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Enhancing sugarcane harvest and load scheduling efficiency: a linear programming approach in East Java, Indonesia

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ABSTRACT

Managing sugarcane harvesting and loading activities can increase the efficiency of sugar factory production. Scheduling this activity has a significant impact on reducing harvesting and loading costs, reducing the area of harvested land, and optimizing sugar production capacity. This study was conducted at a private sugar factory in Malang to develop a sugarcane harvesting and loading scheduling model. This model aims to optimize the sugar harvesting and transport scheduling so that the cost is lower and the sugar production capacity can be met. The model is built using LINGO 11.0 software. The results of the study showed significant improvements, namely the cost of harvesting and loading sugarcane decreased by 33.1% from Rp. 1.90 billion to Rp. 1.27 billion. Meanwhile, the harvested area decreased from 139.69 ha to 137.87 ha. In addition, sugarcane production increased by 24.6% from 11,140 tons to 13,887 tons per milling season, and the need for vehicles decreased by 39% from 2,870 to 1,736 units. The simulation results were then formed into a table containing a detailed schedule of harvesting and loading sugarcane as a recommendation to improve operational efficiency and factory profitability.

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INTRODUCTION

The agricultural, forestry, and fisheries sectors play a pivotal role in Indonesia's economic activities. Among these, the plantation sub-sector holds considerable potential, serving as a significant source of raw materials for the industrial sector, a major employer, and a key contributor to foreign exchange earnings (BPS Republik Indonesia 2023). Within this sub-sector, sugarcane stands out as a crucial commodity for the sugar industry, contributing significantly to Indonesia's economy. Sugar factories in Indonesia are concentrated in twelve provinces, with East Java being the largest producer. From 2018 to 2022, East Java's average sugar production was 1.05 million tons per year, accounting for 47.34% of Indonesia's total sugar production. In 2022, the Directorate General of Plantations estimated that East Java produced 1.05 million tons of sugar, far surpassing other provinces (Kementerian Pertanian Republik Indonesia 2022).

Most sugarcane plantations in East Java engage in activities ranging from sugarcane cultivation to processing the harvested cane into market-ready products such as raw sugar, white sugar, molasses, and bagasse. A critical component of these activities is the harvest and load process, which involves cutting, loading, and transporting sugarcane from the fields to the mill for immediate processing. This process is vital to ensuring the quality and efficiency of sugar production. The predominant tool for cutting sugarcane is the sickle, which is preferred for its cost efficiency compared to engine-powered tools. Loggers who perform are categorized as local loggers from the surrounding community and external loggers from outside the plantation area. After the sugarcane is cleaned and cut, it is typically tied in bundles of 12-15 canes. Local loggers usually bind the canes with sinew rope, while external loggers use sugarcane rope, often dividing it into two or four parts.

Timely transportation of sugarcane to the mill is crucial, as delays exceeding 24 hours can degrade the sugarcane juice quality and yield, reducing overall productivity (Prasetiyo et al. 2016, Kurniawan and Purwono 2018, Antika and Ingesti 2020). Prolonged waiting times can lead to weight shrinkage due to juice loss (Bantacut et al. 2012, Kuspratomo et al. 2012, Mayangsari 2018), inefficient milling capacity (Mahbubi 2018, Magfiroh and Wibowo 2019), and increased production costs, ultimately impacting company profits (Sayyida 2011, Saskia and Waridin 2012, Massie et al. 2018). Transportation methods include large and small trucks, small trains (Lori), and wagons, chosen based on specific conditions.

Effective coordination of harvest and load activities with the milling capacity is essential during the milling season. It includes managing resources, equipment, and field conditions under a unified command. The harvested sugarcane must align with the mill's capacity to avoid overproduction and inefficiency. The time-consuming process of cutting and transporting sugarcane from the fields to the mill necessitates careful planning (Utomo et al. 2022). Optimizing these activities requires comprehensive management from planning to implementation. It involves not only scheduling the harvest and load activities but also minimizing costs. Sugar factories aim to reduce costs while maximizing harvest production and milling targets, often using the minimum number of vehicles, human resources, and areas.

This study focuses on a sugar factory in Malang, East Java, Indonesia, identifying several challenges that affect the optimization of sugarcane harvest and load activities:

- Transportation Delays: Frequent long queues of sugarcane transport vehicles lead to supply buildup and extended waiting times, sometimes reaching 48 hours. This delay affects sugarcane quality and milling productivity.
- Harvest Land Area: The size of the harvest area influences cutting time, labor requirements, transportation capacity, and weather conditions, all which impact costs.
- Resource Allocation: Reducing land area and the number of vehicles can decrease sugarcane production, affecting milling targets.

These challenges highlight the need for an optimization model to enhance planning and management. Research on scheduling optimization in sugarcane harvest and load processes is limited. Early research includes a study by (Abel et al. 1981), who developed the first sugarcane railway scheduling model. Research by (Hansen et al. 2002) employed simulation methods for road transport scheduling, while (Salassi et al. 2002) developed a methodology to maximize economic returns through optimal field harvest scheduling.

Subsequent studies continued to advance this field. A study by (Diaz and Perez 2000) influenced future research with their work on sugarcane simulation and transport process optimization. Another study by (Milan et al. 2006) presented a Mixed-Integer Linear Programming (MILP) model for cost minimization in sugarcane removal and transport. Additionally, a study result (Higgins 2006) implemented a MILP model for road transport operations in an Australian sugar milling company.

Further advancements include (Scarpari and De Beauclair 2010), who introduced a linear programming method for sugarcane agricultural planning, influencing many subsequent studies. A MILP model for cost optimization in sugarcane operations was proposed by (Morales-Chávez et al. 2016), while (Junqueira and Morabito 2017) suggested optimization approaches for scheduling harvest decisions. Furthermore, (Caixeta-Filho and Miyashita 2018) developed a MILP model to maximize revenue from sugar commercialization by optimizing harvest scheduling.

In Indonesia, research on sugarcane harvesting and loading scheduling optimization, particularly utilizing a Linear Programming model, is limited. Previous studies, such as those by (Susila and Hutagaol 2005), have focused on integrating planting and harvesting schedules between farmers and sugar factories. However, our research targets explicitly the optimal milling goal set by the sugar factory, which is approximately 805 tons per month. To meet this target, this study employs a Linear Programming model, incorporating several external factors affecting the harvest and load process, including milling capacity, land area, harvest-load cost, and transport capacity. The linear programming model was chosen for this study due to its suitability in handling linear objectives and constraints and its efficiency in solving problems with thousands of constraints and variables (Taha 2017).

Therefore, to optimize sugarcane harvest and load scheduling, an effective model for planning and management must be established. The proposed model will be integrated into a scheduling optimization framework to ensure an optimal harvest and load scenario that fulfills the required conditions. The optimization process, conducted using the Linear Programming method, aims to address the inefficiencies and challenges identified in the case study, ultimately enhancing the productivity and profitability of the sugar factory in Malang, East Java.

METHOD

Material and Equipment

This study was conducted at a sugar factory located in Malang, East Java, Indonesia. The materials utilized in this research included both primary and secondary data provided by the sugar factory, such as milling capacity, transport capacity, and land area dedicated to sugarcane cultivation. However, specific sensitive data was omitted for confidentiality reasons.

The equipment used in this study comprised software tools essential for data analysis and model development. Specifically, LINGO 11.0 software was employed to solve the linear programming model due to its robustness in handling complex optimization problems with numerous constraints and variables. Additionally, Microsoft Excel was used for data organization, preliminary analysis, and visualization of results. The combination of these tools facilitated the efficient processing of large datasets and the accurate development of the scheduling optimization model.

Mathematical Model

The objective of this mathematical model is to calculate the optimal hectares of sugarcane to be harvested per period for each land area. The study focuses exclusively on a single mode of transportation: medium-sized trucks with capacities ranging from 8 to 12 tons. Harvesting and loading in this study are performed manually. Furthermore, transportation involves a single trip from the field to the mill, with each field assigned a specific number of trucks available for sugarcane loading. This section initially outlines the framework of the mathematical model, detailing its objective function, constraints, and parameters.

Objective function

The decision variables are denoted as L_{ij}, are structured with subscripts where i represents the location number of the area (ranging from 1 to 47) and j denotes the sugarcane milling period (ranging from 1 to 14). In Indonesia, the typical sugarcane milling period spans from May to November, covering seven months. However, for this study, the milling period was discretized into bi-weekly intervals, resulting in 14 distinct periods (j). Here, L_{ij} signifies the area i's harvestable land extent during period j, measured in hectares.

The parameters within the objective function are categorized into costs and land productivity factors. The cost parameters are further classified into two main groups:

- Sugarcane harvesting costs, encompass labor expenses per ton of harvested cane.
- Sugarcane loading costs, encompass the expenditure associated with transporting each ton of sugarcane using dedicated transport equipment like trucks.

Land productivity refers to the sugarcane yield capacity of each hectare of land, expressed in tons of sugarcane per hectare. The estimation of sugarcane land productivity is derived from data collected across 47 sampled areas managed by the sugar factory. Table 1 presents a detailed breakdown of these objective function parameters.

To minimize the total cost of harvesting and loading, we need to account for both the harvesting cost and the loading cost, which are affected by land productivity and the decision variables. To derive the cost in Indonesian Rupiah, we first calculate the total tons of sugarcane by multiplying the land productivity (tons per hectare) by the decision variable (hectares). Subsequently, we multiply this product by the respective harvesting and loading costs (IDR per ton) to convert it into Rupiah. This procedure results in the cost in Rupiah, which is formulated in the objective function as described mathematically below.

$$Min\ Z = \sum_{i=1}^{47}\sum_{j=1}^{14} (P_i \,.\, L_{ij}) \,.\, C_j + (P_i \,.\, L_{ij}) \,.\, D_j \qquad (1)$$

Model constraint

The model constraints are represented by Equations 2 to 5. These constraints encompass milling capacity, land area, harvest-load cost, and transport capacity. The parameters used in each model constraint are detailed in Table 2.

Milling capacity constraint

The milling capacity constraint (KG) sets the minimum limit on the amount of sugarcane that the factory must mill. The factory must meet or exceed this capacity. The milling capacity is determined for each milling season, which spans seven months. However, the mathematical model is adjusted to align with the company's operational period, analyzed every two weeks (denoted as j).

$$\sum P_i \,.\, L_{ij} > KG_j \qquad (2)$$

Land area constraint

The total land area (LT) serves as a parameter in the land area constraints, measured in hectares (ha). This area is derived from 47 samples of company-owned land based on the company's primary data. All the land considered is productive and used exclusively for producing sugarcane as raw material for milling. The optimized land area should not exceed the total available land area to minimize the total cost.

$$\sum L_{ij} < LT \qquad (3)$$

Table 1 Parameters

Symbol	Description	Unit
C_j	Cost of sugarcane harvesting in period *j*	Rupiah/ton
D_j	Cost of sugarcane loading in period *j*	Rupiah/ton
P_i	Land productivity in area *i*	Ton/ha

Table 2 Parameters

Symbol	Description	Unit
KG_j	The factory's milling capacity in the j period	Ton
LT	Total area owned by the company	Hectare
BTA_{ij}	Harvest-load cost budgeted by the company for i area in j period	Rupiah
KTR	Average total truck carrying capacity	Ton

Harvest-load cost constraint

The harvest-load cost (BTA) represents the budget allocated by the company for each hectare of harvested land, encompassing the total cost of cutting and transporting the sugarcane. The BTA typically remains constant for each area and harvest period. The mathematical model aims to optimize this harvest-load cost, reducing it to the minimum possible amount.

$$\sum (P_i \,.\, L_{ij}) \,.\, C_j + (P_i \,.\, L_{ij}) \,.\, D_j < BTA_{ij} \quad (4)$$

Transport capacity constraint

The transport capacity (KTR) pertains to the maximum cargo load that transport vehicles can carry to the milling site. The company's fleet consists of medium-sized trucks. Transport capacity data is sourced from the company records.

$$\sum P_i \,.\, L_{ij} < KTR \quad (5)$$

Model Verification and Validation

The linear programming model developed in this study employs face validation techniques as outlined by (Sargent 2013), which include the following steps and considerations:

- Expert Evaluation: This step involves the manager of the harvest and load division at the sugar factory reviewing the datasets used in the objective function and constraints of the model.
- Structured Walkthroughs: Academics evaluate the linear programming model to verify its correctness. This process helps identify any errors or inaccuracies in the model logic.
- Use of Traces: Tracing is conducted throughout the entire linear programming model to ensure logical correctness and maintain the required accuracy.

By involving knowledgeable experts, face validation enhances the credibility and accuracy of the linear programming model. Consequently, the model is verified and can be considered valid.

Limitations of The Model

The current linear optimization scheduling model for harvesting and transportation requires further development to achieve more detailed and accurate planning. Moreover, not all variables are explicitly stated in mathematical equations, limiting the comprehensiveness and accuracy of the model. Specifically, the model needs enhancement to address the following limitations:

- Detailed Planning of Harvest Site Locations: The model should be expanded to facilitate more precise planning of harvest site locations.
- Accurate Timing of Harvests: The model needs refinement to provide more accurate scheduling of harvest times.
- Target Yield of Sugar: The model does not currently account for the target yield of sugar produced from milled sugarcane.

RESULT AND DISCUSSION

Table 3 below shows the results before and after the mathematical model simulation. The results are significantly optimized compared to the actual condition, given the requirements above.

Land usage activities

Land usage activities involve the company's efforts to harvest sugarcane fields in a manner that minimizes costs while fulfilling the sugarcane milling target. The optimal area of land designated for cutting by the company is 139.69 hectares. However, following the optimization process, the actual harvested area is reduced to 137.87 hectares, resulting in a savings of 1.82 hectares.

In the mathematical model, the assumed land area is the total available land, constrained to a maximum of 139.69 hectares. The optimization constraints applied in the model do not differentiate between the areas of individual land plots. Consequently, the optimization results do not provide a comparison of the harvested areas of each plot owned by the company. Despite this, the optimization outcome adheres to the mathematical model's condition of remaining within the total land area limit.

These findings are consistent with prior research (Scarpari and De Beauclair 2010, De Oliveira Florentino and Pato 2014, Morales-Chávez et al. 2016, Junqueira and Morabito 2019), which highlights the significant impact of minimizing land area on the efficiency of sugarcane harvesting and transportation processes. This alignment with existing literature underscores the validity of the optimization model in achieving cost-effective and efficient land usage while meeting production targets.

Table 3 Comparison between actual data and simulation result

No.	Variable	Actual	Simulation result	Difference
1.	Total land area	139,69 ha	137,87 ha	Saved 1,82 ha
2.	Milling target/period	805 ton	Avg. 1000 ton	Increased
3.	Vehicles needed	2870 units	1736 units	Saved 39%
4.	Total harvest-load cost	Rp.1,905,072,000, -	Rp.1,273,368,000, -	Saved 33.1%
5.	Harvest-load cost budget/area	Rp.13,650,000, -	Rp.12,000,000, -	Saved by Rp.1,650,000, -
6.	Sugarcane production/milling season	11.140 ton	13.887 ton	Increased by 24.6%

Sugarcane harvesting activity

The optimization results reveal the quantity of sugarcane that can be harvested from the company's land. Assuming no sugarcane is damaged during the process, this harvest will be transported to the mill. The optimization of milling capacity has adhered to the specified limits, with nearly all periods reaching the 1,000-ton milling target. The total sugarcane production from the optimization results amounts to 13,887 tons, which satisfies the current milling capacity of the plant. It represents an increase compared to the actual sugarcane production in 2020, which was 11,140 tons. Therefore, the designed mathematical model has been successfully validated.

This observation is consistent with findings from previous studies (Purwaningsih et al. 2010, Afifah et al. 2018), which emphasize the importance of daily harvesting in continuous process-oriented enterprises like sugar factories. Daily harvesting is crucial to ensure uninterrupted production processes and to prevent stockouts, thereby highlighting the necessity of an optimized and efficient harvesting schedule.

Sugarcane loading activity

In an optimal operational scenario, the requisite fleet comprises 1,736 trucks. However, the current demand of the company stands at 2,870 trucks, signifying an excess beyond optimal requirements. Through effective optimization strategies, a notable reduction of 39% in truck utilization has been achieved. This outcome aligns with a pre-established mathematical model aimed at enhancing operational efficiency and cost-effectiveness in fleet management.

The number of trucks directly influences the transportation costs associated with sugarcane harvesting and loading activities, which constitute a substantial portion, approximately 60%, of total production costs (da Silva et al., 2015; Kaur et al., 2022). Moreover, the logistics involved in sugarcane transportation play a pivotal role in ensuring the timely availability and quality of sugarcane delivered to the mills. It underscores the critical importance of transportation logistics in maintaining operational continuity and meeting stringent quality standards (Asrol and Delfitriani, 2021; Kaur et al., 2022). Consequently, strategies aimed at optimizing truck utilization not only reduce costs but also enhance the overall efficiency and competitive edge of sugarcane production and processing operations.

Harvest-load costs

The optimization of the objective function using LINGO 11.0 software has yielded a total cost of Rp.1,273,368,000 for optimal harvest and load activities. It represents a cost saving of Rp.631,704,000 compared to the actual cost of Rp.1,905,072,000. The costs include both harvesting costs (wages of loggers) and transportation costs.

For the optimal harvested land, the cost incurred is, at most, the company's budget limit for each plot, which is Rp.13,650,000. The mathematical model has demonstrated cost savings of up to Rp.12,000,000, indicating that there has been an unnecessary expenditure of Rp.1,650,000 compared to actual cost data. This finding is consistent with previous research (da Silva et al. 2013, 2015, da Silva and Marins 2014, Morales-Chávez et al. 2016, Caixeta-Filho and Miyashita 2018, Junqueira and Morabito 2019), which highlights the focus of sugarcane optimization models on minimizing total costs.

As noted by (da Silva et al. 2015), approximately 60% of total supply chain costs in the sugarcane industry are attributed to harvesting and loading activities, highlighting the substantial influence of cost-effective harvesting on overall industry efficiency. This optimization represents a significant opportunity for cost reduction and aligns with the broader objective of improving operational efficiency within the sector.

Schedule table on harvesting and loading activity

Based on the analysis results of the linear programming model, an optimal scenario emerges for minimizing the cost of sugarcane transport at the sugar factory. The optimal scenario identified through linear programming using LINGO software resulted in several key savings: a reduction in land area by 1.82 hectares; a decrease in the number of transport fleets by 39%; a savings of Rp.1,650,000 per hectare in cutting and transport costs; and a total cost reduction of Rp.631,704,000. Moreover, this scenario also increases milling capacity by 15%.

The policy recommendation for the sugar factory is to develop a sugarcane harvesting schedule based on the constraints and optimized scenarios derived from this study's results. Consequently, a sugarcane harvest and loading schedule has been prepared, encompassing optimal plantation locations for harvesting, planning the quantity of milled sugarcane raw material, determining the necessary transportation fleets and labor, and budgeting costs. Table 4 below illustrates an example of a sugarcane harvest schedule aligned with the Linear Programming optimization results.

Enhancing the complexity of the harvesting and transportation scheduling model at the sugar factory requires integrating variations in harvesting times specific to each plot. These variations should account for critical factors such as the timing of planting, the maturity of sugarcane, varietal characteristics, and soil attributes. The current model's omission of these nuanced variables limits its ability to accurately reflect the dynamic conditions inherent in sugarcane cultivation and transport operations. By incorporating these factors, future iterations of the model can better capture the variability and intricacies encountered in real-world agricultural settings. This enhancement is crucial for improving the model's predictive accuracy and its practical utility in guiding efficient and effective decision-making within the sugar industry. Addressing these limitations represents a significant opportunity to advance the applicability and relevance of modeling efforts aimed at optimizing sugarcane harvesting and transportation logistics.

Table 4 Schedule table (1st harvest month example)

Weeks	Number of areas harvested	Land area harvested (ha)	Sugarcane production (ton)	Number of trucks (units)	Workforces needed (people)	Cost (Rupiah)
1	3	1.09	112	14	5	12,117,650
	5	1.11	111	14	6	12,000,003
	10	1.11	111	14	6	12,000,003
	19	1.05	106	13	5	11,412,194
	20	1.11	111	14	6	12,000,003
	22	1.09	112	14	5	12,117,650
	29	1.11	111	14	6	12,000,003
	39	1.11	111	14	6	12,000,003
	40	1.09	112	14	5	12,117,650
TOTAL		9.87	1000	125	49	107,765,161
2	3	1.09	112	14	5	12,117,650
	5	1.11	111	14	6	12,000,003
	10	1.11	111	14	6	12,000,003
	19	1.05	106	13	5	11,412,194
	20	1.11	111	14	6	12,000,003
	22	1.09	112	14	5	12,117,650
	29	1.11	111	14	6	12,000,003
	39	1.11	111	14	6	12,000,003
	40	1.09	112	14	5	12,117,650
TOTAL		10	1000	125	49	107,765,161

CONCLUSION

This study showcases the practical application of the Linear Programming model in optimizing sugarcane harvesting and loading operations aimed at minimizing costs at a sugar factory in East Java. The research successfully reduced harvesting land area by 1.82 hectares, resulting in substantial savings. Moreover, the optimized processes boosted sugarcane production to 13,887 tons per milling season, surpassing previous targets and validating the model's capability to enhance productivity targets. Fleet management improvements led to a notable 39% reduction in truck utilization, aligning with cost-saving objectives and highlighting the pivotal role of logistics in maintaining operational continuity and product quality. However, the study also identifies key limitations in the current model, such as the need for more detailed harvest site planning, enhanced accuracy in scheduling, and integration of sugar yield targets. Addressing these shortcomings through further research will refine the model's applicability, ensuring it accurately mirrors the complexities of real-world sugarcane operations and enhances decision-making in agricultural management.

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