-del-sector.html (accessed on 28 November 2021).