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Supply Chain Optimization for Hydrotreated Vegetable Oil (HVO) Products

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Abstract

This research presents an optimization model specifically designed to enhance the efficiency of operations within the Hydrotreated Vegetable Oil (HVO) supply chain. The key participants in this supply chain encompass suppliers of Refined, Bleached, Deodorized Palm Oil (RBDPO), raw material storage facilities, HVO production facilities (biorefineries), HVO product storage, and end users. The model incorporates decision variables related to inventory management, feedstock and product delivery, and production processes. The results of the tests reveal a global optimum value of $55,982.30, which consists of various cost components: the raw material purchase cost and total handling cost (Z1), totaling $12,754.94; total inventory storage cost (Z2) of $928.60; total production cost (Z3) of $35,605.56; and total transportation cost between processing facilities (Z4) of $4,643.21. The process of identifying the optimal solution necessitated 476 iterations. The model was validated utilizing optimization software to derive the best solution, thereby assisting strategic decision-making for sustainable and economic biofuel supply chain management. The application of this optimization model allows companies to minimize production costs, mitigate environmental impacts, and enhance the overall sustainability of the HVO supply chain. The findings suggest that this optimization approach can effectively reduce total supply chain costs and improve operational efficiency.

Keywords
Hydrotreated Vegetable Oil (HVO), supply chain model, optimization.

1. Introduction
With increasing awareness of the importance of renewable energy and environmental sustainability, the fuel industry is shifting away from fossil fuels to more environmentally friendly alternatives. The biofuel industry in Indonesia has experienced rapid growth in recent years, influenced by government policies, private sector investments, and increasing market demand (Agus Cahyono, 2022). Indonesia has abundant biomass resources, but some are carbon-intensive (Gapor Md Top, 2010). One alternative that is receiving increasing attention is hydrotreated vegetable oil (HVO). HVO is a biofuel produced through a hydrogenation process of vegetable oil, resulting in a fuel with properties similar to conventional diesel, but with lower emissions. Knothe (2010) has conducted an in-depth study of its terminology and production methods. HVO is a second-generation biofuel produced through the hydrogenation process of vegetable oils or animal fats. A supply chain optimization model is needed to improve the efficiency and sustainability of HVO production, including raw material procurement, production process, distribution, and final consumption.

In its implementation, the HVO supply chain has its complexity, as it involves various aspects such as the availability of raw materials (vegetable oils), production processes, distribution, and final consumption. Supply chain optimization is important to ensure cost efficiency, smooth distribution, and sustainability of raw material supply. Factors such as the uncertainty of vegetable oil supply, fluctuating production costs, and strict environmental regulations are the main challenges in managing the HVO supply chain. Therefore, a supply chain optimization model that can account for various variables in this system is needed. This optimization model is expected to improve operational efficiency, reduce production and distribution costs, and ensure the sustainability of raw material supply.

Habib et al. (2020) developed an animal fat waste-based biodiesel supply chain optimization model to reduce environmental impacts and costs while improving social welfare. Garai et al. (2021) designed an effective subsidy policy for farmers and biofuel producers to increase profits in a closed-loop herbal and medicinal supply chain system. Habib et al. (2021) developed a network of animal fat-based biodiesel supply chain optimization models to reduce operating costs and carbon emissions. Gautam et al. (2017) developed a biofuel supply chain model by integrating forest terminals and biorefineries to minimize costs. Murillo-Alvarado and Flores Russell (2022) proposed a supply chain model for bioethanol production by utilizing agro-industrial waste to increase economic benefits. Meanwhile, Habib et al. (2022) designed an animal fat-based biodiesel supply chain optimization model using a fuzzy method to reduce the total cost of the biodiesel supply chain. Kanan et al. (2022) developed a second-generation biodiesel supply chain network model by considering sustainability aspects, namely economic, environmental, and social, to reduce total supply chain costs and environmental emission costs.

Jana et al. (2022) designed a biofuel supply chain distribution network based on life cycle energy consumption and CO2 emissions to minimize both factors under uncertainty. Kalhor et al. (2022) proposed a Mixed Integer Linear Programming (MILP) model to manage and design biofuel supply chain networks, focusing on reducing the total supply chain cost and the environmental impact of biofuel transportation and production. Zarrinpoor and Khani (2021) designed a sustainable biofuel supply chain by considering economic, environmental, and social factors to optimize profit and social benefits. Kwon and Han (2021) developed a biofuel supply chain network model to reduce fuel production costs. Memişoğlu and Üster (2021) developed a similar model to optimize producer profits. Shavazipour et al. (2020) and Akbarian-Saravi et al. (2020) modeled the bioethanol supply chain under uncertainty with a focus on increasing profits, reducing environmental impacts, and increasing social benefits. Azadeh and Vafa Arani (2016) developed a hybrid approach that combines dynamic systems and mathematical programming in biodiesel supply chains to maximize profits. Huang et al. (2014) designed an integrated biofuel supply chain model using stochastic programming to reduce the total system cost. Meanwhile, Azadeh et al. (2014), Kazemzadeh and Hu (2013), and Awudu and Zhang (2013) developed a stochastic programming-based biofuel supply chain model to increase profits.

The growing demand for green energy is driving the development of biofuels such as HVO as a cleaner alternative to fossil fuels. However, the production and distribution of HVO faces several challenges, including sustainable feedstock availability, production process efficiency, and distribution optimization to keep costs low and supply stable. In addition, increasingly stringent government regulations to reduce carbon emissions require the energy industry to develop a more efficient and competitive supply chain system. Based on these problems, this research is designed to create and analyze a supply chain optimization model. The supply chain optimization model is an important solution to ensure that the entire process from raw material procurement, production, and distribution to end users can run optimally by minimizing cost, time, and environmental impact. Therefore, this research becomes essential in supporting a sustainable green energy transition.

1.1. Objectives
This study aims to minimize total supply chain costs, including production, transportation, storage, and distribution costs, while ensuring the sustainability of feedstock supply and compliance with environmental regulations. This optimization model takes into account various variables such as the availability of vegetable raw materials, the production capacity of HVO refineries, market demand, and logistical constraints. This approach is expected to provide an optimal supply chain configuration to improve the sustainability of the HVO industry.

2. Literature Review
HVO is a renewable diesel fuel produced from various vegetable oils and fats containing triglycerides and fatty acids (ETIP, 2020). The term HVO is used for renewable diesel fuels derived from the hydrogenation and cracking of hydrocarbons from various feedstocks such as tall oil, rapeseed oil, used cooking oil, and animal fats. HVO is also called Hydroprocessed Esters and Fatty Acids (HEFA). Overall, HVO has similar chemical properties to fossil diesel. Some differences are that it has a lower density and energy content than fossil diesel. HVO is free of sulfur, oxygen, and aromatic hydrocarbons and has a high cetane number. HVO production uses hydrogen as a catalyst at high temperatures and pressures. Using this process, the HVO product is called a drop-in fuel because it can replace conventional fuels without modifying engines, fuel systems, and distribution networks. On the other hand, HVO fuel has the same H and C ratio characteristics as conventional diesel fuel. Potential biofuel production pathways in Indonesia include several types of technologies, feedstocks, fuel outputs, and blending rates.

The biofuel supply chain consists of a network of feedstock (biomass) producers, biorefineries, storage facilities, blending stations, and end users. Biofuels have recently received much attention as an alternative energy source and a complement to fossil fuels (Awudu and Zhang, 2012). To realize this vision, a robust supply chain is required to ensure the distribution of competitive biofuels to end-user markets. In general, a supply chain consists of a network that includes suppliers, producers, and end users. There are three main types of decisions in supply chain management: strategic, tactical, and operational (Awudu and Zhang, 2012). Strategic decisions in biodiesel supply chain management include determining the number of locations, the capacity of facilities (such as the initial processing plant, biorefinery, distribution center, and storage), and the production technology used in the biorefinery (Singh et al., 2023). In recent decades, biofuels have become an increasingly popular energy alternative as a solution to reduce dependence on fossil fuels and mitigate environmental impacts. However, biofuel supply chains face complex challenges, mainly related to uncertainties in various aspects such as feedstock availability, market prices, government regulations, and environmental factors. Modeling uncertainty in the biofuel supply chain is critical to understanding and managing the risks that can affect the viability and efficiency of the industry. With the right modeling approach, companies and policymakers can develop strategies that are more adaptive and robust to the variability that occurs throughout the supply chain, from feedstock production to final product distribution.

Uncertainty in the biofuel supply chain makes it an important factor that must be taken into account in the decision-making process. Therefore, it is necessary to further explore solution methods that can overcome this uncertainty. Uncertainty will affect supply chain performance and should be factored into many decisions. Major uncertainties in the biofuel supply chain include, but are not limited to: (1) feedstock supply uncertainty, (2) transportation and logistics uncertainty, (3) production and operations uncertainty, (4) demand and price uncertainty, and (5) other uncertainties (Awudu and Zhang, 2012).

In some studies, mathematical model approaches were applied. For example, Habib et al. (2020) proposed a biodiesel supply chain optimization model based on animal fat waste that minimizes environmental impacts and supply chain costs while maximizing social welfare. The complex and dynamic biodiesel production environment introduces a high degree of uncertainty, which affects the effectiveness of supply chain decisions. Singh, Chauhan, and Sarkar (2023) developed a multi-objective mathematical optimization model for designing a sustainable biodiesel supply chain network from waste animal fat. The proposed model minimizes the biodiesel supply chain cost, furthermore, minimizing the environmental impact while maximizing social impact. Jazi and Sangroudi (2020) discussed the design of a biomass supply chain for biofuel in a multi-period hybrid generation system by considering environmental, economic, and technological aspects. This study aims to optimize the total profit that can be obtained by biofuel producers, taking into account various practical constraints such as biomass availability, plant capacity, storage, greenhouse gas (GHG) emissions, and limited transportation capacity. A major challenge in biodiesel development is the high production cost, which can be reduced by optimally designing the supply chain network. Rezaei et al. (2020) proposed a scenario-based robust optimization model for designing biodiesel supply chain networks under uncertainty.

3. Model Development

This study focuses on developing optimal supply chain strategies for producing, distributing, and using HVO as a renewable fuel.

3.1 System Description

HVO is produced from vegetable oils derived from various sources, including palm oil, soybean oil, used cooking oil, and other vegetable feedstocks. Sustainability of feedstock supply is an important factor in supply chain efficiency. HVO is produced through a hydrogenation process that converts vegetable oil into a more stable diesel fuel with properties similar to fossil fuels. This process requires sophisticated production infrastructure and optimized energy resources to improve conversion efficiency. The design of the HVO supply chain network optimization model is carried out through the following stages: (1) identification of the activities in the HVO supply chain system; (2) analysis of the characteristics of the HVO supply chain system; and (3) formulation of the supply chain mathematical model. The activities in the HVO supply chain system consist of: (1) RBDPO supplier; (2) raw material storage; (3) HVO production (biorefinery); (4) HVO product storage; (5) end users.

This research develops an HVO supply chain optimization model, based on the model proposed by Habib et al. (2020). The model includes an integrated process from raw material supply to final product distribution. The RBDPO feedstock is obtained from two suppliers and then pretreated to improve its purity before further processing. Next, the feed is transferred to biorefineries to undergo treatment reactions, including desulfurization, denitrogenation, and deoxygenation, to produce HVO. The HVO product is then stored in product warehouses and distributed according to customer demand. This study optimized the entire process, and operating costs were analyzed over three periods to determine overall cost efficiency. An illustration of the HVO supply chain system is shown in Figure 1.

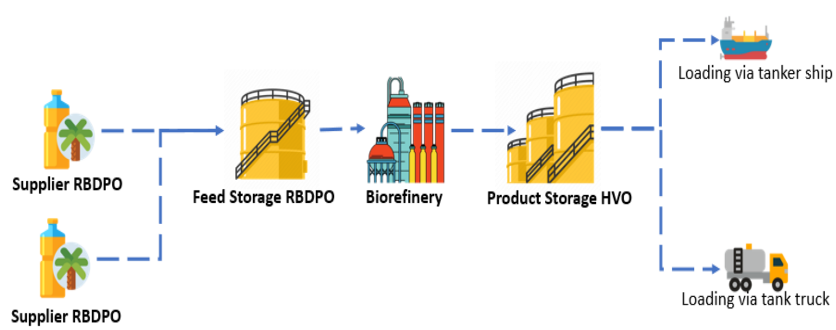

Figure 1. HVO supply chain system

In this study, the supply chain model developed is a closed system, which means that it is not influenced by external factors such as government policies or transportation constraints. Based on real conditions, the characteristics of this system are time-dependent and uncertain. However, the developed model is static, so it does not consider the time factor. In addition, the model is also deterministic, which means it is formulated assuming exact conditions, using data such as biorefinery production capacity and HVO demand levels.

3.2 Notation and Assumptions

The decision variable in this study is the HVO product produced as the primary product for further distribution to meet customer demand. The assumptions used in this study are as follows: (1) the model developed is deterministic; (2) the HVO referred to in this study is the production of green diesel from RBDPO feedstock (palm oil that has been cleaned of impurities).

The HVO supply chain optimization model was designed to minimize the total supply chain cost, which consists of raw material purchase cost, total handling cost, total order cost, total inventory storage cost, total production cost, and total transportation cost between processing facilities.

Notation:

s	Supplier index
f	Feedstock storage index
o	Biorefinery index
p	Product storage index
d	Biofuel demand zone index
t	Planning period index
FPC_{st}	Cost of purchasing feedstock from supplier s in period t ($/liter)
$HPPC_{ft}$	Feedstock handling cost at feedstock storage f in period t ($/liter)
OC_s	Feedstock order cost at supplier s ($)
IHF_{ft}	Feedstock inventory storage cost at feedstock storage f in period t ($/liter)
IHB_{ot}	Biofuel inventory storage cost at biorefinery o in period t ($/liter)
IHD_{pt}	Cost of storing biofuel inventory at product storage p in period t ($/liter)
$CPPC_{ft}$	Feedstock production cost at feedstock storage f in period t ($/liter)
CBP_{ot}	Feedstock production cost at biorefinery o in period t ($/liter)
CCT_{sft}	Feedstock transportation cost from supplier s to feedstock storage f in period t ($/liter)
COT_{fot}	Biofuel transportation cost from feedstock storage f to biorefinery o in period t ($/liter)
CBO_{opt}	Biofuel transportation cost from biorefinery o to product storage p in period t ($/liter)
$CBDT_{pdt}$	Biofuel transportation cost from product storage p to demand zone d in period t ($/liter)
$DBdt$	Biofuel demand in demand zone d in period t (liters)
QFS_{st}	Amount of feedstock available at supplier s in period t (liters)
$CapF_f$	Maximum feedstock storage capacity f (liters)
$CapO_o$	Biorefinery production capacity o (liters)
$CapP_p$	Product storage capacity p (liters)
Qs	Proportion of feedstock from supplier s
η	Conversion factor of RBDPO feedstock converted to HVO
IF_{ft}	Feedstock inventory in feedstock storage f in period t (liters)
IB_{ot}	Biofuel inventory at biorefinery o in period t (liters)
ID_{pt}	Biofuel inventory in product storage p in period t (liters)
QFF_{sft}	Amount of feedstock delivered from supplier s to feedstock storage f during period t (liters)
QFO_{fot}	The amount of feedstock delivered from feedstock storage f to biorefinery o during period t (liters)
FOT_{ft}	Amount of feedstock produced at feedstock storage f in period t (liters)
VBO_{ot}	Volume of HVO produced at biorefinery o in period t (liters)
VBP_{opt}	Volume of biofuel delivered from biorefinery o to product storage p in period t (liters)
VBD_{pdt}	Volume of biofuel delivered from product storage p to demand zone d during period t (liters)
$U_f = \begin{cases} 0 \\ 1 \end{cases}$	1 if feedstock storage f; 0 otherwise
$X_o = \begin{cases} 0 \\ 1 \end{cases}$	1 if biorefinery o; 0 otherwise

$Y_p = \begin{cases} 0 \\ 1 \end{cases}$ 1 if product storage p; 0 otherwise

The primary goal of the mathematical model for the HVO supply chain is to minimize the overall costs associated with the entire supply chain process. This objective can be expressed in a formalized manner. Below are the specific components and considerations that contribute to the formulation of this objective function:

Feedstock purchase, handling, and ordering costs:

$$Z1 = \sum_{s}^{S}\sum_{f}^{F}\sum_{t}^{T} FPC_{st}QFF_{sft} + \sum_{s}^{S}\sum_{f}^{F}\sum_{t}^{T} HPPC_{ft}\,QFF_{sft} + \sum_{s}^{S}\sum_{t}^{T} OC_{s}L_{st} \tag{1}$$

Inventory cost:

$$Z2 = \sum_{f}^{F}\sum_{t}^{T} IHF_{ft}IF_{ft} + \sum_{o}^{O}\sum_{t}^{T} IHB_{ot}IB_{ot} + \sum_{p}^{P}\sum_{t}^{T} IHD_{pt}ID_{pt} \tag{2}$$

Production costs:

$$Z3 = \sum_{f}^{F}\sum_{t}^{T} CPPC_{ft}FOT_{ft} + \sum_{0}^{O}\sum_{t}^{T} CBP_{ot}VBO_{ot} \tag{3}$$

Transportation costs:

$$Z4 = \sum_{s}^{S}\sum_{f}^{F}\sum_{t}^{T} CCT_{sft}\,QFF_{sft} + \sum_{f}^{F}\sum_{o}^{O}\sum_{t}^{T} COT_{fot}\,QFO_{fot}$$

$$+ \sum_{o}^{O}\sum_{p}^{P}\sum_{t}^{T} CBO_{opt}\,VBP_{opt} \sum_{p}^{P}\sum_{D}^{D}\sum_{t}^{T} CBDT_{pdt}\,VBD_{pdt} \tag{4}$$

The constraints in this model are:

1. The amount of raw material sent to the warehouse is less than the available inventory at the supplier in each period.

$$\sum_{f}^{F} QFF_{sft} \leq QFS_{st} \qquad \forall_{s,t} \tag{5}$$

2. The ratio of raw materials from the supplier to the warehouse according to the production in the warehouse in period t.

$$\sum_{s}^{S} Q_{s}QFF_{sft} = FOT_{ft} \qquad \forall_{f,t} \tag{6}$$

3. Allocation constraints for the purchase of raw materials show the order to the supplier in each period.

$$\sum_{f}^{F} QFF_{sft} \leq BM\,L_{st} \qquad \forall_{s,t} \tag{7}$$

4. The feedstock deliveries to the biorefinery do not exceed production in storage in period t.

$$\sum_{o}^{O} QFO_{fot} \leq FOT_{ft} \qquad \forall_{f,t|t=1} \tag{8}$$

$$\sum_{o}^{O} QFO_{fot} \leq FOT_{ft} + IF_{f,t-1} \qquad \forall_{f,t|t>1} \tag{9}$$

5. Initial stock of feedstock equals production minus deliveries to the biorefinery in period t.

$$IF_{ft} = FOT_{ft} - \sum_{o}^{O} QFO_{fot} \qquad \forall_{f,t|t=1} \tag{10}$$

6. Feedstock stock balance constraint in storage for the second period onwards.

$$IF_{ft} = IF_{f,t-1} + FOT_{ft} - \sum_{o}^{O} QFO_{fot} \quad \forall_{f,t|t\geq 2} \tag{11}$$

7. The RBDPO to HVO conversion factor determines the total biofuel produced by the biorefinery in period t.

$$\eta \sum_{f}^{F} QFO_{fot} = VBO_{ot} \qquad \forall_{o,t} \tag{12}$$

8. Constraints on biofuel supply balance in biorefineries:

$$IB_{ot} = VBO_{ot} - \sum_{p}^{P} VBP_{opt} \qquad \forall_{o,t|t=1} \tag{13}$$

$$IB_{ot} = IB_{ot-1} + VBO_{ot} - \sum_{p}^{P} VBP_{opt} \qquad \forall_{o,t|t\geq 2} \tag{14}$$

9. Biofuel deliveries to storage do not exceed production at the biorefinery in period t.

$$VBO_{ot} \geq \sum_{o}^{O} VBP_{opt} \qquad \forall_{o,t|t=1} \tag{15}$$

$$VBO_{ot} + IB_{ot-1} \geq \sum_{o}^{O} VBP_{opt} \qquad \forall_{o,t|t>1} \tag{16}$$

10. Constraints on biofuel inventory in product storage:

$$ID_{pt} = \sum_{o}^{O} VBP_{opt} - \sum_{d}^{D} VBD_{pdt} \qquad \forall_{p,t|t=1} \tag{17}$$

$$ID_{pt} = ID_{p,t-1} + \sum_{o}^{O} VBP_{opt} - \sum_{d}^{D} VBD_{pdt} \qquad \forall_{p,t|t\geq 2} \tag{18}$$

11. Each period, biofuel deliveries to storage must exceed distributions to demand points.

$$\sum_{o}^{O} VBP_{opt} \geq \sum_{d}^{D} VBD_{pdt} \qquad \forall_{p,t|t=1} \tag{19}$$

$$\sum_{o}^{O} VBP_{opt} + ID_{pt-1} \geq \sum_{d}^{D} VBD_{pdt} \quad \forall_{p,t|t>1} \tag{20}$$

12. Biofuel deliveries to demand areas exceed their needs each period.

$$\sum_{p}^{P} VBD_{pdt} \geq DB_{dt} \quad \forall_{d,t} \tag{21}$$

13. Feedstock capacity constraints in storage, biorefinery and product storage.

$$FOT_{ft} \leq CapF_f \quad \forall_{f,t} \tag{22}$$
$$IB_{ot} \leq CapO_o \quad \forall_{o,t} \tag{23}$$
$$ID_{pt} \leq CapP_p \quad \forall_{p,t} \tag{24}$$

14. Constraints to ensure that all types of decision variables are non-negative.

Continues decision variable ≥ 0 (25)

15. Binary and non-negative.

$$u_f x_o y_p \quad \in \begin{cases} 0 \\ 1 \end{cases} \quad \forall_{f,o,p} \tag{26}$$

4. Results and Discussion

The model was implemented by inputting the necessary data. The solution was developed using LINGO 18.0 software to minimize the total cost of the supply chain. The data utilized in this study were gathered through direct observation and secondary sources from prior research related to the biofuel supply chain (Table 1).

Table 1. Data Source

Parameters	Data
FPC_{st}	[0.4;0.9] $/litres
$HPPC_{ft}$	[0.01;0.02] $/litres
OC_s	[50;1000] $
IHF_{ft}	0.006 $/litres
IHB_{ot}	0.008 $/litres
IHD_{pt}	0.008 $/ litres
$CPPC_{ft}$	0.4 $/ litres
CBP_{ot}	0.5 $/ litres
CCT_{sft}	0.01 $/ litres
COT_{fot}	0.005 $/ litres
CBO_{opt}	0.01 $/ litres
$CBDT_{pdt}$	0.005 $/ litres
DB_{dt}	[1.800; 2.100] litres
QFS_{st}	15.000 litres
$CapF_f$	400.000 litres
$CapO_o$	1.000.000 litres
$CapP_p$	1.000.000 litres
Q_s	0.9
η	[0.8;0.9]

The model testing achieved a global optimum value of \$55,982.30, with a cost component value of Z1 at \$12,754.94, Z2 at \$928.6, Z3 at \$35,605.56, and Z4 at \$4643.210. Additionally, the optimum values for several decision variables were obtained. Figure 2 illustrates the search for the optimal solution, which involved 476 iterations during the process.

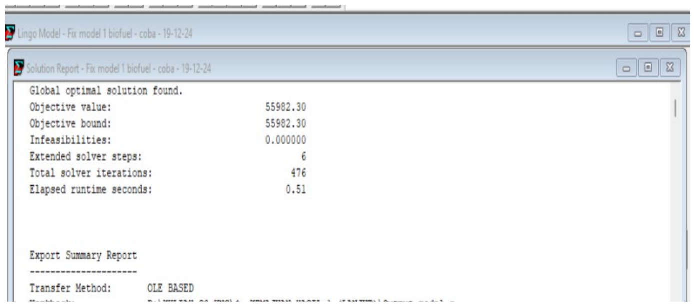

Figure 2. Optimal solution search results

The model developed in this study includes various decision variables to optimize operations in the HVO supply chain. The decision variables in the development of this model are:

a. The quantity of feedstock generated in the feedstock storage, referred to as FOT_{ft}, represents the total amount of raw material processed within the storage facility. This metric is a key indicator of the efficiency and effectiveness of the raw material processing operations. The optimized value for this decision variable, which reflects the ideal outcomes of processing activities, is detailed in Table 2.

Table 2. Amount of feedstock produced in feedstock storage (litres)

Feeds storage	**Period**		
	1	**2**	**3**
1	14,000	13,388.88889	0
2	0	0	0

This data shows a pattern of declining production until it stopped in period 3, with only one feed storage active. Further evaluation is required to determine the root cause of this trend and the strategic path forward.

b. The volume of HVO Produced at the Biorefinery (VBO_{ot}): This metric represents the total quantity of Hydrotreated Vegetable Oil (HVO) generated at the biorefinery. It is a key indicator of the facility's production capacity and the efficiency of converting Refined Bleached Deodorized Palm Oil (RBDPO) into HVO. The ideal values derived from this decision variable are detailed in Table 3, showcasing the optimal levels of production achieved.

Table 3. Volume of HVO produced in biorefinery (litres)

Biorefinery	**Period**		
	1	**2**	**3**
1	6300	5600	0
2	6300	0	6450
3	0	0	0

Hydrotreated Vegetable Oil (HVO) production across various biorefineries exhibits notable fluctuations over time. Biorefinery 1 experienced a steady decline in production levels, ultimately halting operations entirely by period 3. In contrast, Biorefinery 2 had previously been inactive but successfully resumed production in the same period, highlighting a more adaptable operational capacity. Meanwhile, Biorefinery 3 remained completely dormant throughout the entire timeframe, contributing nothing to HVO production.

5. Conclusions and Future Research

The supply chain optimization model for hydrogenated vegetable oil (HVO) products is crafted to enhance the efficiency of both biofuel production and distribution processes. This model meticulously examines a variety of crucial variables, including the availability of raw materials, production capacity, logistics costs, and fluctuations in market demand. By implementing a well-structured optimization framework, companies can minimize production costs, reduce environmental impacts, and promote sustainability throughout the HVO supply chain. This study demonstrates that a targeted optimization strategy can provide more effective solutions for resource management, ultimately strengthening the competitive position of the biofuel industry. Future research could explore the application of multi-objective optimization models, allowing stakeholders to simultaneously balance production costs, distribution logistics, and environmental sustainability. Embracing this comprehensive approach is expected to enhance the appeal of HVO products as environmentally friendly and cost-effective biofuels, thereby improving their market viability in the long term.

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