Journal of Economics AND MANAGEMENT SCIENTIES
https://jems.ink
ISSN 2655-1934 (print), 2655-6685 (online)

Particle Board Supply Chain Design from Palm Oil Solid Waste in West Borneo Province

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ARTICLE HISTORY

Received: 20 December 25
Final Revision: 19 January 26
Accepted: 25 January 26
Online Publication: 31 March 26

KEYWORDS

Supply Chain Network Design, Particleboard, Oil Palm Empty Fruit Bunches (OPEFB), Supply Chain Network, Mixed-Integer Linear Programming (MILP)

A B S T R A C T

As the furniture industry develops, demand for wood-based particle board continues to increase, while the availability of wood from natural forests continues to decline. This situation has led to the need for sustainable alternative raw materials. Solid waste from oil palm in the form of empty fruit bunches (EFB) has great potential to be developed as a raw material for particle board. In West Kalimantan Province, the area of oil palm plantations reached 2,017,456 hectares in 2019, with a potential EFB production of around 7,470,639 tons. Therefore, this study aims to design an optimal supply chain network for the distribution of TKKS from palm oil processing plants in Sanggau Regency to particle board factories, as well as its distribution to all regencies/cities in West Kalimantan. The model developed uses a mixed-integer linear programming (MILP) approach to minimize total costs, including the costs of opening production sites, transportation, and distribution, while taking into account various constraints. The modeling results show that the optimal location for establishing a particle board factory is in Parindu District with a maximum capacity of 120,000 m³/year and a total investment of IDR 82,604,211,380.00. This model is expected to serve as the basis for long-term strategic decision-making for the West Kalimantan Provincial Government and be further developed by integrating TKKS as a by-product of the palm oil industry.

KATA KUNCI

Desain Rantai Pasok, Papan Partikel, Tandan Buah Kelapa Sawit Kosong (TKKS), Jaringan Rantai Pasok, *Mixed-Integer Linear Programming* (MILP)

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DOI

10.37034/jems.v8i2.335

A B S T R A K

Seiring perkembangan industri furnitur, permintaan papan partikel berbahan dasar kayu terus meningkat, sementara ketersediaan kayu dari hutan alam semakin menurun. Kondisi ini mendorong perlunya bahan baku alternatif yang berkelanjutan. Limbah padat kelapa sawit berupa tandan buah kosong kelapa sawit (TKKS) memiliki potensi besar untuk dikembangkan sebagai bahan baku papan partikel. Di Provinsi Kalimantan Barat, luas lahan kelapa sawit hingga tahun 2019 mencapai 2.017.456 Ha dengan potensi produksi TKKS sekitar 7.470.639 ton. Oleh karena itu, penelitian ini bertujuan merancang jaringan rantai pasok optimal untuk penyaluran TKKS dari pabrik pengolahan kelapa sawit di Kabupaten Sanggau ke pabrik papan partikel, serta pendistribusiannya ke seluruh kabupaten/kota di Kalimantan Barat. Model yang dikembangkan menggunakan pendekatan *mixed-integer linear programming* (MILP) untuk meminimalkan total biaya, meliputi biaya pembukaan lokasi produksi, transportasi, dan distribusi, dengan mempertimbangkan berbagai kendala. Hasil pemodelan menunjukkan bahwa lokasi optimal pendirian pabrik papan partikel berada di Kecamatan Parindu dengan kapasitas maksimum 120.000 m³/tahun dan total investasi sebesar Rp82.604.211.380,00. Model ini diharapkan dapat menjadi dasar pengambilan keputusan strategis jangka panjang bagi Pemerintah Provinsi Kalimantan Barat serta dikembangkan lebih lanjut dengan mengintegrasikan TKKS sebagai produk samping industri minyak kelapa sawit.

1. Introduction

Along with the development of the furniture industry, the demand for wood-based particleboard continues to increase. Unfortunately, the availability of timber from natural forests in Indonesia as industrial raw material has been declining. Meanwhile, population growth, changes in lifestyle, and improvements in living standards have driven an increase in furniture consumption. Therefore, it is necessary to explore alternative raw materials with the potential to replace wood-based products for industrial applications, particularly biomass-based materials whose physicochemical and functional properties can be improved through appropriate processing treatments [1].

One potential raw material for particleboard production is lignocellulosic waste from the palm oil industry, particularly oil palm empty fruit bunches (OPEFB). In efforts toward sustainable development, agro-industrial waste should be prioritized as raw material for composite materials to support environmentally friendly and high-productivity development [2].

Oil palm is one of the plantation commodities that plays an important role in Indonesia's economy. As of 2022, Indonesia was the world's largest producer of palm oil. Together with Malaysia, Indonesia accounts for approximately 85% of global palm oil production [3]. Based on a report by the Indonesian Palm Oil Association (GAPKI), crude palm oil (CPO) production reached 3,297 thousand tons by June 2022 [4].

Waste generated from palm oil processing mills consists of solid waste and liquid waste. This waste must be managed properly and promptly because poor waste management not only has negative environmental impacts but can also adversely affect palm oil processing companies themselves [5]. Oil palm empty fruit bunches (OPEFB) are one type of lignocellulosic material that has significant potential as an alternative main raw material to substitute wood-based resources. Lignocellulosic materials, which consist of cellulose, hemicellulose, and lignin, can be classified as natural, non-toxic materials that are abundantly available, sustainable, and renewable, originating from both woody and non-woody plants [6]. In addition, oil palm empty fruit bunches (OPEFB) are considered one of the most cost-effective natural fibers with good quality [7]. One hectare of oil palm plantation land has the potential to produce 16.1 tons of fresh fruit bunches and generate palm oil waste in the form of fronds, trunks, empty fruit bunches, fibers, and shells, amounting to 13.2 tons, 1.4 tons, 3.7 tons, 1.9 tons, and 1.6 tons, respectively [8]. This data is consistent with statistical reports on the Indonesian palm oil industry.

The palm oil industry in West Kalimantan is one of the fastest-growing industries and is expected to remain a priority sector within the plantation industry in the future. Based on statistical data, oil palm plantations in West Kalimantan covered an area of 2,017,456 hectares as of 2019. This extensive plantation area supports the rapid growth of palm oil processing activities in the region, which consequently leads to increasing volumes of palm oil by-products and associated environmental burdens if not managed efficiently, as highlighted in life cycle assessment studies of particleboard and biomass-based industries [9].

As of August 2022, there were 130 palm oil processing mills operating across 12 regencies and cities in West Kalimantan Province. These mills have a total installed capacity of 6,305 tons of fresh fruit bunches (FFB) per hour, with an actual utilized capacity of 5,195 tons of FFB per hour, equivalent to 82.39% of the installed capacity [10]. The high level of capacity utilization reflects the significant scale of palm oil processing activities, which consequently generate a substantial volume of by-products, including oil palm empty fruit bunches (OPEFB) [10]. In large-scale processing systems, such high utilization levels require integrated planning of production and material flows to ensure that by-products are efficiently managed and allocated within the supply chain, as emphasized in supply chain production and transport planning models [11].

At present, oil palm empty fruit bunches (OPEFB) have been utilized mainly as mulch, organic fertilizer, and animal feed. However, these utilization methods face several constraints, including the requirement for large land areas and relatively long processing times. Consequently, the abundant availability of OPEFB in Indonesia has not yet been optimally utilized, particularly as raw material for particleboard production. The utilization of OPEFB for particleboard manufacturing offers a promising alternative to wood-based materials. By producing particleboard from OPEFB, the demand for timber can be reduced, thereby decreasing the number of trees harvested for furniture production. Excessive tree harvesting may lead to the extinction of animal and plant species and can degrade soil quality [12]. Therefore, the use of OPEFB as an alternative raw material not only addresses waste management issues but also contributes to environmental sustainability.

In this study, the design of the particleboard supply chain is developed in West Kalimantan. The raw material used in this research is oil palm empty fruit bunches (OPEFB), which are entirely sourced from palm oil processing mills located in Sanggau Regency. A mixed-integer linear programming (MILP) model is developed to construct an optimal network for the particleboard industry.

The objective of the proposed model is to minimize total supply chain costs, including production costs, transportation costs, and distribution costs, subject to various constraints, including the number of manufacturing facilities to be established. Specifically, this study aims to determine the optimal number and locations of production centers and distribution centers, as well as to identify the most efficient transportation modes within the supply chain network.

2. Research Method

2.1. Model Development

In general, a supply chain can be defined as a set of companies that are directly connected through one or more upstream and downstream flows, including products, services, financial resources, and information, from suppliers to customers [13]. All elements within the distribution network must be well integrated and collaborate effectively as members of a supply chain network to ensure that customer demand is fulfilled efficiently and effectively [14]. An effective collaboration strategy provides opportunities for cost reduction, improvement in customer service, and the achievement of competitive advantages for all members of the supply chain [15].

To enhance supply chain performance, all elements within the distribution network must be well integrated and collaborate effectively as members of a supply chain network, enabling customer demand to be fulfilled efficiently and effectively. Furthermore, an efficient supply chain network can minimize operational costs across the entire supply chain and respond quickly to customer demand. Therefore, designing an optimal supply chain network can address problems involving several strategic decisions, such as determining the number, location, and capacity of facilities required to meet customer demand in an efficient and timely manner [16].

The design of the optimization model for the particleboard supply chain network using oil palm empty fruit bunches (OPEFB) is carried out through several stages. These stages include identifying the activities within the particleboard supply chain system, analyzing the characteristics of the particleboard supply chain, and formulating the mathematical model of the supply chain network. An overview of the particleboard supply chain system based on OPEFB in West Kalimantan is presented in Figure 1.

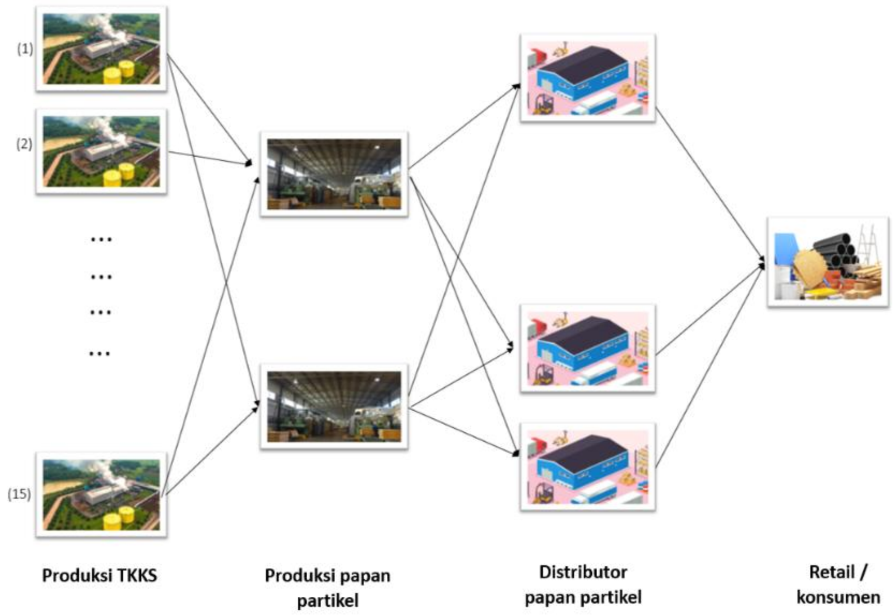

Figure 1. Overview of the Particleboard Supply Chain System Based on Oil Palm Empty Fruit Bunches (OPEFB) in West Kalimantan

Harvested oil palm plantations produce fresh fruit bunches (FFB), which are transported to palm oil mills (POM) for processing into crude palm oil (CPO). In addition to producing CPO, palm oil mills also generate solid waste in the form of palm oil by-products, including shells, fibers, and oil palm empty fruit bunches (OPEFB). The OPEFB are then processed into particleboard at the nearest particleboard manufacturing facilities. Subsequently, the particleboard products are transported to distributors located in regencies and cities across West Kalimantan and finally distributed to end consumers.

The optimization of the supply chain network design is addressed using a facility location and capacity planning approach. The development of the supply chain network design model is conducted across several levels, including suppliers, manufacturing facilities, distributors, and consumers. The optimization model for the particleboard supply chain based on oil palm empty fruit bunches (OPEFB) in West Kalimantan is conceptual in nature and focuses on the network design stage. A mix, the objective function of the proposed model is to minimize the total supply chain cost, which includes investment costs, transportation costs, and operational costs.

The decision-making level addressed in this study is strategic decision-making. Strategic decisions are long-term in nature because they have lasting effects on company performance and focus on facility location, allocation among facilities, and transportation modeling [17]. The data used in this study are secondary data related to the supply chain of solid waste from the palm oil industry. The problem-solving approach employs mathematical programming methods. The formulation of the supply chain network design problem is developed using a Mixed Integer Linear Programming (MILP) model and is solved using LINGO 13 software. Supply chain design problems in biomass-based industries commonly involve long-term strategic decisions such as facility location, capacity planning, and material allocation. A comprehensive review shows that mixed-integer linear programming (MILP) is the most widely used approach to address these decision problems in biomass-for-bioenergy supply chains [18].

2.2. Model Formulation

The mathematical formulation of the model developed to address the particleboard supply chain network design problem is presented as follows on Equation (1).

$$\sum_{k=1}^{k} F_k^1 X_k^1 + \sum_{k=1}^{K} X_k^1 + \sum_{k=1}^{K} F_k^2 X_k^2 + \sum_{k=1}^{k} O_k^1 X_k^1 + \sum_{k=1}^{k} O_k^2 X_k^2 + \sum_{j=1}^{J} \sum_{k=1}^{k} \alpha_{jk}^1 C_{jk}^1 R_{jk} + \sum_{j=1}^{J} \sum_{k=1}^{k} A_{jk}^1 C_{jk}^1 R_{jk} + \sum_{k=1}^{K} \sum_{l=1}^{L} \alpha_{kl}^2 C_{kl}^1 R_{kl}^2 + \sum_{k=1}^{K} \sum_{l=1}^{L} A_{kl}^2 C_{kl}^2 R_{kl} \quad (1)$$

Where:

$\forall J, j =$
1. PT. Agrina Sawit Perdana
2. PTPN XIII Kembayan
3. PT. Tayan Bukit Sawit
4. PT. Bintang Harapan Desa
5. PTPN XIII Kebun Gunung Meliau
6. PTPN XIII Kebun Rimba Belian
7. PT. Multi Prima Entakai
8. PT. Citra Nusa Inti Sawit
9. PT. Mitra Karya Sentosa
10. PT. Sime Darby Plantation Indo Agro
11. PT. Mitra Austral Sejahtera
12. PIRSUS I Parindu
13. PT. Global Kalimantan Makmur
14. PT. Sepanjang Inti Surya Utama
15. PT Sinar Tayan Inti Mulya
16. PT. Surya Borneo Indah
17. PT. Saban Sawit Subur
18. PT. Agro Palindo Sakti
19. PT. Kebun Ganda Prima
20. PT. Sasmita Bumi Wijaya
21. PT. Sumatera Jaya Agro Lestari

$\forall K, k =$
1. PT. Agrina Sawit Perdana
2. PTPN XIII Kembayan
3. PT. Tayan Bukit Sawit
4. PT. Bintang Harapan Desa
5. PTPN XIII Kebun Gunung Meliau
6. PTPN XIII Kebun Rimba Belian
7. PT. Multi Prima Entakai
8. PT. Citra Nusa Inti Sawit
9. PT. Mitra Karya Sentosa
10. PT. Sime Darby Plantation Indo Agro
11. PT. Mitra Austral Sejahtera
12. PIRSUS I Parindu
13. PT. Global Kalimantan Makm
14. PT. Sepanjang Inti Surya Utama
15. PT Sinar Tayan Inti Mulya
16. PT. Surya Borneo Indah
17. PT. Saban Sawit Subu
18. PT. Agro Palindo Sakt
19. PT. Kebun Ganda Prim
20. PT. Sasmita Bumi Wijay
21. PT. Sumatera Jaya Agro Lestar

$\forall L, l =$
1. Distributor in Sanggau Regency
2. Distributor in Landak Regency
3. Distributor in Sintang Regency
4. Distributor in Pontianak City
5. Distributor in Kubu Raya Regency
6. Distributor in Melawi Regency
7. Distributor in Bengkayang Regency
8. Distributor in Mempawah Regency
9. Distributor in Ketapang Regency
10. Distributor in North Kayong Regency
11. Distributor in Kapuas Hulu Regency
12. Distributor in Sambas Regency
13. Distributor in Singkawang City
14. Distributor in Sekadau Regency

The objective of the model is to minimize the total supply chain cost, which consists of investment costs, operational costs, and transportation costs from crude palm oil (CPO) processing mills to particleboard manufacturing facilities and subsequently to distributors. The constraints of the model are as follows:

a. Constraint for determining the particleboard manufacturing facilities to be established can be seen on Equation (2).

$$\sum_{k=1}^{k} X_k^1 + \sum_{k=1}^{K} X_k^2 \leq 1 \quad (2)$$

$\forall k \in K$

b. OPEFB supply constraint from CPO mills to particleboard plants *(A_j)* can be seen on Equation (3).

$$\sum_{j=1}^{J} \sum_{k=1}^{k} A_{jk}^1 \leq \sum_{j=1}^{J} \sum_{l=1}^{L} A_j \quad (3)$$

$\forall j \in J$, $\forall k \in K$

c. Capacity constraint of particleboard plant 1 *($\boldsymbol{Z_k^1}$)* can be seen on Equation (4).

$$\sum_{j=1}^{J} \sum_{k=1}^{k} a_{jk}^1 \text{ß} \leq \sum_{k=1}^{K} Z_k^1 \text{ (Pabrik 1)} \quad (4)$$

$\forall k \in K$, $\forall l \in L$

d. Demand fulfillment constraint for particleboard products *(d_l)* can be seen on Equation (5).

$$\sum_{l=1}^{L} \sum_{k=1}^{k} A_{kl}^2 \geq \sum_{l=1}^{L} dj \quad (5)$$

$\forall j \in J$, $\forall k \in K$

e. OPEFB allocation is allowed only if the particleboard plant is established, which can be seen on Equation (6).

$$\sum_{j=1}^{J}\sum_{k=1}^{k} a_{jk}^{1}\, ß \leq \sum_{k=1}^{K} X_k^1 \quad (6)$$

$\forall j \in J, \forall k \in K$

f. Non-negativity constraints for all decision variables which can be seen on Equation (7).

$$a_{jk}^{1} \geq 0,\ A_{jk}^{1} \geq 0,\ X_k^1 \geq 0,\ \geq 0 \quad (7)$$

3. Result and Discussion

The data used in this study were obtained from secondary sources derived from previous studies related to the particleboard supply chain based on oil palm empty fruit bunches (OPEFB). The following data are required for the implementation of the proposed model, including:

3.1. CPO Mill Capacity

The data used in this study were obtained from palm oil companies producing crude palm oil (CPO) located in Sanggau Regency. Palm oil mills (POM) serving as suppliers of oil palm empty fruit bunches (OPEFB) were selected based on their proximity. The collected data were then used to calculate the amount of OPEFB generated and its potential utilization for particleboard production with a density of 750 kg/m³ [9]. Based on data processing using the referenced parameters, the estimated quantity of OPEFB generated from CPO production in Sanggau Regency and surrounding areas that can be used as raw material for particleboard manufacturing is obtained.

3.2. Locations and Capacities of Particleboard Manufacturing Facilities

The determination of the particleboard manufacturing facility location was conducted through spatial mapping using Google Maps. Candidate locations for the particleboard plant were integrated with existing palm oil mills. The proposed particleboard manufacturing facility was located close to palm oil mills based on considerations of proximity to the main raw material, namely oil palm empty fruit bunches (OPEFB), as well as the availability of supporting infrastructure such as water supply, electricity, and road access. Furthermore, to identify the optimal location, the center of gravity method was applied. Based on this approach, the selected location for the particleboard manufacturing facility is situated near the palm oil mill operated by PT Sasmita Bumi Wijaya. The determination of the plant capacity was conducted by benchmarking existing particleboard manufacturing facilities located in West Kalimantan. Based on this approach, the proposed capacity of the particleboard plant to be established in Sanggau Regency is 120,000 m³ per year, with an initial investment cost of IDR 57,073,000,000.00. Detailed information on the location and capacity of the particleboard manufacturing facility is presented in Table 1.

Table 1. Estimated OPEFB Supply Data

No	Palm Oil Mill Name	Production Capacity (FFB, tons/hour)	OPEFB Production Capacity (tons/year)	Estimated Particleboard Production Capacity (m³/year)
1	PT. Agrina Sawit Perdana	60	91,904	96,353
2	PTPN XIII Kembayan	45	68,928	72,265
3	PT. Tayan Bukit Sawit	60	91,904	96,353
4	PT. Bintang Harapan Desa	45	68,928	72,265
5	PTPN XIII Kebun Gunung Meliau	60	91,904	96,353
6	PTPN XIII Kebun Rimba Belian	60	91,904	96,353
7	PT. Multi Prima Entakai	30	45,952	48,177
8	PT. Citra Nusa Inti Sawit	30	45,952	48,177
9	PT Mitra Karya Sentosa	30	45,952	48,177
10	PT. Sime Darby Plantation Indo Agro	30	45,952	48,177
11	PT. Mitra Austral Sejahtera	30	45,952	48,177
12	PIRSUS I Parindu	45	68,928	72,265
13	PT. Global Kalimantan Makmur	30	45,952	48,177
14	PT. Sepanjang Inti Surya Utama	30	45,952	48,177
15	PT Sinar Tayan Inti Mulya	30	45,952	48,177
16	PT. Surya Borneo Indah	30	45,952	48,177
17	PT. Saban Sawit Subur	45	68,928	72,265
18	PT. Agro Palindo Sakti	45	68,928	72,265
19	PT. Kebun Ganda Prima	45	68,928	72,265
20	PT. Sasmita Bumi Wijaya	60	91,904	96,353
21	PT. Sumatera Jaya Agro Lestari	45	68,928	72,265

3.3. Transportation Costs, Investment Costs, Operational Costs, and Fixed Costs

The transportation of raw materials in the form of oil palm empty fruit bunches (OPEFB) and the distribution of finished products in the form of particleboard is carried out using Colt Diesel Canter trucks with a nominal capacity of 5.5 tons. However, for the transportation of OPEFB, the effective carrying capacity of the Colt Diesel Canter truck is limited to 4 tons. Transportation costs are calculated based on variable costs, which vary according to the distance traveled per unit of transported goods. The transportation costs for each type of transportation are presented in Table 2 and Table 3.

Tabel 2. Transportation Cost Data

Cost Type	Cost (IDR)/liter	Conversion Value (IDR)/km	Conversion Value (IDR)/ton·km	Remarks
Fuel Cost	6,800	1942.86	485.71	Fuel consumption is 3.5 liters/km. One truck can carry up to 4 tons of OPEFB.

Tabel 3. Investment and Operational Cost Components [19]

Cost Type	Unit	Cost
Material	US $/m^3	92.3
Energy	US $/m^3	14.0
Personnel	US $/m^3	15.5
Depreciation	US $/m^3	6.9
Unit Production Cost	US $/m^3	130.0
Miscellaneous Costs	US $/m^3	11.3
Unit Cost of Particleboard Sold	US $/m^3	140.0
Selling Price	US $/m^3	175.3

3.4. Distance

Distance data between locations are used to determine and calculate transportation costs. The distance data are obtained using Google Maps.

3.5. Demand

Particleboard demand data are used to estimate the market potential for particleboard in West Kalimantan. The demand for particleboard in West Kalimantan is determined based on the consumption of furniture made from composite wood materials, which is estimated at 0.04 m^3 per capita per year [20]. The efficiency range of raw wood material utilization in the wood industry is reported to be between 53% and 65% [21]. In addition, the consumption of composite wood products, such as particleboard and medium-density fiberboard, has shown an increasing trend since 2010 [22]. Based on the above considerations, it is assumed that particleboard demand accounts for 50% of total furniture consumption, which is equivalent to 0.02 m^3 per capita per year.

Based on data from the Central Bureau of Statistics (BPS) of West Kalimantan Province in 2021, the population of West Kalimantan Province was 5,470,797 people distributed across 14 regencies and cities. Accordingly, the total demand for particleboard in West Kalimantan is estimated at 109,416 m^3 per year. Detailed demand figures for each regency/city and the corresponding supplying plants responsible for particleboard distribution are presented in Table 4.

Table 4. Estimated Particleboard Demand in West Kalimantan Province

District/City	Annual Demand (1,000 m^3)
Sambas	12,756
Bengkayang	5,819
Landak	8,022
Mempawah	6,113
Sanggau	9,771
Ketapang	11,599
Sintang	8,473
Kapuas Hulu	5,075
Sekadau	4,258
Melawi	4,625
Kayong Utara	2,571
Kubu Raya	12,303
Kota Pontianak	13,274
Kota Singkawang	4,758
Total	109,416

3.6. Model Solution

Table 5 presents the output of the objective function and the decision variables. The developed model is a location–allocation model for particleboard production based on oil palm empty fruit bunches (OPEFB) in West Kalimantan. The model considers transportation costs from crude palm oil (CPO) mills to particleboard manufacturing facilities, as well as transportation costs from particleboard plants to distributors across all regencies and cities in West Kalimantan. In addition, the model incorporates investment costs and operational costs, which represent the expenditures required to establish and operate particleboard manufacturing facilities. The parameters used in this model, which shown on Table 6, include:

a. Transportation Costs: This parameter represents the transportation costs from CPO mills to particleboard manufacturing facilities and from particleboard plants to distributors across all regencies and cities in West Kalimantan. The transportation cost is directly proportional to the travel distance. This implies that shorter distances between CPO mills and particleboard plants result in lower transportation costs.

b. Demand: This parameter ensures that the quantity of particleboard shipped from particleboard manufacturing facilities to distributors is greater than or at least equal to consumer demand for particleboard in West Kalimantan.

c. Particleboard Plant Capacity: This parameter ensures that the quantity transported from CPO mills to particleboard manufacturing facilities does not exceed the capacity of the particleboard plants. The particleboard plant capacities considered in this study include small-scale and medium-scale manufacturing facilities.

d. Fixed Costs: Fixed costs represent the costs incurred when a particleboard manufacturing facility is established.

e. Operational Costs: Operational cost components include raw material costs, labor costs, energy costs, depreciation, and other related expenses [19]. The magnitude of operational costs is determined based on the capacity of the particleboard manufacturing facilities.

Table 5. Objective Function Output and Decision Variables

No.	Notation	Output	Description
1	Z	Rp82,604,211,381	Total optimal cost of the particleboard supply chain based on oil palm empty fruit bunches (OPEFB).
2	X_{20}^{1}		The particleboard manufacturing facility integrated with the palm oil mill (POM) of PT Sasmita Bumi Wijaya is selected to be established.
3	$A_{17\,20}^{1}$	16,418	The quantity of OPEFB transported from the palm oil mill of PT Saban Sawit Subur to the palm oil mill of PT Sasmita Bumi Wijaya
4	$A_{20\,20}^{1}$	91,904	The quantity of OPEFB (tons) transported from the palm oil mill of PT Sasmita Bumi Wijaya to the particleboard manufacturing facility integrated with the same palm oil mill
5	$A_{20\,j}^{1}$	109,416	The quantity of particleboard (m³/year) transported from the particleboard manufacturing facility integrated with the palm oil mill of PT Sasmita Bumi Wijaya to distributors across all regencies and cities in West Kalimantan Province.

Table 6. Data Sources for Objective Function Output and Decision Variables

Parameter	Data	Description	Reference
$C_{jk}^{(1)}$ dan $C_{kl}^{(2)}$	Rp 485.71/ton.km	Transportation cost of OPEFB shipped from CPO mill (j) to particleboard manufacturing facility (k)	Processed
dl	109,416 m³/year	Annual particleboard demand for consumers (l)	Processed
$F_{k}^{(1)}$	Rp 4,756,083,333/month	Total fixed cost of the particleboard manufacturing facility integrated with the palm oil mill of PT Sasmita Bumi Wijaya	[19]
$O_{k}^{(1)}$	Rp 19,797,548,680.00 Per month	Total operational cost of the particleboard manufacturing facility integrated with the palm oil mill of PT Sasmita Bumi Wijaya (k)	[19]
Aj	Table 1	Availability of OPEFB at CPO mills	
$Z_{k}^{(1)}$	580,800 m³/year	Capacity of the particleboard manufacturing facility integrated with the palm oil mill of PT Sasmita Bumi Wijaya (k)	
J	21	Number of CPO mills in Sanggau Regency, West Kalimantan	
K	21	Number of candidate locations for particleboard manufacturing facilities in Sanggau Regency, West Kalimantan Province	
L	14	Number of distributors in West Kalimantan	All regencies/cities in West Kalimantan
β	1,0484	Conversion factor of OPEFB to particleboard (ton/m³)	
n	21	Number of candidate particleboard manufacturing facility locations	

3.7. Sensitivity Analysis

Sensitivity analysis is conducted to examine the robustness of the optimal solution when changes are applied to model parameters. The sensitivity analysis performed in this study includes the following scenarios:

a. Sensitivity Analysis of Particleboard Demand: Sensitivity analysis was conducted by increasing particleboard demand by ±5% and ±10%. The results indicate that an increase in particleboard demand leads to an increase in the total cost reflected in the decision variables, and vice versa. This finding shows a direct relationship between demand levels and total supply chain costs.

b. Sensitivity Analysis of Transportation Costs: Global oil prices tend to increase annually. Based on projections of fundamental factors affecting global oil prices published by the Energy Information Administration (EIA) of the U.S. Department of Energy, crude oil prices under a normal scenario are projected to increase by approximately 4.1% per year. This increase is expected to raise transportation costs for trucks transporting oil palm empty fruit bunches (OPEFB), due to rising fuel prices. The results of the sensitivity analysis on transportation cost parameters show a positive relationship between increases in transportation costs and total supply chain costs. Higher transportation cost parameters result in higher optimal total supply chain costs.

c. Sensitivity Analysis of Operational Costs: Operational costs in the present period differ from those in the future due to the influence of inflation. Inflation is defined as a continuous and general increase in prices. Therefore, sensitivity analysis was conducted on operational cost parameters within a range of ±5% and ±10%. The results indicate that increases in operational cost parameters lead to higher total biomass supply chain costs. However, these changes do not affect the selected location of the particleboard manufacturing facility.

d. Sensitivity Analysis of Investment Costs: Sensitivity analysis was also performed on investment cost parameters within a range of ±5% and ±10%. The results show a direct relationship between increases in investment costs and total supply chain costs. Higher investment cost parameters result in higher optimal total supply chain costs.

Table 7. Total Cost Sensitivity Analysis

Parameter Change	Impact of Change on Total Cost (%)			
	-10%	-5%	5%	10%
Demand	0.21570	0.22768	0.25165	0.26363
Transportation Costs	0.62183	0.65638	0.72547	0.76001
Operational Costs	0.05182	0.05470	0.06046	0.06333

Based on the sensitivity analysis results presented in Table 7, the transportation cost parameter has the greatest impact compared to the other cost parameters.

4. Conclusion

Based on the results of this study, it can be concluded that the particleboard supply chain network in West Kalimantan can be structured starting from oil palm empty fruit bunches (OPEFB) generated in Sanggau Regency, which are transported to particleboard manufacturing facilities for processing and subsequently distributed to distributors across regencies and cities in West Kalimantan before reaching end consumers. The utilization of OPEFB as raw material for particleboard production can be effectively realized by establishing particleboard manufacturing facilities close to the sources of raw materials. The results of the mixed-integer linear programming (MILP) model indicate that the optimal location for the particleboard manufacturing facility is Parindu District, with an annual production capacity of 109,416 m³ and a total cost of IDR 82,604,211,381.

References

[1] Hamid, N. H., Yazid, M. F., Hassan, N., & Mokhtar, M. A. (2015). The selected properties of hybrid particleboard made from oil palm empty fruit bunch (EFB) and merpauh (Irvingla Malayanan Olive) sawdust wastes. *Asian Journal of Applied Sciences*, *3*(4).

[2] Valle, V., Aguilar, A., Kreiker, J., Raggiotti, B., & Cadena, F. (2022). Oil Palm Empty Fruit Bunch (OPEFB) Fiber-Reinforced Acrylic Thermoplastic Composites: Effect of Salt Fog Aging on Tensile, Spectrophotometric, and Thermogravimetric Properties. *International Journal of Polymer Science*, *2022*. https://doi.org/10.1155/2022/6372264

[3] Maluin, F. N., Hussein, M. Z., & Idris, A. S. (2020). An Overview of the Oil Palm Industry: Challenges and Some Emerging Opportunities for Nanotechnology Development. *Agronomy*, *10*(3), 356. https://doi.org/10.3390/agronomy10030356

[4] Gabungan Pengusaha Kelapa Sawit Indonesia (GAPKI) Cabang Kalimantan Barat. (2025). *GAPKI Kalbar – Gabungan Pengusaha Kelapa Sawit Indonesia (Cabang Kalimantan Barat)*. GAPKI-KALBAR. https://www.gapki-kalbar.or.id/

[5] Sadyadharma, H., Matondang, A. R., Nasution, Z., & Mawengkang, H. (2013). Sustainable Production Planning Model of Crude Palm Oil Industry Under Uncertainty. *Int. J. Eng. Res. andTechnology*, *2*(8), 1100–1105. https://doi.org/10.17577/IJERTV2IS80440

[6] Gan, S., Zakaria, S., Chia, C. H., Padzil, F. N. M., & Ng, P. (2015). Effect of hydrothermal pretreatment on solubility and formation of kenaf cellulose membrane and hydrogel. *Carbohydrate Polymers*, *115*, 62–68. https://doi.org/10.1016/j.carbpol.2014.08.093

[7] Padzil, F. N. M., Lee, S. H., Ainun, Z. M. A., Lee, C. H., & Abdullah, L. C. (2020). Potential of Oil Palm Empty Fruit Bunch Resources in Nanocellulose Hydrogel Production for Versatile Applications: A Review. *Materials*, *13*(5), 1245. https://doi.org/10.3390/ma13051245

[8] Lestari, R. I. (2019). Potensi Suplai Limbah Kelapa Sawit Sebagai Pewarna Alam Kain Sasirangan: Isu Dan Pengembangan. *Journal of Industrial Engineering and Operation Management*, *2*(2). https://doi.org/10.31602/jieom.v2i2.2667

[9] Hussain, A., Umair, M., Khan, S., Alonazi, W. B., Almutairi, S. S., & Malik, A. (2024). Exploring sustainable healthcare: Innovations in health economics, social policy, and management. *Heliyon*, *10*(13), e33186. https://doi.org/10.1016/j.heliyon.2024.e33186

[10] Pemerintah Provinsi Kalimantan Barat. (2022). *Portal Resmi Pemerintah Provinsi Kalimantan Barat*. Kalbarprov.Go.Id. https://kalbarprov.go.id/

[11] Mula, J., Peidro, D., Díaz-Madroñero, M., & Vicens, E. (2010). Mathematical programming models for supply chain production and transport planning. *European Journal of Operational Research*, *204*(3), 377–390. https://doi.org/10.1016/j.ejor.2009.09.008

[12] Doustmohammadi, N., & Babazadeh, R. (2019). Design of Closed Loop Supply Chain of Wood Plastic Composite (WPC) Industry. *Journal of Environmental Informatics*, *35*(2), 94–102. https://doi.org/10.3808/jei.201900419

[13] Hadiguna, R. A., & Tjahjono, B. (2017). A framework for managing sustainable palm oil supply chain operations: A case of Indonesia. *Production Planning & Control*, *28*(13), 1093–1106. https://doi.org/10.1080/09537287.2017.1335900

[14] Chopra, S., & Meindl, P. (2007). *Supply chain management: Strategy, planning, and operation* (3. ed). Pearson/Prentice Hall.

[15] Çelebi, D. (2015). Inventory control in a centralized distribution network using genetic algorithms: A case study. *Computers & Industrial Engineering*, *87*, 532–539. https://doi.org/10.1016/j.cie.2015.05.035

[16] Klibi, W., Martel, A., & Guitouni, A. (2010). The design of robust value-creating supply chain networks: A critical review. *European Journal of Operational Research*, *203*(2), 283–293. https://doi.org/10.1016/j.ejor.2009.06.011

[17] Simchi-Levi, D., Kaminsky, P., & Simchi-Levi, E. (2008). *Designing and Managing the Supply Chain: Concepts, Strategies, and Case Studies* (3rd Editio). Irwin McGraw-Hill.

[18] De Meyer, A., Cattrysse, D., Rasinmäki, J., & Van Orshoven, J. (2014). Methods to optimise the design and management of biomass-for-bioenergy supply chains: A review. *Renewable and Sustainable Energy Reviews*, *31*, 657–670. https://doi.org/10.1016/j.rser.2013.12.036

[19] Grzegorzewska, E., Burawska-Kupniewska, I., & Boruszewski, P. (2020). Economic profitability of particleboards production with a diversified raw material structure. *Maderas. Ciencia y Tecnología*, *22*(4), 537–548. https://doi.org/10.4067/S0718-221X2020005000412

[20] Abdulah, L., Suhendang, E., Purnomo, H., & Matangaran, J. R. (2020). Measuring the sustainability of wood consumption at the household level in Indonesia: Case study in Bogor, Indonesia. *Biodiversitas Journal of Biological Diversity*, *21*(2). https://doi.org/10.13057/biodiv/d210205

[21] Massijaya, M. Y. (2014). *Pengembangan Produk Komposit Untuk Mendukung Industri Pengolahan Kayu Indonesia*. IPB Scientific Orations.

[22] Howard, J. L., & Jones, K. C. (2016). US timber production, trade, consumption, and price statistics, 1965-2013. *FPL-RP-679*, *679*, 1-100. https://doi.org/10.2737/FPL-RP-679