Sugarcane Allocation for Sugar Mills in East Java Province: Spatial Distribution and Transportation Method Approach

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Abstract. East Java is the province with the largest sugar production in Indonesia, supported by a large sugarcane plantation area to meet the needs of sugar mills. However, the latest data shows that there is a gap between the sugarcane supply and demand. This study aims to determine the distribution map of sugarcane against sugar mills demand and the optimal sugarcane allocation for sugar mills in East Java. The spatial distribution of sugarcane production and sugar mills demand was built using QGIS 3.34.4 while the optimization of sugarcane allocation using the transportation method approach was done by using OpenSolver in the Microsoft Excel platform. The results show that there are sugarcane plantations spread across 424 sub-districts and 29 sugar mills. The total demand by sugar mills is larger than the total sugarcane production, with the difference of 4,375,804 tons. Therefore, there are two proposed scenarios. First, finding the optimal solution using dummy. Second, calculating optimal solutions by adjusting the demand of sugar mills proportionally to the difference between demand and sugarcane supply. The first scenario produces a total transportation cost of Rp 747,275,819,472, - with 9 sugar mills getting supplies from the dummy. The second optimization scenario produces a total transportation cost of Rp 842,750,679,416. The managerial implications derived from this study can guide policymakers in making more informed decisions regarding procurement strategies, local supply regulations, and cost management.

1 Introduction

The sugar industry is the oldest manufacturing industry in Indonesia. In 1930, this industry enabled Indonesia to become the second-largest sugar exporter after Cuba. Over time, however, the industry has declined due to reduced productivity and efficiency [1]. The ability to apply appropriate technology is one factor that can influence an industry's performance [2]. According to [3], Indonesia's sugar balance shows that sugar consumption in 2020 reached 2.66 million tons. This figure was higher than the sugar production level at that time, which only reached 2.23 million tons. [4] Noted that the government continues to strive to increase sugar production through the national sugar self-sufficiency program.

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East Java is the province with the highest sugar production in Indonesia. In 2021, sugar production in East Java reached 1.03 million tons, or 44.06% of the total national sugar production [5]. This province has the largest number of sugar mills in Indonesia, accounting for 51.9% of all operating sugar mills in the country [6]. In 2020, 30 sugar mills were operating in East Java, contributing 143,350 Tons Cane Day (TCD) out of the total national milling capacity of 334,980 TCD [3]. East Java also has the largest sugarcane plantation area in Indonesia, covering 219,211 hectares in 2022, an increase of 13.28% from the previous year. [7] Noted that sugarcane production in this province fluctuates annually. According to [8], the sugarcane plantation area is currently decreasing, making the availability of sugarcane for sugar mills increasingly limited. [9] Mentioned that many sugar mills are on the verge of bankruptcy due to insufficient sugarcane supply. Consequently, some sugar mills implement policies to start milling earlier to secure sugarcane supplies from other sugar factory areas. This situation indicates a gap between the amount of sugarcane supply and the raw material demand by sugar mills in East Java. Therefore, optimizing sugarcane allocation for sugar mills in East Java is necessary.

However, existing research on sugarcane allocation mostly focuses on general logistics and conventional transportation models, often overlooking region-specific constraints such as dynamic road infrastructure, supply deficits, and unique cost structures [10,11]. These studies also frequently lack integrated spatial analysis to effectively visualize and handle geographically dispersed plantations. Hence, a critical research gap exists in developing a comprehensive approach that combines geospatial methods with a robust allocation optimization technique.

Optimization involves finding or determining the most effective and efficient variable values to achieve the desired results [10]. In response to the identified gap, this study applies the transportation method within a Geographical Information System (GIS) framework to offer a more holistic solution for sugarcane allocation in East Java. This method is a technique for arranging the distribution of goods from sources to destinations optimally, with minimal costs. Minimum costs can be achieved if resource allocation is carefully managed due to differences in allocation costs from various sources to different destinations [11,12]. The goal of this allocation is to determine the quantity of goods shipped so that the resource distribution process can be more optimal [13]. Nevertheless, the proposed method may be limited by data availability, potential shifts in regional infrastructure, and annual variations in sugarcane yields.

This study aims to determine the distribution of sugarcane relative to the demand of sugar mills in East Java Province. Additionally, the study aims to determine the optimal sugarcane allocation for sugar mills in East Java Province using the transportation method approach.

2 Research Method

This research was conducted at sugar mills in East Java. The research took place from February to July 2024. Data processing and analysis were performed at the Laboratory of Agro-industrial Computing & Systems, Faculty of Agricultural Technology, Universitas Brawijaya. The software used in this research includes: QGIS 3.34.4-Prizren for spatial data processing, Google Maps for determining latitude and longitude coordinates, and Microsoft® Excel® 2021 for data preparation and executing allocation optimization using the transportation method with the OpenSolver add-in.

2.1 Problem scope and assumptions

Scope of this investigation includes:

- This research is limited to the transportation of sugarcane from plantation areas to sugar mills.
- The sugarcane production data utilized is at the sub- district level within East Java Province for the year of 2023, sourced from the East Java Provincial Plantation Office.
- The sugarcane demand by the mills corresponds to their milling capacity during the 2023 milling season, based on data from the East Java Provincial Plantation Office.
- Transportation costs are derived from the average rates found in the 2022 technical freight data provided by the East Java Provincial Plantation Office.
- Transportation costs are adjusted according to the freight rate calculation mechanism employed by the sugar mills, expressed in IDR per Quintal of sugarcane.

Three assumptions need to be incorporated are:

- The locations of the sugarcane plantations and sugar mills are assumed to remain constant throughout the research period.
- The areas of the sugarcane plantations and the milling capacities of the sugar mills are assumed to be stable during the research period.
- It is assumed that all types of trucks can access every road route between the sugarcane plantations and the sugar mills.

2.2 Mathematical formulation

The transportation method for this problem was formulated as follows:

1. **Decision Variables**: the decision variable in this problem is the quantity of sugarcane transported from plantation i to sugar factory j (X_{ij}). The parameter used is the freight rate per Quintal of sugarcane from plantation i to sugar factory $j(Cij)$.
2. **Objective Function**: the objective function aims to minimizes the total cost of sugarcane allocation from plantations to sugar mills. This includes the cost of transporting the sugarcane and the freight rates between each sub-district centroid and the sugar mills. The objective function is defined in Equation (1)

$$\text{Min Z} = \sum_{i=1}^{m}\sum_{j=1}^{n} C_{ij}X_{ij} \qquad (1)$$

Constraints:

a. The first constraint ensures that the amount of sugarcane transported from plantation i to sugar factory j does not exceed the available sugarcane production from each sub-district.

$$\sum_{j=1}^{n} X_{ij} \leq a_i, \qquad (2)$$

b. The second constraint guarantees that the amount of sugarcane transported from plantation i to sugar factory j meets the demand of the sugar factory. This means the factory's sugarcane needs are fully satisfied according to the specified requirements.

$$\sum_{i=1}^{m} X_{ij} = b_j, \qquad (3)$$

c. The third constraint stipulates that the amount of sugarcane transported from each plantation i to sugar factory j must be non-negative, i.e., greater than or equal to zero.

$$X_{ij} \geq 0 \quad \textit{for all } i \textit{ and } j \qquad (4)$$

2.3 Data processing

2.3.1 Construction of spatial distribution maps

The spatial distribution maps were created by layering the prepared data. Sugarcane production data were integrated with sub-district polygon attributes, with polygon colours adjusted to reflect production levels—darker shades indicating higher production volumes. The demand of sugar mills was represented by the size of the location symbols, with larger symbols indicating higher demand.

2.3.2 Optimization of sugarcane allocation using the transportation method

1. Construction of the transportation cost matrix: The cost matrix was derived by converting the distance matrix into sugarcane freight rates in IDR per quintal. The distance matrix was obtained from the Origin- Destination Matrix in QNEAT3, showing distances between sub-districts and sugar mills. Freight rates were calculated as the average of the available freight rate data.
2. Optimal solution was computed by using OpenSolver in Microsoft Excel with two proposed scenarios: (a) Optimization with dummy variables; (b) Optimization with demand adjustment.
3. Creation of the optimal sugarcane allocation map: Based on the optimization results, a map showing the optimal sugarcane allocation was created using QGIS 3.34.4. This map illustrates the supply sources for each sugar factory in East Java Province, depicted by lines connecting the sources to the mills.
4. Calculation of revenue loss costs: Revenue loss costs were calculated based on the unmet sugarcane demand at each sugar factory. The amount of sugarcane shortfall was converted into the equivalent sugar production loss, and the corresponding revenue loss was estimated based on the price of the unproduced sugar.
5. Managerial implications: This section discusses the managerial considerations necessary for implementing the optimized sugarcane allocation results from this research.

3 Result and Discussion

3.1 Overview of sugarcane plantations and the sugar industry in East Java

3.1.1 Sugarcane plantations in East Java

The total sugarcane harvesting area in East Java in 2023 covered 167,000 hectares, yielding 14 million tons of sugarcane. Malang Regency recorded the highest sugarcane production, with 4,016,351 tons harvested from 44,825 hectares. This was followed by Kediri Regency with 2,304,690 tons and Lumajang Regency with 1,159,369.57 tons. The regions with the lowest production were Ponorogo Regency with 723 tons, Bangkalan with 999.9 tons, and Batu City with 1,355 tons.

According to [14], factors such as planting schedules, sugarcane varieties, land type (dry land or paddy fields), fertilizer application, and seedling quality can significantly impact sugarcane productivity. Data from [15] shows that the sugarcane harvest area in East Java has fluctuated over recent years. Between 2021 and 2023, the harvest area increased by 12.98% in 2022, but then decreased by 2.12% in 2023. [16] Predict that the conversion of sugarcane plantation land from 2011 to 2031 could reach 75,737 hectares. Currently, only

223,199 hectares are considered suitable for sugarcane plantations, which poses a threat to the sustainability of sugarcane production in East Java.

3.1.2 Sugar industry in East Java

In 2023, East Java Province hosted 29 sugar mills, managed by six different groups: PT Sinergi Gula Nusantara (SGN), PT PG Candi Baru, PT PG Rajawali I, PG Kebon Agung, PT Kebun Tebu Mas, and PT Rejoso Manis Indo. The East Java Provincial Plantation Office reported a total milling capacity of 18,477,369.69 tons across these mills in 2023. PG Kebon Agung in Malang Regency had the largest milling capacity at 2,172,192 tons, while PG Wringinanom in Situbondo had the smallest, with 148,807.44 tons.

3.2 Sugarcane allocation in sugar mills

3.2.1 Sugarcane allocation (existing condition)

The procurement of sugarcane at sugar mills is typically managed by the Plantation Division. Unlike general goods procurement, the process of sugarcane procurement is influenced by several factors, including land ownership, soil conditions, and the timing of sugarcane planting. The sugarcane supply is sourced from both Company-Owned Sugarcane or *Tebu Sendiri* (TS) and Farmer-Owned Sugarcane or *Tebu Rakyat* (TR). According to [17], TR refers to sugarcane cultivated by farmers on their own land, while TS is grown by sugar mills on leased land. In this study, sugarcane land data from the East Java Provincial Plantation Office is used, without distinguishing between TR and TS.

The group of sugar mills called PT SGN utilizes an information system called E-Farming to support the sugarcane procurement process at each of its sugar mill units. E-Farming is a GIS- and satellite-supported application for land registration and plantation monitoring. All sugarcane plantation plots must be registered with the relevant sugar mill to identify the supply sources. Generally, sugarcane demand exceeds supply, partly due to the addition of new sugar mills as part of efforts toward sugar self-sufficiency. Sugar mills also compete to increase their capacity without expanding sugarcane planting areas. Since farmers are not strictly bound to specific sugar mills, they can choose to send their sugarcane to mills that offer more favorable terms, such as better credit facilities or payment systems.

3.2.2 Sugarcane procurement

Before the milling season begins, sugar mills conduct production assessments to estimate sugarcane productivity in plantations. According to [18], these assessments are a stage in crop production forecasting based on the crop's age and its regional classification. Sugar mills in East Java conduct assessments twice a year, in December and March, to predict productivity. The assessments utilize data analysis, visual inspections, and field observations. The Harvesting, Loading, and Transporting (HLT) process marks the culmination of all sugarcane cultivation activities. In East Java Province, the HLT system is predominantly manual, with human labor performing both harvesting and loading activities. The manual system is advantageous when HLT labor is abundant; however, semi-mechanical and mechanical HLT systems are also in use.

Key considerations in the HLT process include the volume of sugarcane to be harvested, the size of the harvesting area, road infrastructure, and the availability of Transporting Personnel. Sugarcane harvesting is conducted based on the Harvest Order and Transport Order issued by the sugar mill. Upon arrival at the mill, sugarcane transporters exchange the SPA for a queue number. During the milling season, sugar mills hold daily evening harvest meetings to evaluate the day's sugarcane harvesting results and plan for the following day. These evaluations include analyzing challenges encountered and ensuring the day's sugarcane requirements are met. The harvesting plan is then adjusted according to the daily sugarcane milling target.

3.3 Spatial distribution map of sugarcane and sugar mills in East Java

The spatial distribution map in Figure 1 shows that out of 38 regencies and cities in East Java, 8 regions did not produce sugarcane in 2023. These regions include Sampang, Pamekasan, Sumenep, Pacitan, Surabaya City, Pasuruan City, Madiun City, and Blitar City, which are indicated by white polygons on the map. Overall, 424 out of 666 sub-districts in East Java Province produce sugarcane. Sugar mills in East Java Province are distributed across 19 regencies and 2 cities.

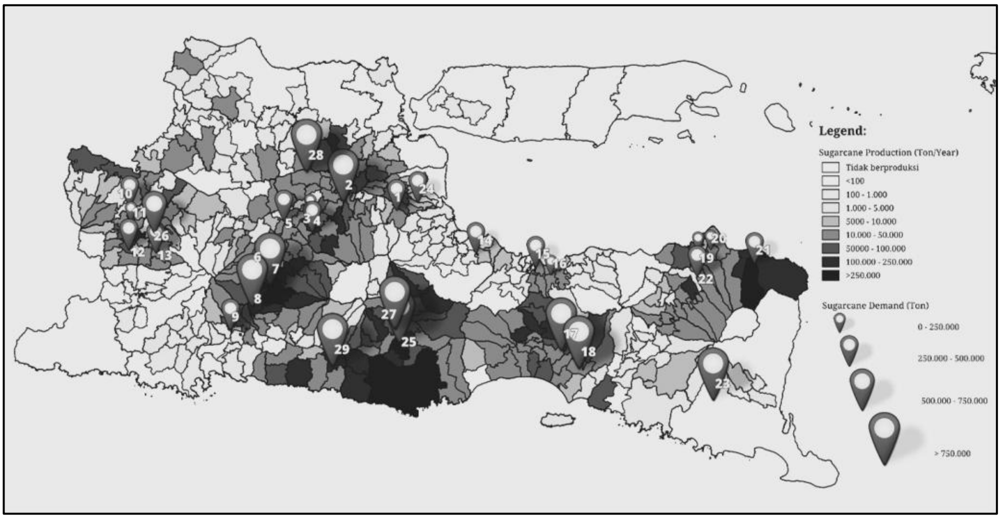

Fig. 1. Spatial distribution of sugarcane and sugar mills in East Java Province

The highest sugarcane demand in East Java in 2023 was recorded in Malang Regency with 4,121,072 tons, followed by Lamongan Regency with 1,848,000 tons, and Blitar Regency with 1,301,229.65 tons. The regions with the lowest sugarcane demand are Ngawi with 254,400 tons, Pasuruan Regency with 258,150.34 tons, and Nganjuk Regency with 300,990.48 tons.

The spatial distribution map of sugar mills in Figure 1 indicates that most sugar mills are in regions with abundant sugarcane supply, such as PG Krebet Baru and PG Kebon Agung in Malang Regency, PG Asembagus in Situbondo, and PT Rejoso Manis Indo in Blitar. Regions with high milling capacities tend to have high sugarcane production levels, as seen in Malang Regency. This proximity between supply and demand is beneficial as it ensures that the sugar mills' sugarcane needs can be met by nearby plantations. The map in Figure 1 also reveals that certain sugar mills are situated in regions with low sugarcane production. For instance, PG Glenmore in Banyuwangi and PT SGN PG Kedawoeng in Pasuruan are in areas where the surrounding sugarcane production only ranged between 100 and 10,000 tons in 2023, as indicated by the map's legend.

3.4 Optimal sugarcane allocation using the transportation method

Finding optimal solution for sugarcane allocation in this study was done through two main stages which were carried out carefully.

3.4.1 Establishing the transportation cost matrix

1. Distance matrix calculation: The distance matrix between each sugar mill and all sub-districts was derived by measuring the Origin-Destination (OD) Matrix using the "From Layers as Lines (m)" tool in QNEAT3. As described by [19], the OD Matrix algorithm calculates the shortest route distance between all point combinations on two layers: the origin layer (sub-district) and the destination layer (sugar mill).
2. Determination of transport tariff: The transport tariff for sugarcane, priced per quintal (IDR/Quintal), was determined based on distance ranges. These ranges vary across sugar mills according to their respective policies. In this study, a distance range of 10 km was used as the benchmark, given that transport tariffs often change after 10 km at certain sugar mills. For distances exceeding 100 km, the tariff was adjusted according to the rate for each distance range under 100 km.
3. Conversion of distance matrix to transportation cost matrix: The transport tariff data was utilized to create the cost matrix by converting the distances in the OD Matrix. This conversion was performed using the "VLOOKUP" function in Microsoft Excel for each distance range category. The resulting distance matrix is presented in Table 1.

Table 1. Transportation cost matrix (IDR/Quintal)

Sub-District	**1. PG Djombang Baru**	**2. PG Gempolkrep**	**3. PG Glenmore**	**4. PG Kremboong**	**…**	**29. PT Rejoso Manis Indo**
1. Arjasa	41.211	35.402	19.302	32.193	…	45.288
2. Asembagus	37.746	34.496	19.302	33.039	…	40.680
…	…	…	…	…	…	…
213. Kedamean	6.892	5.565	34.496	6.143	…	19.302
214. Menganti	7.022	6.143	34.496	6.143	…	19.302
215. Ujungpangkah	13.737	10.272	41.211	10.272	…	24.009
216. Wringinanom	6.892	5.565	34.496	5.565	…	19.302
217. Bandarkedungmulyo	4.719	6.143	40.680	7.928	…	13.737
218. Bareng	5.565	6.143	37.746	7.022	…	10.272
219. Diwek	4.077	6.143	37.746	7.022	…	13.206
220. Gudo	4.719	6.143	40.680	7.022	…	13.206
…	…	…	…	…	…	…
423. Kedopok	19.302	17.814	20.759	10.272	…	19.880
424. Wonoasih	19.302	17.814	20.629	10.272	…	19.880

3.4.2 Optimal sugarcane allocation

1. Scenario 1: Optimal solution with dummy

The amount of sugarcane supplied by plantations in each sub-district (supply) does not match the demand from sugar mills. The total annual demand for sugarcane by sugar mills is 18,477,369.69 tons, while the supply is only 14,101,565.69 tons, resulting in a deficit of 4,375,804.05 tons. This creates an unbalanced transportation problem, where the supply does not meet the demand [20]. To address this issue, a dummy supply source is introduced in the transportation table that can be seen in Table 2, with a value equal to the difference between demand and supply. The optimization of sugarcane allocation was conducted using OpenSolver, a Microsoft Excel add-in that is ideal for case studies with large numbers of variables, as it does not impose a variable limit [21].

Table 2. Transportation table

Sub-District	**1. PG Djombang Baru**	**2. PG Gempolkrep**	**3. PG Glenmore**	**4. PG Kremboong**	**…**	**29. PT Rejoso Manis Indo**	**Supply (Quintal)**
1. Arjasa	X_{11}	X_{12}	X_{13}	X_{14}	X_{ij}	$X_{1,29}$	**452.403**
2. Asembagus	X_{21}	X_{22}	X_{23}	X_{24}	X_{ij}	$X_{2,29}$	**2.725.286**
…	X_{ij}	X_{ij}	X_{ij}	X_{ij}	X_{ij}	X_{ij}	**….**
213. Kedamean	$X_{213,1}$	$X_{213,2}$	$X_{213,3}$	$X_{213,4}$	X_{ij}	$X_{213,29}$	**364.038**
214. Menganti	$X_{214,1}$	$X_{214,2}$	$X_{214,3}$	$X_{214,4}$	X_{ij}	$X_{214,29}$	**52.140**
215. Ujungpangkah	$X_{215,1}$	$X_{215,2}$	$X_{215,3}$	$X_{215,4}$	X_{ij}	$X_{215,29}$	**14.000**
216. Wringinanom	$X_{216,1}$	$X_{216,2}$	$X_{216,3}$	$X_{216,4}$	X_{ij}	$X_{216,29}$	**708.900**
217. Bandarkedung M.	$X_{217,1}$	$X_{217,2}$	$X_{217,3}$	$X_{217,4}$	X_{ij}	$X_{217,29}$	**118.503**
218. Bareng	$X_{218,1}$	$X_{218,2}$	$X_{218,3}$	$X_{218,4}$	X_{ij}	$X_{218,29}$	**1.001.414**
219. Diwek	$X_{219,1}$	$X_{219,2}$	$X_{219,3}$	$X_{219,4}$	X_{ij}	$X_{219,29}$	**1.163.826**
220. Gudo	$X_{220,1}$	$X_{220,2}$	$X_{220,3}$	$X_{220,4}$	X_{ij}	$X_{220,29}$	**350.322**
…	X_{ij}	X_{ij}	X_{ij}	X_{ij}	X_{ij}	X_{ij}	**…**
423. Kedopok	$X_{423,1}$	$X_{423,2}$	$X_{423,3}$	$X_{423,4}$	X_{ij}	$X_{423,29}$	**4.913,7**
424. Wonoasih	$X_{424,1}$	$X_{424,2}$	$X_{424,3}$	$X_{424,4}$	X_{ij}	$X_{424,29}$	**5.638,5**
Dummy	$X_{dummy,1}$	$X_{dummy,2}$	$X_{dummy,3}$	$X_{dummy,4}$	X_{ij}	$X_{dummy,29}$	**43.758.040**
Demand (Quintal)	**1.879.244**	**8.303.177**	**8.381.297**	**2.717.897**	**…**	**13.012.296**	

X_{ij} : Amount of sugarcane transported from Sub-district i to sugar mill j

In the optimization solution with this dummy, the total transportation cost amounted to 747,275,819,472 IDR for the entire sugarcane shipment from each sub-district to sugar mills in East Java Province. The optimal sugarcane allocation derived from the transportation table was subsequently mapped, as shown in Figure 2.

The highest sugarcane acquisition was achieved by PG Krebet Baru, amounting to 19,488,800 tons from 14 sub- districts in Malang Regency and 1 sub-district in Batu City. The lowest acquisition was by PG Kedawoeng, amounting to 230,184.8 tons from 13 sub-districts in Pasuruan Regency and 2 sub-districts in Probolinggo Regency. Based on the optimization results, it was found that nine sugar mills received supplies from the dummy, as shown in Table 3.

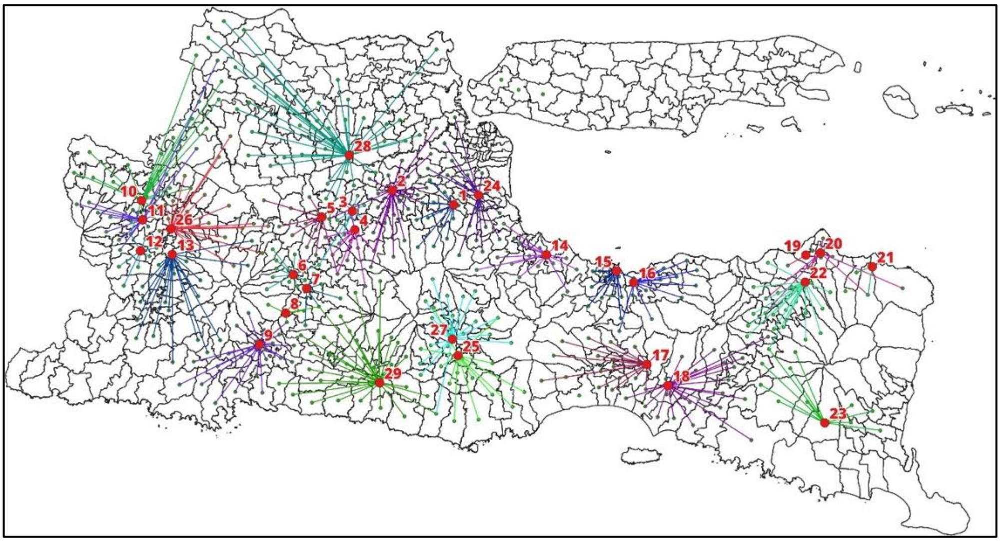

Fig. 2. Optimal sugarcane allocation map with dummy

Table 3. Sugar factory with dummy supply

No	Sugar Factory	Dummy Supply (Quintal)	Demand (Quintal)	Dummy Supply Percentage
1	PG Glenmore	7,851,145.30	8,381,296.90	93.67%
2	PG Kebon Agung	6,236,386.40	21,721,920.00	28.71%
3	PG Kedawoeng	2,351,318.60	2,581,503.40	91.08%
4	PG Pagottan	2,261,533.60	3,432,000.00	65.90%
5	PG Rejo Agung Baru	5,279,958.80	7,183,440.00	73.50%
6	PG Semboro	4,322,061.00	8,570,468.00	50.43%
7	PG Wonolangan	1,473,866.60	3,040,930.00	48.47%
8	PT Kebun Tebu Mas	12,152,154.00	18,480,000.00	65.76%
9	PT PG Candi Baru	1,829,616.20	4,285,358.00	42.69%

The dummy in the transportation table is an artificial construct and not a real supply source. Therefore, the transportation cost associated with this dummy is zero, indicating there is no actual shipment from the dummy source [22]. Table 3 shows that PG Glenmore and PG Kedawoeng had the highest percentage of supply from the dummy source. PG Glenmore received 93.67% of its sugarcane supply from the dummy source, amounting to 785 thousand tons, meaning that under this transportation method, PG Glenmore only met about 6.33% of its total demand for milling capacity.

When compared with the spatial distribution map of sugarcane and sugar mills in Figure 1, it is evident that PG Glenmore in Banyuwangi, which had a sugarcane demand of 8,381,297 quintals in 2023, was in an area where the surrounding sub-districts produced only about 100–10,000 tons. A similar situation occurred with PG Kedawoeng in Pasuruan, which is also located in an area with limited sugarcane production. In contrast, Figure 1 shows that PG Kebon Agung, which also received dummy supplies, is in Malang Regency, the largest sugarcane-producing area in East Java Province. The allocation of dummy sources to PG

Kebon Agung may be attributed to the presence of another sugar mill with equally high demand in Malang Regency, namely PG Krebet Baru, necessitating the allocation of available sugarcane to PG Krebet Baru. According to the official OpenSolver website, this add-in analyzes and extracts the transportation model, which is then sent to the CBC solver engine for optimal results. In this study, no final solution search or optimality test, such as the Modified Distribution (MODI), was conducted. Instead, the results used were directly from the OpenSolver solution tables.

Considering these results, our findings suggest that unbalanced sugarcane allocation can significantly increase potential financial risk and revenue loss, highlighting the importance of strategic partnerships among sugar mills and farmers. By exploring shared procurement schemes, sugar mills could distribute risk more evenly and reduce overall shortages.

2. Scenario 2: Optimal solution with demand adjustment

Optimization with demand adjustment was performed by reducing the sugar mills' demand to account for the supply-demand gap, which was 4,375,804 tons, or 23.68% of the total sugarcane demand. In this optimization model, the demand for each sugar mill was capped at 76.32% of the original demand, effectively balancing the transportation problem by eliminating the gap between supply and demand. Consequently, the dummy source was removed from the transportation table. The total transportation cost resulting from this second optimization approach was 842,750,679,416 IDR, which is 12.78% higher compared to the optimization solution using the dummy. The allocation results are depicted in Figure 3.

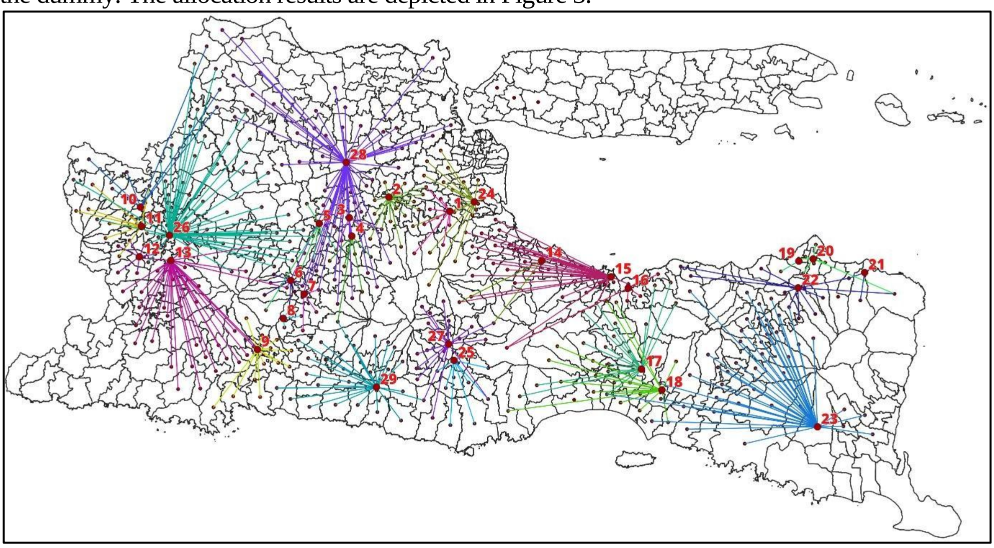

Fig. 3. Optimal sugarcane allocation map with demand adjustment

The highest sugarcane acquisition was recorded by PG Kebon Agung, totaling 1,657,774.276 tons from 14 sub- districts in Malang Regency, 3 sub-districts in Malang City, and 2 sub-districts in Batu City. The lowest acquisition was by PG Wringinanom, amounting to 113,566.92 tons from two sub-districts in Situbondo. The highest transportation cost in this analysis was incurred by PG Krebet Baru, amounting to 106,633,311,083 IDR, with a sugarcane acquisition of 1,487,346.94 tons.

These allocation results emphasize how proportional adjustment can mitigate extreme deficits at particular mills. Moreover, by quantifying revenue loss, sugar mills can assess potential investments in expanding sugarcane cultivation or upgrading transport infrastructure. This strategic viewpoint is critical to ensuring long-term efficiency and competitiveness in the sugar sector.

3.5 Calculation of revenue loss costs

Data from the East Java Provincial Plantation Office (2024) recorded that the total sugarcane milled by sugar mills in East Java in 2023 was 15,593,562.64 tons, with a sugar production of 1,126,796.24 tons, resulting in a productivity of 7.23% ton of sugar/ton of sugarcane. The price of sugar per kilogram was obtained based on the retail price from the Agricultural Data and Information System Center 2023, which was 14,959 IDR. In the solution with the dummy, the sugar mill with the highest revenue loss was PT Kebun Tebu Mas, amounting to 1,313,578,001,362 IDR. This value corresponds to the large supply of sugarcane from the dummy source, which was 1,215,215 tons. The optimization solution with the dummy yielded a revenue loss value of 4,729,992,673,193 IDR. When added to the transportation cost, the total cost amounted to 5,477,268,492,665 IDR.

In the solution with demand adjustment, the amount of sugarcane shortage in all sugar mills due to the demand limitation to 76.32% was calculated. The highest revenue loss cost was incurred by PG Kebon Agung, amounting to 556,055,992,325 IDR. This value corresponds to the unmet sugarcane demand at this mill, which was 514,417 tons. The optimization solution with demand adjustment resulted in a revenue loss value of 4,729,992,624,282 IDR, only 48,911 IDR less than the solution with the dummy. This may be because this study used the same productivity value for each mill. When added to the transportation cost, the total cost amounted to 5,572,743,303,699 IDR. This value is 95,474,811,034 IDR higher than the dummy solution.

Considering future expansions, the model may be applied to other regions with similar sugarcane supply challenges, provided that relevant local cost structures, transportation distances, and plantation data are available. This adaptability underscores the scalability of our approach.

3.6 Managerial implications

The implementation of the optimized sugarcane allocation results needs to be supported by policies related to regulations that limit the sugarcane acquisition area for each sugar mill. Additionally, the implementation of optimal sugarcane allocation also needs to be supported by government policies to regulate the shipment of farmers' sugarcane to sugar mills. The policies could include restrictions on local sugarcane farmers to prevent them from sending sugarcane outside the designated area. These policies should be accompanied by guarantees of profit for local sugarcane farmers, whether through credit provisions, transportation tariff costs, or the payment system for their sugarcane. These policies should benefit not only the sugar mills but also the sugarcane farmers in East Java.

Moreover, as a practical step, sugar mills and local authorities could pilot short-term trials or demonstration plots under regulated supply conditions to evaluate the real-world feasibility and acceptance among farmers. While such interventions foster regional supply security, they must be coupled with clear incentive schemes and continuous engagement with local stakeholders [7]. Finally, decision-makers should remain mindful of the model’s limitations, including annual variability in yields and transport infrastructure changes, ensuring that policy guidelines are revisited regularly and adjusted to emerging conditions.

4 Conclusion

There are 29 sugar mills spread across 19 regencies and 2 cities in East Java. These mills are supported by the availability of sugarcane supplies from plantations distributed across 424 sub-districts in East Java. Malang Regency is the region with the highest sugarcane demand, amounting to 4,121,072 tons, as well as the highest sugarcane production, amounting to

4,016,351 tons. The region with the lowest sugarcane demand is Kediri City, with 228,935.59 tons, and the lowest production is Banyuwangi Regency, with 4,450.74 tons. Most sugar mills are in productive sugarcane-producing areas, but some are also in areas with low sugarcane production. The total annual demand for sugarcane by sugar mills is 18,477,369.69 tons. This value is greater than the total sugarcane production of only 14,101,565.68 tons, resulting in a deficit of 4,375,804 tons. Allocation optimization was performed using the transportation method. The optimal solution with the dummy resulted in a total transportation cost of 747,275,819,472 IDR, with nine sugar mills receiving supplies from the dummy and a revenue loss value of 4,729,992,673,193 IDR. The optimal solution with demand adjustment was carried out by limiting the demand.

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