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Highlighting Sustainability Criteria in Residual Biomass Supply Chains: A Dynamic Simulation Approach

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Abstract: As environmental sustainability gains importance, enhancing supply chains to minimize environmental hazards is essential, particularly in industries using residual biomass. This study tackles this by investigating the integration of sustainability criteria into supply chain optimization for a biomass energy company in Portugal, using a combination of simulation modeling through anyLogistix software (version: 2.15.3.202209061204) and multi-criteria decision-making. Four supply chain scenarios were designed and simulated, differing in their number of distribution centers, the adoption of green logistics, and split-by-ratio distribution strategies over a 305-day period. Through the weighted sum model, Scenario C emerged as the optimal configuration, achieving a balance between operational efficiency and sustainability by reducing CO_2 emissions by up to 90% and lowering transportation costs without compromising revenue. Sensitivity analysis further highlighted the trade-offs between cost efficiency, lead times, and environmental impact, showing that the strategic placement of distribution centers and the use of eco-friendly vehicles significantly improve the sustainability of the biomass supply chain. These findings provide practical insights for decision-makers, demonstrating how digital modeling tools can enhance supply chain management by optimizing environmental and operational goals simultaneously. This research contributes to the fields of sustainable logistics and supply chain management by validating the effectiveness of green logistics strategies and multi-criteria decision-making approaches in reducing environmental impact while maintaining economic viability.

Keywords: digital twin; supply chain; residual biomass; anyLogistix; sustainability criteria; simulation; multi-criterion decision-making; optimization

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1. Introduction

The global challenge of reducing greenhouse gas (GHG) emissions has created an urgent need to transition toward sustainable energy sources. Renewable energy technologies like solar, wind, geothermal power, and electric vehicles (EVs) are increasingly being recognized as essential components in this transition [1]. These technologies offer significant potential for reducing emissions, promoting energy security, and supporting economic growth. However, alongside these renewable solutions, biomass energy (specifically from residual biomass in agroforestry) presents a key yet underutilized renewable resource that can complement existing efforts to decarbonize the energy sector.

Residual biomass from agroforestry resources is a major potential energy source for meeting the future needs of renewable energy. It is a renewable resource with so much possibility for energy production, biofuels, and other uses. It is made up of organic waste and residues from forestry, agriculture, and industrial processes [2,3]. Regardless, the use of residual biomass for energy faces several logistical problems, especially related to its collection, storage, and transportation. Hence, to effectively use residual biomass as a reliable and renewable energy source, a methodical procedure is needed to guarantee sustainability throughout the whole supply chain [4]. The accuracy and flexibility required to handle changing environmental conditions and stakeholder demands are occasionally lacking in conventional structures. As a result, supply chain processes can be optimized through the use of digital twin technology, which offers real-time insights and predictive capabilities [5]. Despite the increasing awareness of digital model technologies and the application of the same in supply chain management, there is a noticeable lack of studies on the incorporation of sustainability criteria with digital twin simulations for the optimization of a residual biomass supply chain [6,7]. Multi-criteria decision-making (MCDM) methods are essential for managing complex decision-making scenarios that require balancing multiple, often competing, sustainability criteria. Several MCDM techniques have emerged with relevance for optimizing residual biomass supply chains [8]. This research aims to fill this gap by implementing a sustainability-driven residual biomass supply chain for the purpose of improving it through a digital dynamic simulation approach. The highlights of this study are presented as follows:

(a) The simulation model is performed for the residual biomass supply chain to analyze economic, social, and environmental criteria based on real-life input parameters.
(b) Test scenarios were modeled based on the number of distribution centers, green vehicles, and the percentage distribution of the residual biomass across the supply chain.
(c) An analysis of the differences in the key performance indicators (KPIs) for finances, time, ratio, and CO_2 emissions based on variations from four different model scenarios as obtainable from anyLogistix software.
(d) The application of multi-criterion decision-making using weighted sum models and inclusion of the overall sustainability score.
(e) This study proffers insights for individuals and experts in the industry to make informed decisions to enhance operational performance and meet sustainability goals.
(f) We contribute a variation in economic, social, and environmental potentials to the literature due to different scenarios of a residual biomass supply chain.

The remainder of the article is structured as follows: a review of the relevant literature is included in Section 2, along with the concepts and strategies that go into creating a residual biomass supply chain employing dynamic simulation technology that is driven by sustainability. The research design, sustainability criteria used in the project, definitions of the main performance indicators used, and the case study presentation are all highlighted in Section 3. The analysis and outcomes of the simulation experiments derived from the case study are presented in Section 4. The study's conclusion, primary effects on industry experts and society, as well as recommendations for future research are included in Section 5.

2. Dynamic Simulation Approach for a Sustainable Residual Biomass Supply Chain

A dynamic simulation approach offers a powerful tool for managing the complexities of a sustainable residual biomass supply chain. By providing real-time analysis, scenario planning, and data-driven decision support, it enables stakeholders to optimize logistics, reduce costs, and minimize environmental impact [9,10]. Dynamic simulations in biomass supply chains lead to enhanced efficiency, sustainability, and resilience. It reduces costs by optimizing routes, supports environmentally friendly practices, ensures adaptability to disruptions, and facilitates informed, data-driven decisions, ultimately creating a more sustainable and efficient biomass supply chain.

Enterprises can simulate and evaluate complicated supply chain networks for residual biomass by incorporating anyLogistix software, which is a potent tool for supply chain optimization, into the digital twin architecture [11,12]. By using this method, stakeholders can better assess sustainability requirements by visualizing the entire supply chain, identifying inefficiencies, and assessing alternative scenarios.

A digital twin is essentially a computer representation that mimics the traits and actions of its real counterpart [13]. According to Kritzinger et al., a digital twin is a dynamic, real-time virtual replica of a physical object or system that is fully integrated with the physical object in both directions [14]. This means that data flow seamlessly between physical and digital objects, enabling the digital twin to monitor, simulate, and control the physical counterpart. Changes in the state of the physical object are instantly reflected in the digital twin, and conversely, changes or inputs to the digital twin can directly influence and control the physical object. Additionally, other physical or digital entities can interact with and induce changes in the digital twin, providing a comprehensive and interconnected system for real-time decision-making and optimization.

A supply chain digital twin is a detailed simulation model of an actual supply chain that predicts the behavior and dynamics of a supply chain to make mid-term, short-term, and long-term decisions [15,16].

The key components of digital twin methodology using anyLogistix are listed below:

- Supply chain modeling: All the components of the supply chain, such as the sources of biomass, the transportation systems, the processing plants, and the final consumers, are meticulously modeled in the digital twin [17,18]. Stakeholders obtain a thorough grasp of the dynamics of the supply chain by identifying the interdependence and restrictions within the system;
- Sustainability metrics: The digital twin incorporates into the optimization framework sustainability metrics like revenue generation, energy consumption, carbon emissions, and waste generation. Decision-makers can rank the methods that minimize ecological footprints while optimizing resource efficiency by evaluating the environmental impact of various supply chain typologies [19,20].

2.1. Sustainable Residual Biomass Supply Chains Design and Optimization

Sustainable residual biomass supply chain design and implementation are difficult but essential tasks that require effective management of the flow of residual biomass materials to minimize environmental impact and promote long-term profitability [21].

According to Nunes et al. [22], the notion of a sustainable biomass supply chain is based on the ideas of social justice, economic feasibility, and environmental responsibility. It takes into account the whole life cycle of biomass, from sourcing and harvesting to processing, transportation, and its final utilization, going beyond the simple creation of energy. The key to creating a biomass supply chain that supports sustainability objectives is striking a balance between supplying energy needs and maintaining ecological integrity [23]. This can be achieved through implementing a few strategies:

- Life cycle assessment (LCA): putting in place a thorough LCA is essential to comprehend the supply chain's overall environmental impact. This entails assessing every phase, from biomass gathering to its final application, to pinpoint problem areas and maximize the use of available resources [24,25];
- Digital twin technology: The design and optimization process can be improved by utilizing digital twin technology. Through the development of a virtual model of the residual biomass supply chain, interested parties can replicate, track, and evaluate the system's operation in real-time. By reducing inefficiencies, this not only makes decision-making easier but also advances sustainability [26,27];
- Circular economy principles: Recycling and reusing techniques can be adopted throughout the supply chain to embrace the circular economy. This entails finding ways to turn garbage into bioenergy, bio-fuels, or other worthwhile byproducts to gain additional value from leftover biomass [28,29];
- Integration of renewable energy: Incorporating renewable energy sources into the activities of the supply chain can be considered. The works of Kalak, Minoofar et al., and Paraschiv & Paraschiv [30–32] reveal that the overall carbon footprint can be greatly decreased by powering biomass processing facilities and transportation with solar, wind, or other sustainable energy sources;

- Apply Multi-Criteria Decision Analysis (MCDA): Methods to evaluate and rank various sustainability criteria can be utilized. Several MCDA techniques have emerged with relevance for optimizing residual biomass supply chains such as the following:

SESP-SPOTIS (Sustainable Energy Supply Planning with Sequential Spot Selection): This hybrid approach blends sequential selection and SPOTIS for a balanced evaluation of sustainability metrics. In biomass supply chains, it can optimize critical factors, such as resource availability, carbon emissions, and logistics efficiency [8]. With the help of this method, decision-makers may optimize the residual biomass supply chain while taking the environment, society, and economy into consideration [33,34];

- Collaborate: Collaboration with stakeholders from a range of backgrounds, such as governmental organizations, neighborhood associations, and business associates, can be effective [35]. Working together can produce creative answers and guarantee that optimization and design support more general sustainability objectives [36].
- Green logistics: Green logistics refers to the process of minimizing the environmental impact of logistics activities, such as transportation, warehousing, and distribution, while still maintaining efficiency in the supply chain. The primary goal is to reduce carbon emissions, energy consumption, and waste generated throughout the logistics processes by employing eco-friendly practices and technologies [37,38].

In summary, designing and optimizing a sustainable residual biomass supply chain requires a comprehensive strategy that incorporates technology, environmental concerns, circular economy ideas, and stakeholder participation. Organizations can contribute to a future that is more sustainable by implementing these measures.

2.2. Review of Related Literature

In this section, a review of past related work is conducted to ascertain the degree of missing links in the body of existing literature. Using the keywords (digital twin, supply chain, residual biomass, anyLogistix, sustainability criteria, simulation, and optimization), we searched Google Scholar and SCOPUS for related literature published since 2020.

For the blockchain-enabled industrial hemp supply chain, Wang et al. [39] created a simulation-based digital twin called the cyber-physical system. Digital twin was used to guide quality control verification, enhance end-to-end process understanding, and expedite the creation of an automated, safe, efficient, and dependable supply chain system. The results from this study reveal an improvement in the performance of the system. There is still a gap in that these studies worked on a cyber-physical system while our work is focused on a residual biomass supply chain.

Pehlken & Baumann [40] show that urban mining is a high-impact application of sustainable engineering within life cycle management. Though it was not analyzed from the point of view of supply chain management, the outcome of the study implies that digital twins help boost the impact on sustainability.

The study of Granache [41] presents a digital twin of the process and energy system architecture that interactively converts decision-makers' requirements and preferences into an optimization-based model and produces insightful results. With consideration for many factors like the influence of uncertainties and multi-criteria analysis, the interactive digital twin helps decision-makers navigate the solution space and direct them toward pertinent system design decisions.

An investigation into the use of digital twins along the entire energy value chain, from power generation and storage to energy consumption in buildings, transportation, and industrial uses, was carried out by Ghenai [42]. They concluded from this study that the energy business is becoming more interested in deploying digital twins, and the literature primarily focuses on lowering energy use. Recent advances in artificial intelligence and machine learning, along with the creation of increasingly complex control systems, could facilitate the growth of digital technologies by improving the efficacy and efficiency of energy systems. This will support the clean energy transition and transform the energy landscape.

Figueiredo [43] conducted a comprehensive literature review of the concepts of digital twins and the life-cycle sustainability assessment in a construction company based on the sustainability pillars, which are economy, society, and environment. Their findings revealed that there was still a gap in the evaluation and incorporation of sustainability criteria with digital twin technology, even though many articles reported on digital twins. This also aligns with our work but differs in such a way that the focus is on the building industry while we are proposing to work on residual biomass.

Piqueiro [44] developed a simulation/optimization framework to aid decision-making by integrating designs produced by an optimization model for resource distribution with the modeling of disruptive wildfire scenarios in the forest biomass supply chain. This study is adapted to the theme of our work. However, the methodology, software, and input parameters utilized differ from it. Also, the sustainability criteria were not considered here.

Bui-Duy [45] developed a discrete event simulation model for the pellet supply chain in Vietnam using anyLogistix. For the analysis, they considered economic and environmental criteria and key performance indicators. This research work is also in alliance with the proposed aim of our work, except that it does not include the social component of the sustainability criteria initiated.

Iyanov [46] examined sustainability from an emission-based environmental standpoint. The work evaluated how two sustainable recovery strategies (additive manufacturing and electric trucks) affect the environmental and resilience performance of supply chains using a simulation-based analysis alongside the anyLogistix digital supply chain model. Despite the relevance of this work in sustainability concepts, it still did not address the residual biomass supply chain.

To summarize, these reviews and assessments indicate that digital twins have demonstrated beneficial effects on sustainability, effectiveness, and decision-making across a variety of industries, including supply chain management, urban mining, energy, and construction. Additionally, they draw attention to the existence of a research gap, the necessity of more research, and the incorporation of sustainability standards into digital twin technologies.

The novelty of this study is in its innovative approach to integrating sustainability criteria into supply chain optimization for a biomass energy company in Portugal. This is achieved through the use of simulation modeling in the anyLogistix software and multi-criteria decision-making (MCDM) with a distinct emphasis on balancing environmental, operational, and economic goals. The peculiarity of this study is in its ability to simulate various scenarios, including the introduction of green logistics strategies and a split-by-ratio multiple-sourcing distribution policy. Their impact is evaluated on key performance indicators (KPIs) related to sustainability. This holistic approach enables a thorough understanding of how supply chain designs can simultaneously achieve cost efficiency, reduce greenhouse gas emissions, and improve operational performance, demonstrating a novel methodology for sustainability-oriented supply chain optimization in the renewable energy sector.

3. Materials and Methods

The materials utilized in this study comprise anyLogistix software (version: 2.15.3.2022 09061204), data on a biomass energy company (a major player in Portugal related to biomass production) located in the central region of Portugal, computers and workstations enabled to run the anyLogistix software for modeling and simulation purposes, real-life input parameters, and documentation/references related to supply chain optimization, sustainability criteria, and simulation techniques. The software offers various advantages for solving simple and complex biomass energy supply chain problems [47] compared to other software tools (FlexSim v23.2, Arena v17, and Simio v14.4) such as the following:

Hybrid Modeling: combines both optimization and simulation within one platform, ideal for managing multiple objectives like cost, emissions, and lead time.

Sustainability Metrics: built-in tools for tracking CO_2 emissions and other environmental KPIs, which are crucial for analyzing green logistics strategies.

GIS Integration: provides the real-time geospatial mapping of supply chain entities, enhancing route optimization and decision-making.

Customization: allows for user-defined tables and logic, offering flexibility to model specific supply chain elements like seasonal demand or multi-sourcing.

Multi-Sourcing Support: efficiently manages multi-sourcing policies, improving inventory and supplier coordination.

Cost Optimization: built-in models for analyzing transportation and total costs, crucial for optimizing supply chain efficiency.

Scenario Analysis: simplifies the comparison of multiple scenarios, allowing the rapid evaluation of different configurations and sustainability strategies.

Pre-built Supply Chain Elements: ready-to-use elements accelerate model creation.

These features make anyLogistix particularly well-suited for the residual biomass energy case study, balancing environmental, economic, and operational goals effectively. The methods are described in the subsection ensuing.

3.1. Design and Implementation

To implement this work, the following procedures were followed. Figure 1 shows the flowchart of the methodology, design, and implementation of the proposed model.

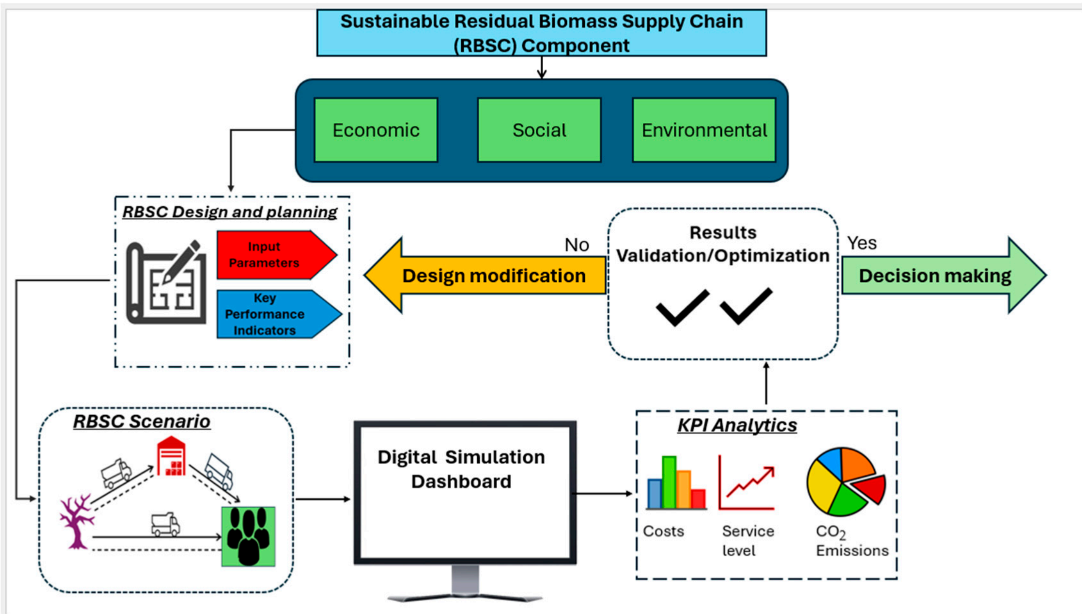

Figure 1. Methodological framework of the proposed model.

As seen in the framework, the methods involve defining the supply chain's objectives in alignment with the sustainability criteria, structure, and input variables. Next, the input variables need to be parameterized, scenarios created, and the supply chain's customer demand, transportation, and sourcing policies defined. Subsequently, the associated key performance indicators (KPIs) for the sustainability criteria can be defined. The simulation experiment is conducted to determine the impact, evaluate the KPIs, collect statistics on supply chain performance, and validate the obtained results.

The implementation was achieved in a case study that simulates the real case study data of the supply chain for a biomass energy company in Portugal using anyLogistix software to model multiple scenarios. The aim was to achieve sustainability across operational, environmental, and economic dimensions. The scenarios involve the use of digital platforms for monitoring consumption, decentralized production, and logistical decision-making to enhance efficiency. By utilizing simulation techniques, this study creates virtual replicas based on real-life data of the supply chain to evaluate performance under different configurations, such as adding distribution centers and using green logistics.

3.2. Sustainability Criteria and the Associated KPIs

The sustainability criteria and associated KPIs are briefly stated below:

- Environmental sustainability: This criterion is related to the reduction in greenhouse gas emissions through the determination and control of CO_2 from production to supply. The goal here is to achieve a carbon footprint reduction by measuring the exhaust emissions of the supply chain using total CO_2 emissions as a simulation indicator;
- Social/operational efficiency: This is referred to as improved overall operational efficiency through customer satisfaction in terms of the orders placed and demand fulfilled. By analyzing this criterion, we intend to improve customer satisfaction by measuring and optimizing demand fulfillment and service level, thereby covering the social factor in sustainability;
- Economic functionality: This is regarded as improved revenue generation, profitability, and total cost minimization. The essence of this criterion is to minimize the total cost of production through supply chain optimization and to maximize the profits and the overall revenue.

This is further summarized in Table 1, which shows the sustainability criteria and associated KPIs.

Table 1. Sustainability criteria and the associated KPIs.

Criteria	Goal	Key Performance Indicator
Environmental sustainability	To contribute to keeping the environment greener and safe	CO_2 emissions from supply chain operation
Social/operational efficiency	To satisfy customers' needs and improve the operation of the supply chain	Service level, lead time, and demand fulfillment
Economic functionality	To improve revenue, profit and minimize cost	Revenue, total cost, and profit

3.3. Definition of the Key Performance Indications (KPIs) Utilized in the Model

Supply chain KPIs are sets of quantitative metrics used to monitor and ascertain the performance of the supply chain with the aim of improving it. The KPIs used in this model are briefly defined [47]:

- Lead time: The lead time, or the number of days from the time an order was placed to the actual delivery, is the amount of time that the customer can anticipate receiving the product or the amount of time that a supplier company needs to have products available

$$\text{Lead Time} = \text{Order Delivery Date} - \text{Order Placement Date}.$$

- Service level: service level is the probability that a customer's demand will be met without experiencing a backorder or lost sale.

$$\text{Service Level} = \frac{\text{Number of Orders Delivered on Time}}{\text{Total Number of Orders}} \times 100\%;$$

- Demand fulfillment: This is an estimate of the value and satisfaction customers obtain from receiving their orders. It is derived from dividing the total number of outbound orders by the number of orders that arrived on time.

$$\text{Demand Fulfillment} = \frac{\text{Number of On} - \text{Time Outbound Orders}}{\text{Total Number of Orders}} \times 100\%.$$

- Expected lead time (ELT) service level: The ELT service level is defined as the ratio of orders delivered within the "Expected lead time" to total orders.

$$\text{ELT Service Level} = \frac{\text{Number of Orders Delivered Within Expected Lead Time}}{\text{Total Number of Orders}} \times 100\%.$$

- ELT or service level by order: This is defined as the ratio of the number of on-time orders to the number of outgoing orders. Here, the number of on-time orders is the number of orders that are delivered within the expected lead time, and the number of outgoing orders is the summation of the on-time orders and delayed orders;
- ELT or service level by revenue: This is defined as the ratio of the value of products for on-time orders to the value of the products for outgoing orders. Here, the value of products in on-time orders is the value of products from orders that were delivered within the expected lead time, and the value of products from outgoing orders is the summation of the values of products from on-time orders and delayed orders;
- ELT or service level by product: This is derived by calculating the ratio of the products that were on-time orders to the products in outgoing orders. Where products in the on-time orders are the products from orders that were delivered within the expected lead time, products in the outgoing orders are the summation of the products from on-time orders and delayed orders;
- Total CO_2 emissions: this refers to the statistics relating to the total CO_2 emitted during and within the entire supply chain.

$$\text{Total } CO_2 \text{ Emissions} = \sum CO_2 \text{ emissions from all activities in the supply chain.}$$

- Revenue: these data show statistics on the income generated by a facility from selling products to customers.

$$\text{Revenue} = \sum(\text{selling price of product} \times \text{quantity sold}).$$

- Total costs: This is the summation of all the costs incurred in the supply chain process; this includes transportation, inventory, and operational costs. Hence,

$$\text{Total costs} = \sum(\text{Transportation costs+ Inventory costs+ Operational costs});$$

$$\text{Profit} = \text{Revenue} - \text{Total costs}.$$

- Distance traveled: This describes the entire distance traveled by all outgoing vehicles (trucks, trains, ships, or airplanes) during the movement of commodities within a supply chain network. It is a crucial indicator that can be used to evaluate the effectiveness of transportation routes as well as the general operation of the logistics network.

3.4. Case Study

The case study simulates the supply chain of a biomass energy company in Portugal using anyLogistix software to model multiple scenarios. The aim is to optimize sustainability across operational, environmental, and economic dimensions. The scenarios involve the use of digital platforms for monitoring consumption, decentralized production, and logistical decision-making to enhance efficiency. By utilizing simulation techniques, the study creates virtual replicas based on real-life data of the supply chain to evaluate performances under different configurations, such as adding distribution centers and using green logistics.

To demonstrate this process, a simulation study of the supply chain of a biomass energy company located in the Central region of Portugal was carried out. The company deals in energy production projects through co-generation and renewable sources (solar, wind, biomass, and biogas). They also use a digital multi-platform to continuously monitor the consumption and decentralized production of customers, thus allowing for automatic, fast, and assertive decision-making in order to improve efficiency. The model was designed using the anyLogistix software, which is a decision-oriented tool with user-defined tables and logic that combines supply chain optimization and simulation for logistics, network design, inventory, and production capacity planning [47]. The metrics are filtered and evaluated based on the supplier, customer, distribution center, factory, and products. The supply chain entities are designed in relation to their properties and interactions with other entities within the scope of the supply chain under study.

3.5. Simulation Model Settings

In this study, five scenarios were modeled. The first scenario was the base scenario and real situation of the case study company, a wood purchasing company. The company obtains its supplies from third parties who are forestry dealers in 30 regions of the country, with a periodic demand duration of 5-day intervals. The final destination of the biomass product is a power plant facility, which is a unit of wood purchaser located in Portugal. The total amount of biomass products consumed by the plant per year is about 300,000 tons.

The product flows are organized in such a way that they move from the forest (third party) to the wood purchasing company and finally to the customer. In Figure 2, the symbols of the supply chain entities as obtainable from the software are displayed side by side with the corresponding pictorial representations for the supplier and customer.

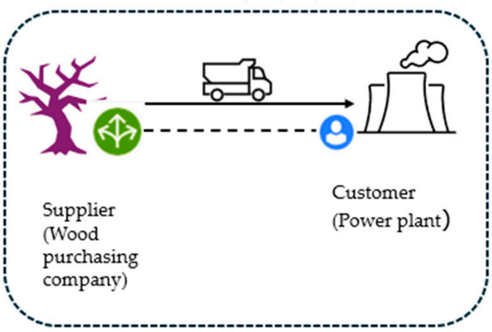

Figure 2. Pictorial view of base scenario.

The supply chain for the base scenario is the same as the real case, which has one supplier and one customer based on the information above. The Geographical Information System (GIS) diagram of the base scenario is presented in Figure 3.

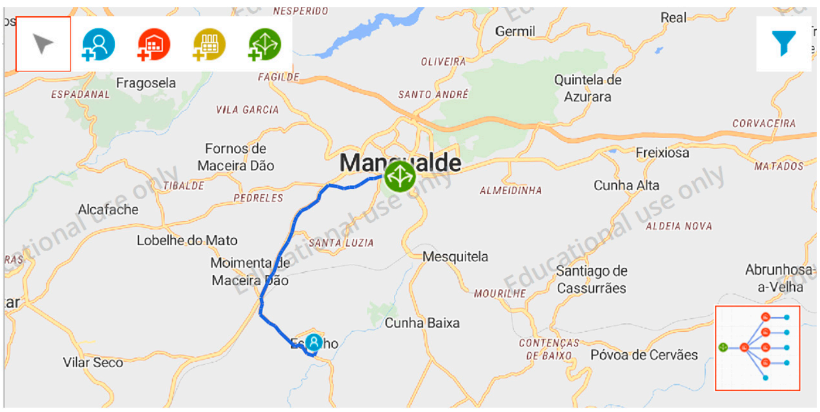

Figure 3. GIS view of all entities and the flow of materials in the base supply chain (scenario 0).

The unit cost price in tons of all forms of the chip, as obtained from the company, is woody biomass chips purchased at EUR 45; forestry and eucalyptus biomass were acquired at the rate of EUR 40. See Table 2 for the product type and its price allocation.

Table 2. Product type and cost specification.

Product	Cost Price (EUR)/ton	Selling Price (EUR)/ton	Quantity Per Year (ton)
Woody biomass	45	150	32,720.14
Forest biomass	40	100	54,303.21
Eucalyptus biomass	40	100	10,138.45

The selling price was deduced from the average selling prices in Portugal for the year under study.

A summary of the data used for the model setup is presented below:

- Demand: periodic demand, order interval = uniform (5–7 days), quantity = uniform (10,140; 54,303), and expected lead time = 1 day;
- Sourcing policy: multi-sourcing, mostly inventory;
- Shipping: LTL (Less Than Truck Load), FIFO (First In, First Out);
- Inventory: periodic demand.

The vehicle specification is a lorry with a 95 m^3 capacity (equivalent to 28 tons) at a velocity of 50–100 km/h. The average value of 75 km/h was used. The cost of transportation per ton is EUR 10. Table 3 shows the input parameters and their specifications.

Table 3. Vehicle specification.

Vehicle Type	Capacity (m^3)	Speed (Km/h)	Transportation Cost (EUR)	Vehicle Capacity (m^3)
Lorry	95	75	280	90

The model is simulated for a period of 10 months. This time is pre-determined based on the fact that 2 months out of the year (during summer) residues, are not harvested due to the avoidance of the risk of wildfires, which is predominant in the country (Portugal) of the case study. Table 4 presents a comparison of the results obtained from simulations and the real-life data.

Table 4. Summary of results for base supply chain.

KPI	Real Historical Data (Company)	Simulated Values (anyLogistix)	Error (%)
Service level (%)	100	100	0
Demand fulfillment (m^3)	300,000	282,750	5.7
Lead time (days)	5	5	0
Total CO_2 emissions (ton)	154,000	137,530	10.6
Revenue (EUR)	113,521,870	110,000,000	3.1
			Average error = 3.88

The validation of the simulation model was performed by comparing the sustainability criteria KPIs from the real-world case study with the simulated outcomes. The purpose of the percentage error level determination was to control and balance the model's accuracy, precision, and practicality. An average error of 3.88% was observed, which is within the acceptable limits for discrete event simulation models, as outlined in works like Law & Kelton [48] and Banks et al. [49]. This minimal error validates the model as accurately reflecting real-world processes.

Test Scenarios Definition

To compare the changes in the sustainability of the supply chain under different design outlines, four scenarios (Scenario A, Scenario B, Scenario C, and Scenario D) were considered. These scenarios are based on the current residual biomass generation and utilization in Portugal. Biomass-powered energy is generated from 19 biomass power plants across the country [50]. Table 5 displays the regional/district distribution and location of biomass power plants across the country. Figure 4 shows the network representation of the system in a graphical mode.

Table 5. Location of biomass power plants (BPPs) in Portugal.

Region	District (Number of BPP)
Central region	Aveiro (4) Viseu (2) Castelo Branco (5) Coimbra (3) Santarem (2)
Northern region	Viano do Castelo (1)
Southern region	Setubal (2)

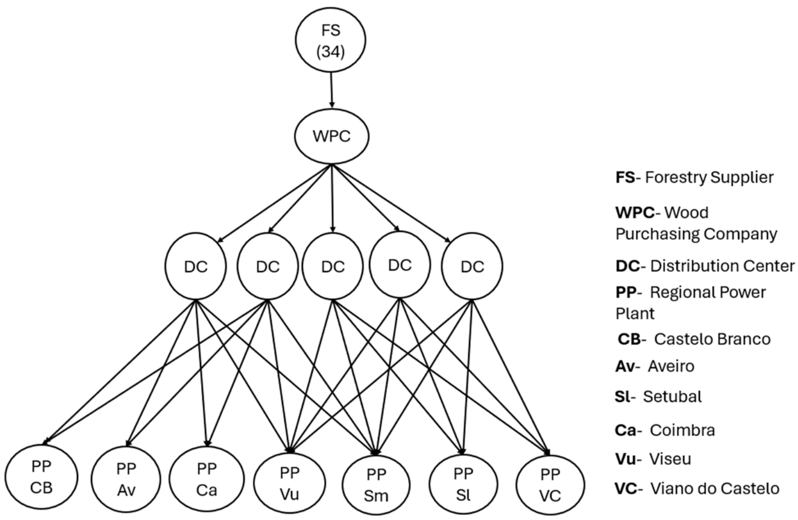

Figure 4. Graphical network representation of the system.

The basic supply chain formulation for the test scenarios is based on the information in Table 5. The supplies are obtained from 34 types of forestry located in some districts across the regions. The test scenarios are described in the succeeding texts.

Scenario A

This scenario has a supply chain formulation of 34 forestry suppliers and 19 power plants. The demand type is order on demand. The vehicle specification is that of a truck with a capacity of 95 m^3 at a speed of 50 km/h. The product's name is biomass chips, at a selling price of EUR 150 per ton and a cost price of EUR 45 per ton. The expected lead time is 1 day. The CO_2 produced during shipping = 1.98 (kg/m^3). Since there was no distribution center in this scenario, the only vehicle type used was the truck with a capacity of 95 m^3 at a speed of 50 km/h. Figure 5 presents the GIS map view of all the supply chain entities and their precise locations as obtained from the simulation software.

The supply of biomass chips flows from the closest dynamic source to the power plants. This implies that the power plants receive their supply of biomass from the closest possible forestry distribution source. Like the base scenario, the simulation was run for a period of 10 months to obtain the results.

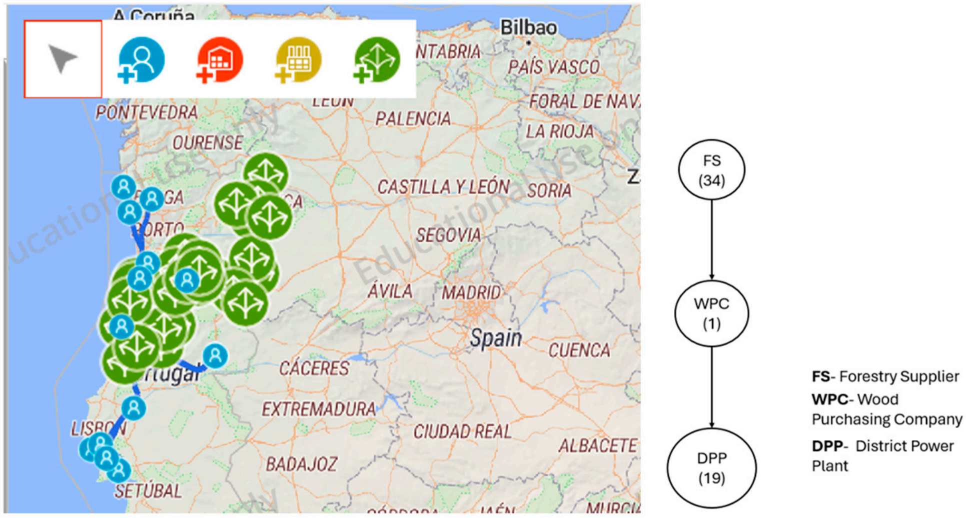

Figure 5. GIS map view of supply chain entities.

Scenario B

This test scenario considers the inclusion of five DCs strategically spread in the supply chain of Scenario A, considering the regions and their proximity to suppliers and customers concurrently. Figure 6 presents the GIS map view for that formulation.

Figure 6. Test scenario with 5 DCs spread across the supply chain.

In this case, the distribution centers are located at Macedo de Cavaleiros, Vila Nova de Gaia, Viseu, Coimbra, and Torres Vedras.

Scenario C

This supply chain involves the adoption of Scenario B. However, the vehicle specifications are selected so that we can focus on green logistics systems to see how the system performs to enforce the sustainability criteria.

Scenario D

In this formation, Scenario C is adopted with the inclusion of a percentage distribution of the biomass product. Hence, 20% of the biomass is transported straight from the source to the power plants, while the remaining 80% is sent to the DCs. The percentage sent to the DCs takes a minimum of 1 to 3 days to be sent to the power plants.

4. Results

The simulation experiment was run for a period of 10 months for all test scenarios (A, B, C, D). Table 6 presents a summary of the results obtained from the simulator tool in alignment with the predefined sustainability criteria and its associated key performance indicators.

Table 6. Summary of results.

KPI	Scenario A	Scenarios B	Scenario C	Scenario D
Total cost (EUR)	882,529,439	727,490,483	661,354,985	661,354,985
Transportation cost (EUR)	882,529,439	727,490,483	661,354,985	661,354,985
Revenue by customer (EUR)	19,840,649,550	19,840,649,550	19,840,649,550	19,840,649,550
Lead time (day)	1	16	17	28
Total CO_2 Kg/m^3	317.7	261.9	66.1	59.5
Demand received (order)	1406	1159	1159	38,186
Fulfillment received (order)	1406	976	976	1159
ELT by order (ratio)	1	0.842	0.842	1
ELT by product (ratio)	1	0.564	0.564	1
ELT by revenue (ratio)	1	0.564	0.564	1
Service level by revenue (ratio)	1	1	1	1
Distance traveled (Km)	6,263,000	69,640,650	73,508,050	74,520,650

The results reveal that the introduction of distribution centers to the supply presents a variation in the values of different metrics. For Scenario C, a vehicle specification of 90 m^3 was selected with an eco-friendly reduction rate of 90% in CO_2 emissions for which the vehicle was applied. The results show an improvement and reduction in transportation costs and total CO_2 emitted by vehicles during transportation.

4.1. Analysis

Operational Efficiency

The operational efficiency experiment shows the results for the demand and fulfillment received, the lead time, ELT service level by product, and ELT service level by order. From the results displayed in Table 6, there was a significant increase in the lead time with the introduction of distribution centers and eco-friendly vehicles. This is logical since it takes more time for orders to be fulfilled because of additional entities (DCs and vehicles). Looking at Figure 6, it can be observed that the service level by revenue remained constant and optimal basically because the customers and income generated from them were not altered. The ELT service level by product and order experienced some variations with the introduction of DCs and the green logistics strategy for scenarios B and C.

Environmental sustainability

The sequel to the simulation for the measurement and control of greenhouse gas emissions and the various types of CO_2 emitted as obtainable are presented in Figure 7.

The types of measurable CO_2 are presented in the bar chart in order of their magnitude. CO_2 from outbound processing had the highest value with 86.7% of the total CO_2 and the lowest percentage of 0.1% from facility size-based CO_2 and others (CO_2 from other causes, CO_2 by facility opening/closure, CO_2 from production, and CO_2 produced from vehicles). After conducting the simulation experiment, the results for the total greenhouse gas emissions in each scenario were as follows:

- Scenario A: 317.7 kg/m;
- Scenario B: 261.9 kg/m:
- Scenario C: 66.1 kg/m;
- Scenario D: 59.9 kg/m.

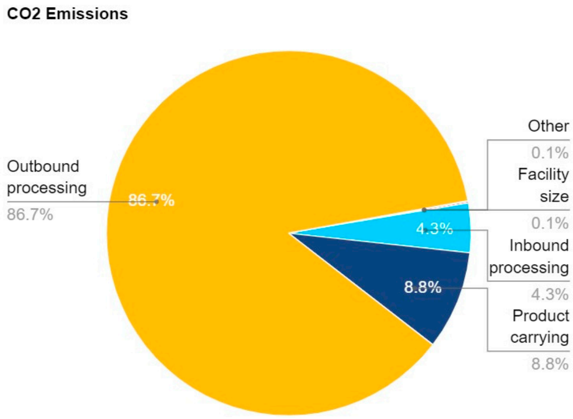

Figure 7. Types of CO_2 emissions obtained from the simulator.

The data demonstrate a consistent decline in emissions as parameters were adjusted in accordance with the specifications. These findings suggest that increasing the number of distribution centers (DCs) and implementing green logistics strategies not only enhance operational efficiency and reliability but also significantly reduce the overall greenhouse gas emissions released into the atmosphere.

Economic Functionality

The metrics for determining the economic resilience of the system are measured by the transportation cost, revenue, and total costs. As seen in Table 6, the simulation result displays the outcomes for the different test scenarios. The initial and daily running costs in all scenarios were essentially the same since the simulation's initial cost was determined based on the total demand rather than accounting for the varying costs of buildings in various locations. The revenue generated by the power plants (customers) remained the same regardless of the supply chain formation. The transportation cost and total cost kept improving with the introduction of distribution centers. The number of DCs introduced into the supply chain was directly proportional to the reduction in CO_2 emissions and the total cost incurred. However, the total distance traveled, and frequency of travel increased with the addition of more DCs to the supply chain. With scenario C (the introduction of green logistics), the transportation cost also improved.

4.2. Discussion

In this section, the analysis of the results obtained from the simulation is presented. Multi-criterion decision-making and sensitivity analysis were applied to the study.

In the case study of the biomass energy company located in the central region of Portugal, multi-criterion decision-making (MCDM) is applied to evaluate the different scenarios of the supply chain setup using a set of sustainability-oriented key performance indicators (KPIs). MCDM allows for a structured decision-making process that accounts for various criteria that are important to the company, such as operational efficiency, environmental sustainability, and economic functionality.

Criteria

The main sustainability criteria for the supply chain, as reflected in the case study, are categorized as follows:

1. Operational efficiency:
   - Lead time (days);
   - Demand fulfillment (order count).
2. Environmental sustainability:
   - Total CO_2 emissions (kg/m^3).
3. Economic functionality:

- Total cost (EUR);
- Revenue (EUR).

Assignment of Weights to the Criteria

To apply MCDM, it is crucial to assign weights to each criterion according to its relative importance to the company. Hence, we assigned the following:

- Operational efficiency: 40%;
- Environmental sustainability: 40%;
- Economic functionality: 20%.

The scores attached to each KPI selected for the sustainability criteria are given as follows:

Total CO_2—40%;
Lead time—20%;
Demand fulfilled—20%;
Total cost—20%.

The 20% weights assigned to each KPI considered under operational criteria made up for the 40% weight assigned to it. These weights reflect the company's prioritization of reducing environmental impact while maintaining economic resilience and operational efficiency.

Alternative Scores (Scenarios)

Each of the four scenarios (A, B, C, and D) were scored against the defined criteria.

Operational efficiency:

- Lead time: Scenario A (1 day) performs better than Scenarios B (16 days), C (17 days), or D (28 days).
- Demand fulfillment: Scenario A has the highest fulfillment (1406 orders), while Scenario D improves on the demand received (38,186 orders).

Environmental sustainability:

- Total CO_2 emissions: Scenario D (59.5 kg/m^3) has the lowest emissions, while Scenario A has the highest (317.7 kg/m^3). Scenario C also shows a significant improvement in CO_2 emissions (66.1 kg/m^3).

Economic functionality:

- Total cost: Scenario D (661,354,985 EUR) offers the lowest cost, followed by Scenario C and B, with Scenario A having the highest cost (882,529,439 EUR).
- Revenue: all scenarios have the same revenue (19,840,649,550 EUR), which simplifies this criterion as a constant.

Decision-Making

Various MCDM methods such as the weighted sum model (WSM) or analytic hierarchy process (AHP) can be applied to aggregate the performance of each scenario based on the criteria and their weights. In this case study, the WSM method was applied to all four scenarios.

Applying WSM:

In this case study, the WSM was used to aggregate the performance of each scenario. It also assigned scores to each alternative based on its performance in each criterion and then combined these scores according to the predefined weights, see Equation (1).

$$\text{Total score for each scenario} = (W_{OE} \times S_{OE}) + (W_{ES} \times S_{ES}) + (W_{EF} \times S_{EF}) \quad (1)$$

where

- W_{OE}, W_{ES} and W_{EF} are the weights for operational efficiency, environmental sustainability, and economic functionality, respectively.
- S_{OE}, S_{ES}, and S_{EF} are the scores for each scenario in their respective criteria [50].

Applying Equation (1) to Scenario A would then produce the following:

$$\text{Score for Scenario A} = (0.4 \times S_{OEA}) + (0.4 \times S_{ESA}) + (0.2 \times S_{EFA}). \quad (2)$$

where S_{OEA}, S_{ESA}, and S_{EFA} are criteria scores aggregated from Scenario A. Equation (2) can be applied to scenarios B, C, and D.

The overall sustainability criteria score on a general term can be given as follows:

$$S = \left(\sum_{i=1}^{n} S_{OEi} + S_{ESi} + S_{EFi}\right) \quad (3)$$

If there are changes in any of the KPIs over time or due to adjustments in operations, we can measure the change in the sustainability criteria score ΔS by comparing the scores before and after the change. The change from $S_{initial}$ to S_{new} can be expressed mathematically as follows:

$$\Delta S = S_{new} - S_{initial} \quad (4)$$

Results Analysis

To determine the WSM for the scenarios, it is necessary to normalize all the salient KPIs for the sustainability criteria, where the normalized value for each KPI is a preferred lower value and is given as follows:

$$\text{Normalized value} = \frac{\text{Worst value} - \text{Actual value}}{\text{Worst value} - \text{Best value}} \quad (5)$$

In a situation where higher values of KPIs are preferred, the normalized value is given as follows:

$$\text{Normalized value} = \frac{\text{Actual value} - \text{Worst value}}{\text{Best value} - \text{Worst value}} \quad (6)$$

Table 7 shows the presentation of Scenarios A to D and a statement of the best and worst values obtained from the simulations.

Table 7. Statement of best and worst values.

KPI	Scenario A	Scenarios B	Scenario C	Scenario D	Best Value	Worst Value
Total cost (EUR)	882,529,439	727,490,483	661,354,985	661,354,985	661,354,985	882,529,439
Lead time (day)	1	16	17	28	1	28
Total CO_2 Kg/m^3	317.7	261.9	66.1	59.5	59.5	317.7
Demand received (order)	1406	1159	1159	38,186	38,186	1159

The normalized value for the selected KPIs for the weighted sum model is shown in Table 8.

After the computation of Equations (1)–(6), the weighted scores for each scenario are presented in Table 8. The scenario with the highest overall score is Scenario C.

Applying MCDM to the supply chain case study enables the company to evaluate the impact of various supply chain configurations (scenarios A, B, C, and D) on multiple criteria simultaneously. By assigning weights to the sustainability criteria, the company can make informed decisions to optimize its supply chain not only for cost efficiency but also for environmental sustainability and operational performance.

In this case, based on the results derived from the weightings applied to each criterion, Scenario C emerged as the best option due to its balance of lower total costs and lead time, significantly reduced CO_2 emissions, and improved demand fulfillment. It is also evident that the introduction of green logistics/eco-friendly vehicles could greatly improve the sustainability of a residual biomass supply chain.

Table 8. Normalized values for KPIs.

KPI	Scenario A	Scenarios B	Scenario C	Scenario D
Total cost (EUR)	0.00	0.700980	1.000000	1.0000
Lead time (days)	1.00	0.444444	0.407407	0.0000
Total CO_2 (Kg/m³)	0.00	0.216112	0.974438	1.0000
Demand received (order)	0.9933	1.000000	1.000000	0.0000
Weighted score	0.398	0.515	0.871	0.7

Sensitivity Analysis

The study focused on operational efficiency, economic performance, and environmental sustainability across four scenarios (A, B, C, and D). The key parameters varied and included the number of distribution centers, and the CO_2 emission rates (introducing eco-friendly vehicles) across the supply chain. From the values in Table 6, the major findings from the sensitivity analysis carried out with reference to the sustainability criteria are stated as follows:

Operational efficiency:

- Lead time: Adding DCs (Scenario B) significantly increases the lead time as more steps are introduced into the supply chain. However, lead time can be optimized by reducing the number of DCs or improving transportation strategies (Scenario D).
- Demand fulfillment: a higher demand frequency or quantity can slightly reduce service levels if infrastructure or capacity is not adjusted, especially in direct-to-customer scenarios like Scenario A.

Economic performance:

- Total cost: the supply chain is highly sensitive to changes in transportation costs. Scenarios with more DCs (Scenario B) or green logistics (Scenario C) reduce transportation costs by optimizing routes and using eco-friendly vehicles.
- Revenue: revenue remains constant across all scenarios since the supply chain design does not alter customer demand or the selling price.
- Effect of distribution centers: More DCs reduce transportation costs but increase operational complexity. A balance between cost efficiency and lead time is critical.

Environmental sustainability:

- CO_2 emissions: Introducing green logistics (Scenario C) drastically reduces CO_2 emissions by up to 90%, making it the most environmentally sustainable scenario. Emissions also decrease with the strategic placement of DCs (Scenario B) by reducing the distance traveled.
- Vehicle capacity: larger, eco-friendly vehicles further reduce emissions, but smaller vehicles lead to more trips and higher emissions.

This analysis highlights the trade-offs between cost, operational efficiency, and environmental sustainability in the biomass energy supply chain. Adding DCs and adopting green logistics strategies can significantly reduce transportation costs and CO_2 emissions, but they may also increase lead times. This analysis provides valuable insights for decision-makers to optimize the supply chain based on their priorities, whether cost, speed, or sustainability.

4.3. Contributions of the Findings to Science

The findings from the biomass energy company's supply chain simulation provide significant contributions to scientific research in sustainable logistics, supply chain optimization, and environmental management. In this section, we discuss these contributions in relation to the operational, environmental, and economic aspects explored through the multi-criteria decision-making approach in this case study.

Operational Efficiency

This case study provides empirical evidence that enhancing operational efficiency through the integration of distribution centers (DCs) and green logistics can result in significant improvements in service levels, lead time management, and overall supply chain performance. This aligns with established research in logistics, such as that by Ivanov et al. [49], who argued that optimizing supply chain networks through digital platforms and advanced logistics software improves operational decision-making.

The introduction of distribution centers in Scenario B (Figure 6) demonstrated a marked reduction in transportation costs and travel distances, as well as a notable impact on order fulfillment and lead time. While introducing DCs increased the lead time slightly due to more complex routes, the service level remained high. These findings support the growing body of literature that stresses the importance of supply chain network design in achieving high operational efficiency and customer satisfaction, especially in renewable energy sectors where logistics play a critical role [51].

Green Logistics

A key contribution of this study lies in its focus on environmental sustainability, specifically the reduction in CO_2 emissions through green logistics strategies. The findings showed a drastic decline in emissions when eco-friendly logistics strategies were implemented, especially in Scenario C (Table 6), where transportation emissions dropped by 80% compared to Scenario A. This reinforces and validates the significance of sustainable logistics practices, such as the use of low-emission vehicles and optimized routing, which are well-documented by scholars such as Sbihi and Eglese [52].

The findings also add to the scientific discourse on the importance of reducing carbon footprint in supply chains. Various studies have noted that transportation is a major contributor to CO_2 emissions within supply chains [53], and this case study validates the use of simulation tools to model green logistics interventions that result in meaningful reductions in greenhouse gas emissions. Scenario D, with its hybrid strategy of direct and DC-based distribution, further highlights the need for dynamic supply chain configurations that balance operational and environmental goals [54].

Cost Efficiency

Economically, the case study's findings contribute to research on the balance between sustainability and cost-efficiency in supply chains. The simulation demonstrated that adding DCs and employing green vehicle logistics (Scenarios B and C) led to significant reductions in transportation costs without compromising the revenue generated by power plants. This aligns with the economic principle that cost reductions through sustainability measures (such as green logistics) do not necessarily come at the expense of profitability [55].

The result of Scenario C, where a 90% reduction in CO_2 emissions was achieved while maintaining the same level of revenue, provides a compelling case for industries to invest in eco-friendly technologies without fearing adverse effects on their financial outcomes. The consistency of revenue across all scenarios also demonstrates the feasibility of implementing sustainability measures in supply chains without sacrificing economic growth, which is a critical consideration in industries reliant on biomass energy and renewable resources [56].

Multi-Criteria Decision-Making in Supply Chains

The use of multi-criteria decision-making (MCDM) in this case study showcases its application in assessing trade-offs between sustainability, cost, and operational efficiency. By analyzing different scenarios (A through D), the study provides a framework for evaluating multiple supply chain configurations under varying operational conditions. This approach resonates with the findings from Faccio et al. [57], who assert that MCDM methods are essential for optimizing complex supply chains, especially those that involve multiple conflicting objectives such as cost reduction and environmental sustainability.

The use of anyLogistix software for simulation-based decision-making adds another dimension to the scientific contribution. The software's ability to combine network design, inventory planning, and production capacity within a single tool demonstrates how advanced simulation tools can help supply chain managers navigate complex decision landscapes. This complements the broader research on simulation-based decision support systems, which have become increasingly important for logistics planning and sustainability [58].

4.4. Comparison to Existing Studies and Scientific Contributions

The results and contributions of this study are compared to previous studies and the literature to highlight its scientific contributions.

Operational Efficiency:

Ivanov et al. [52] highlighted how optimizing supply chain network structures leads to improved decision-making and customer service levels. The introduction of distribution centers improves logistics efficiency and demonstrates a slight trade-off in lead time while maintaining a high service level. This aligns with the findings that network restructuring can enhance overall performance in complex supply chains.

Environmental Sustainability:

Studies like McKinnon [55] have shown the logistics sector's significant contribution to CO_2 emissions. Green logistics strategies, such as low-emission vehicles and route optimization, can mitigate this. The reduction in emissions by 90% in Scenario C mirrors the findings in previous studies in that eco-friendly practices can dramatically lower the carbon footprint of supply chains.

Economic Functionality:

Carter & Rogers [57] emphasized the potential for green supply chain management to improve financial outcomes through cost savings in transportation and other logistics activities. This case study confirmed that green logistics interventions, like optimizing distribution networks and using environmentally friendly vehicles, can reduce transportation costs without sacrificing revenue.

Multi-Criteria Decision-Making:

Faccio et al. [58] and Longo et al. [59] argue that multi-criteria decision-making and simulation tools are essential for optimizing supply chains facing conflicting objectives. The case study demonstrated the successful use of anyLogistix for evaluating trade-offs between operational, economic, and environmental KPIs, contributing to MCDM research by providing an overall sustainability score, change in sustainability score, and a practical example of its application in the agroforestry residual biomass energy sector.

Scientifically, this study presents a valuable contribution to the intersection of green logistics, supply chain optimization, and sustainable energy. It provides empirical evidence supporting the application of simulation and multi-criteria decision-making in achieving environmental and economic sustainability. By demonstrating the effectiveness of distribution centers and green vehicle logistics in reducing both costs and emissions, this research contributes to ongoing discussions about the viability of sustainable supply chain strategies in industries reliant on biomass energy and renewable resources. Additionally, this study validates the use of advanced digital platforms like anyLogistix for complex supply chain analysis, thereby reinforcing the importance of simulations in the evolving field of sustainable logistics and supply chain management.

4.5. Managerial Insights and Impact of Study on the Society

This section delves into the practical insights and societal impact derived from this study, highlighting how sustainable supply chain strategies can shape managerial decisions and contribute positively to society.

- Strategic decision-making: The study underscores the importance of adopting a Multi-criteria decision-making (MCDM) approach to evaluate various supply chain configurations. Managers should prioritize integrating sustainability criteria into their strategic planning to balance operational efficiency with environmental and economic goals.
- Investment in green logistics: The findings demonstrate that investing in eco-friendly vehicles and distribution centers can significantly reduce CO_2 emissions and transportation costs. Managers should consider these investments as part of their long-term strategy, as they not only enhance sustainability but also lead to cost savings over time.
- Supply chain resilience: The introduction of distribution centers improves logistics flexibility and responsiveness. Managers should leverage this to build a more resilient supply chain that can adapt to changes in demand or disruptions, ensuring consistent service levels.
- Operational efficiency: The study reveals that while the addition of distribution centers can increase lead times, they can also improve service levels and demand fulfillment. Managers should focus on optimizing routes and inventory management to mitigate potential delays while capitalizing on the benefits of DCs.
- Stakeholder engagement: The importance of stakeholder perspectives on supply chain decisions is highlighted. Managers should engage with various stakeholders, including customers, suppliers, and regulatory bodies, to ensure the alignment of sustainability goals and foster collaborative approaches to achieving them.
- Continuous improvement: The insights from this study emphasize the need for continuous monitoring and improvement of supply chain practices. Managers should adopt performance metrics and feedback mechanisms to evaluate the effectiveness of sustainability initiatives and adjust strategies as necessary.

Impact of the Study on Society

- Environmental sustainability: The study contributes to the broader goal of reducing greenhouse gas emissions and promoting environmental sustainability. Demonstrating the effectiveness of green logistics practices encourages businesses to adopt eco-friendly strategies, ultimately leading to improved air quality and reduced carbon footprints in the community.
- Economic growth: The findings suggest that sustainable supply chain practices can lead to cost savings without sacrificing revenue. This creates economic opportunities, potentially boosting local economies and enhancing the financial stability of businesses that prioritize sustainability.
- Public awareness: By highlighting the importance of sustainable logistics, this study raises public awareness about the environmental impact of supply chains. Increased awareness can lead to greater consumer demand for sustainable products and practices, pushing companies to prioritize eco-friendly strategies.
- Regulatory compliance: As environmental regulations become more stringent, the study's insights provide a roadmap for companies to comply with emerging sustainability standards. This can facilitate smoother transitions to greener practices, reducing the regulatory burden on businesses while benefiting the environment.
- Innovation and technological advancement: The emphasis on integrating advanced logistics solutions, such as eco-friendly vehicles, promotes innovation within the industry. This could drive technological advancements in sustainable practices, encouraging research and development with greener alternatives and the creation of new markets.
- Social responsibility: The outcomes of this study encourage companies to adopt a more holistic approach to corporate social responsibility (CSR). By focusing on

sustainability in their supply chain operations, businesses can contribute positively to their communities, enhancing their reputation and fostering consumer trust.

Overall, the managerial insights and societal impact derived from this study highlight the critical role that sustainable supply chain practices play in shaping a more environmentally responsible and economically viable future.

5. Conclusions and Future Studies

The case study conducted on a biomass energy company in Portugal provides valuable insights into optimizing supply chain operations through the application of multi-criteria decision-making (MCDM) methodologies. The simulation experiment analyzed various scenarios (A, B, C, D) over a period of 10 months, revealing the intricate balance between operational efficiency, environmental sustainability, and economic functionality. The results indicate that the introduction of distribution centers (DCs) and eco-friendly vehicles significantly impacts key performance indicators (KPIs), particularly in reducing CO_2 emissions and transportation costs. Scenario C, which employed a green logistics strategy, emerged as the most favorable configuration due to its ability to lower costs and emissions while maintaining demand fulfillment and service levels. Furthermore, the study highlights the critical role of MCDM in facilitating informed decision-making within the supply chain, enabling the company to navigate trade-offs between competing objectives effectively. The findings advocate for the adoption of sustainable practices in supply chain management, underscoring their feasibility and potential for enhancing both environmental and economic outcomes.

Future Research

For futuristic development, we propose the following:

The inclusion of a wildfire risk metric as a sustainability criterion for social dimensions in supply chain management: One often overlooked yet significant factor is wildfire risk, which can have profound social and economic consequences. Integrating wildfire risk metrics into the sustainability criteria of the social dimension in supply chain management can enhance resilience, protect communities, and ensure long-term viability.

Resilience planning and robustness analysis: This examines how resilient the sustainable biomass supply chain is to unforeseen circumstances and interruptions, such as harsh weather or modifications to laws and regulations. Creating contingency planning and resilience measures can ensure the system can adjust to unforeseen obstacles.

Advanced simulation models: Incorporating more complex simulation models that consider real-time data, varying demand patterns, and supply disruptions could enhance the robustness of the decision-making framework. This would allow companies to better prepare for unforeseen challenges and optimize their operations accordingly.

Case studies on various geographic situations: This study can be expanded by carrying out case studies in diverse geographic settings to take into consideration regional differences in the availability of biomass, legal frameworks, and market dynamics. This might shed light on how broadly applicable the developed framework is.

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