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Designing a Sugarcane Based Raw Material Procurement Model for the Sugar Industry

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ABSTRACT

This study aims to design a system dynamics model to analyze and improve sugarcane-based procurement at PT Sukses Mantap Sejahtera (PT SMS). The model integrates three subsystems—plantation, production, and demand—to represent the interactions among supply sources, milling capacity, and regional sugar needs. Model validation using Theil's Inequality Statistics confirms the simulation results with actual data, indicating that most deviations arise from random noise rather than systematic bias. Five policy scenarios were designed to enhance system performance: (1) increasing sugarcane prices, (2) introducing subsidies for machinery rental and fertilizers, (3) improving sugarcane yield to 7.68%, (4) expanding livestock routes in the nucleus estate to 210 hectares, and (5) combining Scenarios 2, 3, and 4. Scenario 5 demonstrates the best performance, increasing sugarcane and WCS production by 4.06% and 8.32% annually. By 2030, sugarcane reaches 510,396.56 tons (+6.74%) with 68.05% milling utilization, producing 39,198.46 tons of WCS (+12.14%) and meeting 64.91% of demand in Eastern Indonesia. These results underscore the importance of integrated management, stakeholder collaboration, and Good Agricultural Practices.

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INTRODUCTION

The sugarcane agroindustry is one of the drivers of the Indonesian economy [1]. With a sugarcane area of around 489,340 hectares, this agroindustry is a source of income for thousands of farmers and workers, and plays a role in providing raw materials for the food and beverage industry [2]. As the population and industry grow, the demand for domestic sugar also increases annually. However, domestic production has not met this increase for direct consumption or industrial use. According to the USDA [3], Indonesia's sugar demand for the 2023/2024 period reached 7.50 million tons, while domestic production capacity was only 2.30 million tons, resulting in sugar imports of 5.00 million tons. In fact, during the 2013-2022 period, Indonesia's sugar import volume continued to increase by an average of 9.99% per year [4].

The government has implemented various strategies to reduce import dependence, including a land extension program outside of Java. West Nusa Tenggara (NTB) is one of the provinces that has become a focus for new development [5]. PT Sukses Mantap Sejahtera (PT SMS) is a sugar factory and sugarcane plantation located in Pekat District, Dompu Regency, NTB, which began operations in September 2015 with an installed capacity of 5,000 TCD (tons of cane per day), with raw material supplies sourced from partner plantations and nucleus plantations [6]. However, the factory has not been able to optimize its installed capacity. In 2023, the total sugarcane that could be processed was only 230,653.78 tons, yielding 7.31%, resulting in 16,860.79 tons of white crystal sugar (WCS) [7]. For a milling capacity of 5,000 TCD, approximately 10,000 hectares of sugarcane plantations are ideally required to achieve optimal utilization [4]. PT SMS currently manages 5,500 hectares of nucleus plantation and collaborates with partner farmers who have a potential area of 11,881 hectares, however, this potential has not yet been fully realized, resulting in suboptimal milling capacity utilization [8].

Generally, low WCS production is caused by various complex factors, primarily related to the procurement of raw materials. Some of these factors include a higher proportion of ratoon canes, land conversion [9], pest infestation [10], limited human resource competencies [11], as well as less adaptive plant varieties (genotypes) and suboptimal management practices [12]. Procurement is the process of providing production inputs and operational support materials in accordance with the specific needs of the industry [13]. Furthermore, procurement plays a strategic role in ensuring supply continuity through identifying, accessing, and managing resources to support company performance [14]. Effective supplier monitoring is essential to maintain raw material availability and procurement reliability in agroindustrial systems [15]. Evidence from other manufacturing sectors also confirms this view. Syahrir [16] found that effective logistics management and governance significantly enhance both competitiveness and operational performance. This highlights that strengthening raw material procurement systems is key to maintaining production continuity in the sugar industry, given the perishable nature of sugarcane, its varying quality, and its seasonal availability, and the complexity of supply chain interactions and sustainability challenges. [17], [18], [19].

PT SMS also faces various conditions and problems in the procurement of raw materials, which require solutions that can be developed. To overcome these problems, a systematic approach is needed. This approach focuses more on the relationships between variables in the system, feedback, and overall system behaviour [20]. The systems approach uses the system dynamics method to model the sugarcane raw material procurement system. This method was chosen for its ability to identify complex relationships between system components and simulate the temporal behaviour of the system [21]. Additionally, system dynamics is used to understand the operational mechanisms of a system and design strategies to improve its performance [22].

There are relatively few previous studies that have sought to address the challenges in sugarcane production using system dynamics, with some focusing on sustainability and others on productivity improvement. Wirjodirdjo et al. [23] highlighted the importance of sustainability and circular economy principles in smallholder-based sugarcane agribusiness by identifying key driving factors such as economic viability, social inclusion, environmental conservation, and technological innovation. Meanwhile, a system dynamics framework was developed to enhance sugarcane productivity in East Java by emphasizing intensification, extensification, and by-product utilization strategies to support sustainable cultivation [24]. Although these studies highlight essential perspectives, they have not sufficiently integrated procurement systems, mill capacity utilization, and supply–demand dynamics into a comprehensive decision-making model. To address this gap, this study makes a distinct contribution by designing a system dynamics model that explicitly focuses on raw material procurement in the sugar industry.

Specifically, the model integrates plantation, production, and regional demand subsystems into a single framework, thereby directly linking procurement policies with mill utilization and WCS supply in Eastern Indonesia. Furthermore, the model is applied to PT SMS, an industrial case that has not previously been studied with respect to its raw material procurement system. Based on these considerations, this study aims to design a system dynamics model for raw material procurement to increase sugarcane-based WCS production at PT SMS. The model is expected to generate recommendations for sugarcane raw material procurement planning, supporting the company's target of meeting national WCS needs, particularly in the eastern region.

RESEARCH METHOD

Research Time and Location

The research was conducted from April 2024 to May 2025. It was carried out at PT SMS, Pekat Subdistrict, Dompu Regency, West Nusa Tenggara Province. The research location was selected using purposive sampling because it was the only sugar factory and sugarcane plantation operating in West Nusa Tenggara that had not yet achieved optimal production performance.

Data Types and Sources

The data used in this study consist of primary and secondary data. Primary data was collected through field observations and interviews with stakeholders of PT SMS's raw material procurement system. Secondary data were obtained from various sources, including literature reviews, company internal documents and reports, as well as government agencies such as the Central Bureau of Statistics (BPS), the Department of Agriculture and Plantations of Dompu Regency, the Department of Industry, and the Department of Agriculture and Plantations of West Nusa Tenggara Province.

Research Stages

The stages of this study follow the system approach stages described by Manetsch and Park [25]. The research was conducted through the verification and validation stages, followed by the proposal of recommendations for the optimal scenario in raw material procurement based on the model simulations performed. The research stages are presented in Figure 1.

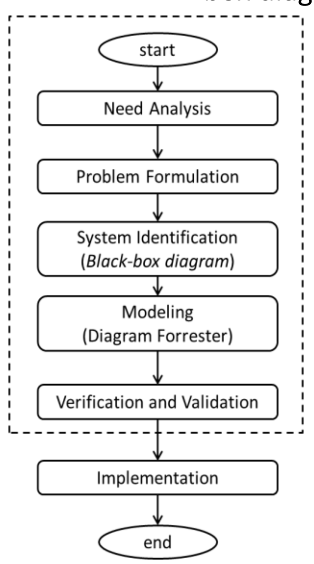

Figure 1. Research Stages

1.1 Need Analysis

Initial stage in conducting a system study, aimed at identifying the needs of each system stakeholder, including PT SMS, partner farmers, livestock breeders, consumers, and relevant government authorities.

1.2 Problem Formulation

At this stage, the contradictory needs of stakeholders are identified, which may hinder the achievement of the system's objectives. The details of these contradictory needs require resolution. Therefore, this stage serves as a foundation for achieving the final goals of the modeling process.

1.3 System Identification

System identification was carried out to understand the mechanisms involved, with the aim of analyzing the relationship between the statement of needs and the statement of problems that must be addressed to fulfill those needs. The approach used at this stage involved constructing an input-output diagram (black box diagram).

1.4 Modeling

Modeling was carried out using a Forrester diagram, which serves as the basis for establishing quantitative relationships among variables. Based on this diagram, computer programming was performed

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using Microsoft Visual Basic 6.0. The sugarcane raw material procurement model was developed using three submodels: the plantation submodel, which analyzes the amount of sugarcane produced from the cultivated land area; the production submodel, which analyzes the volume of WCS production and the utilization ratio of the factory's installed milling capacity on an annual basis; and the demand submodel, which calculates the WCS demand in Eastern Indonesia (NTB, NTT, Makassar) and analyzes the level of demand fulfillment by PT SMS.

1.5 Verification and Validation

The model was simulated with 2019 as the starting point (t = 0). Subsequently, verification and validation were conducted to assess the model's consistency with the real system. Verification was performed by checking the model's structure and parameters. Meanwhile, validation was carried out using Theil's Test (Theil's Inequality Statistics), which decomposes the Mean Squared Error (MSE) into three components: U^m, U^s, and U^c. The mathematical equations for each component are as follows [26] :

$$U^m = \frac{(\bar{S} - \bar{A})^2}{MSE} \quad (1)$$

$$U^s = \frac{(S_S - S_A)^2}{MSE} \quad (2)$$

$$U^c = \frac{2(1-r)S_S S_A}{MSE} \quad (3)$$

Description:

U^m : Bias
U^s : Unequal variation
U^C : Unequal covariation
$\bar{S}$: Mean of simulated values
S_A : Standard deviation of actual values
S_S : Standard deviation of simulated values
r : Coefficient of correlation
$\bar{A}$: Mean of actual values
MSE : Mean Squared Error

RESULT AND DISCUSSION

Situational Overview

As the raw material for white crystal sugar (WCS) production at PT SMS, sugarcane is sourced from nucleus estates, which the company directly manages under the Right to Cultivate status, and plasma farms, which are farmer-owned lands managed under a partnership scheme. Currently, the nucleus estate covers 5,500 hectares, while the potential land area owned by partner farmers is 4,751 hectares in the eastern region and 7,130 hectares in the western region of the factory. The partnership is carried out through a buy-out system, accompanied by seed subsidies for planting on newly developed land. However, in 2023, there was a decline of 33.81% in the nucleus estate. The conversion rate from planted to harvested area in the nucleus estate averaged only 17.38% from 2019 to 2022 but rose significantly to 77.09% in 2023. In contrast, partner farms demonstrated relatively stable conversion efficiency, with an average of 75.53%. One of the factors contributing to the low conversion rate in the nucleus state in previous years was the high incidence of livestock pest attacks, which damaged the sugarcane before the harvest period.

In 2023, the total production of sugarcane raw material reached 230,653.78 tons, sourced from the nucleus estate and partner

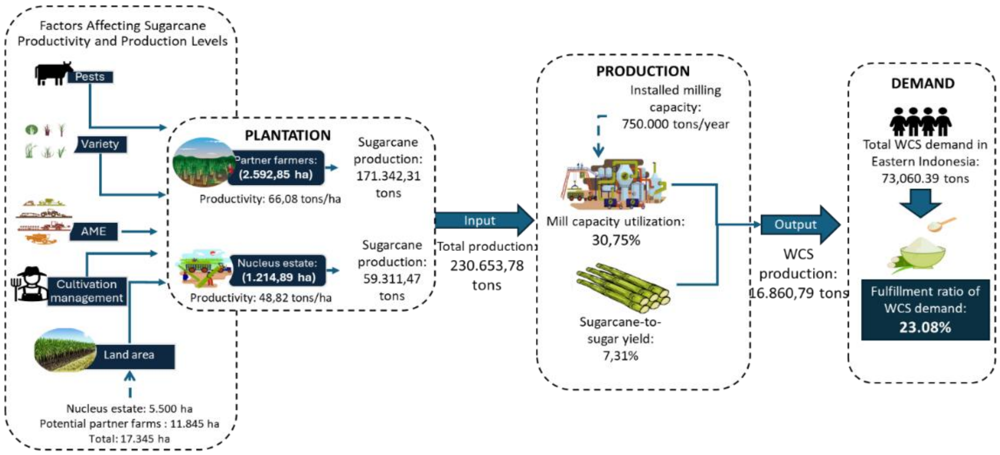

Figure 2. Rich picture of the integrated sugarcane raw material procurement system at PT SMS

farmers' plantations, with harvested areas of 1,214.89 and 2,592.85 hectares, respectively. The productivity of the nucleus estate was 48.82 tons per hectare, while that of the partner farmers' plantations reached 66.08 tons per hectare. With a sugarcane yield of 7.31%, the total production of WCS amounted to 16,860.79 tons. Meanwhile, the total population of the NTB, NTT, and Makassar regions in the same year reached 12,603,748 people. Based on the national average WCS consumption of 5.8 kg/capita/year, the total WCS demand amounted to 73,060.39 tons. Consequently, PT SMS contributed only 23.08% to meeting the total demand in this region. The integrated sugarcane-based raw material procurement system, encompassing plantation, production, and demand subsystems, is illustrated in Figure 2.

System Dynamic Model

Need Analysis

The stakeholders involved in sugarcane raw material procurement at PT SMS have specific needs that can influence the system's performance. The results of the needs analysis are presented in Table 1.

Table 1. Results of the analysis for sugarcane raw material procurement at PT SMS

Stakeholder	Needs
Partner farmers	a. Mechanization for land preparation and extensification processes
	b. Increased sugarcane land productivity
	c. Low cultivation costs
Livestock Breeders	a. Adequate livestock crossing pathways
PT SMS	a. Increased number of partner farmers
	b. Increased supply of raw materials
	c. Higher utilization of milling capacity
	d. Optimal use of the nucleus estate land
	e. Expansion of partner farmers' sugarcane areas
Government	a. Increase in the number of partner farmers
	b. Availability of sufficient and high-quality sugarcane seeds
	c. Expansion of sugarcane planting areas
	d. Improved farmers' welfare
	e. Increased WCS production
Consumer	a. Fulfillment of WCS demand

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Problem Formulation

Based on the identification results from the previous stage, several synergistic and contradictory needs were found. Three needs were identified as conflicting among stakeholders, which could hinder the achievement of system objectives: optimal use of the nucleus estate, farmers' cultivation costs, and the availability and adequacy of raw materials in terms of quantity and quality. Table 2 presents the results of the problem formulation.

Table 2. Problem formulation results for sugarcane raw material procurement at PT SMS

Contradictory needs	Remarks	Alternative solution
Optimal use of the nucleus estate for sugarcane cultivation	The company aims to optimize sugarcane cultivation in the nucleus estate, but livestock breeders allow their animals to enter the estate and damage the sugarcane crops	An agreement on the allocation of the nucleus estate utilization between cattle breeders and PT SMS, facilitated by the government
Cultivation costs of partner farmers	When farmers carry out land preparation, the costs are high due to minimal subsidies from the company for these activities	Increase in the types of subsidies provided by the company for partner farmers
Availability and adequacy of sugarcane raw materials in terms of quantity and quality	The sugarcane supply is still insufficient to meet the company's needs for fulfilling East Indonesia's WCS demand	Expansion of sugarcane cultivation area and improvement of land productivity

System Identification

The input-output diagram was developed based on the established model scope. This diagram illustrates the outputs generated from the given inputs. The desired output is the quantity of sugarcane procurement needed to meet WCS demand in Eastern Indonesia, while undesired output, represented by the unmet quantity of sugarcane procurement, is fed back into the system through management control mechanisms. This feedback process allows adjustment of controllable inputs to minimize the gap and achieve the desired output. The input-output diagram for PT SMS's sugarcane procurement system is presented in Figure 3.

Figure 3 illustrates the input–output structure of the sugarcane raw material procurement system at PT SMS. The system is influenced by controlled inputs, uncontrolled inputs, and environmental factors that affect the achievement of the desired output, namely fulfilling sugar demand in Eastern Indonesia. A feedback management mechanism is also included to evaluate undesired outputs and support continuous system improvement. Controlled inputs include managerial and operational factors that can be directly regulated by the company, such as partnership patterns, plantation management systems, and installed factory capacity. In contrast, uncontrolled inputs represent external factors that may influence procurement performance, including climate, population growth, sugar consumption, and pest disturbances. Environmental inputs, particularly government programs and policies, also play an important role in shaping procurement system performance.

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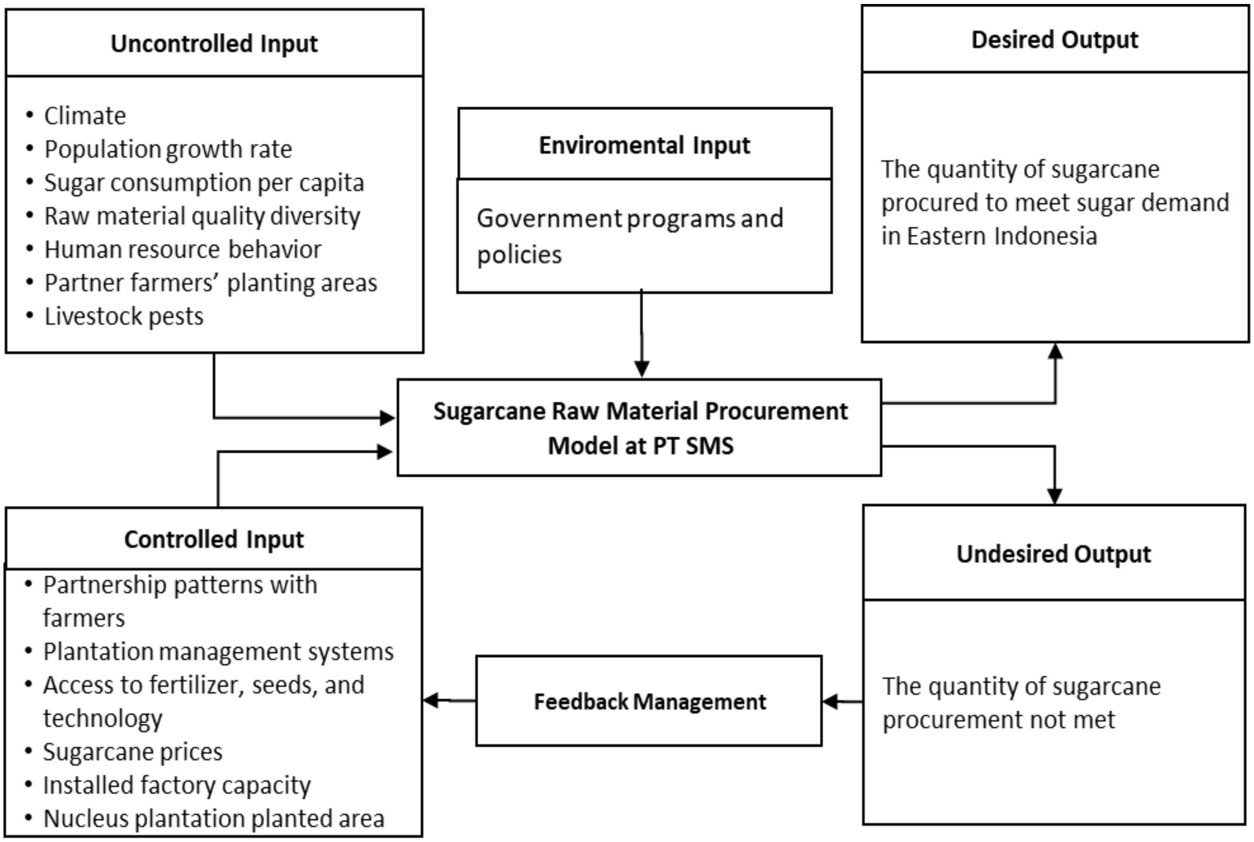

Figure 3. Input-output diagram of the sugarcane procurement system at PT SMS

Modeling

Modeling the system consists of the plantation, production, and demand submodels. Each submodel is interconnected, forming the overall dynamic system model for sugarcane raw material procurement at PT SMS. The relationships among variables in the model are illustrated using a Forrester Diagram, which represents the interactions, feedback loops, and dynamic behavior within the system. Based on this diagram, mathematical equations are developed through the flow of information from one variable or rate to another. This approach enables the simulation of system behavior under different scenarios and supports decision-making in raw material procurement planning. Figure 4 shows the Forrester diagram of the overall model.

Verification and Validation

Several assumptions are used in the simulation. n the plantation submodel, the conversion of partner farmers to planted area is assumed to be 0.99 hectares/person, and a Rp1 increase in net income adds 5.42 $\times 10^{-5}$ partner farmers. In the production submodel, 150 milling days per year are assumed. Meanwhile, in the demand submodel, the average national WCS consumption is assumed to be 6.63 kg/capita/year with a growth rate of -3.84. The population growth rate is set at 1.38% per year, with a population of 12,053,265 in 2019. These assumptions were used as baseline parameters to simulate the dynamic behavior of the sugarcane raw material procurement system under various conditions and scenarios.

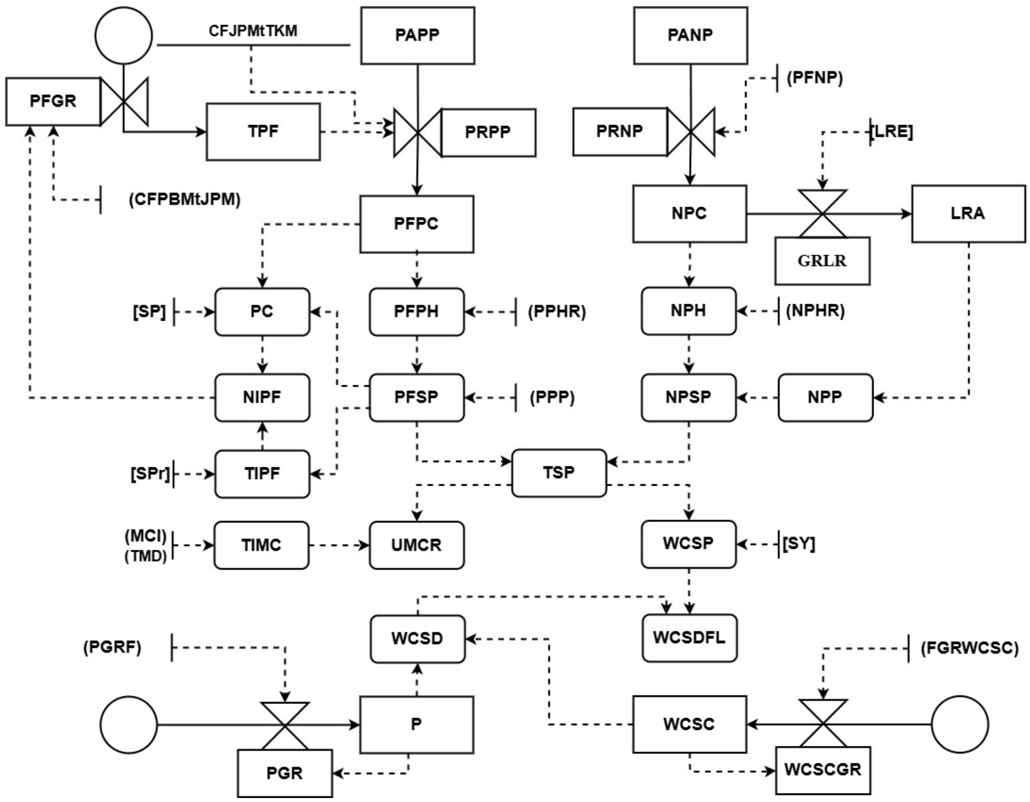

Figure 4. Forrester Diagram of the sugarcane raw material procurement model at PT SMS

Nomenklatur

PFGR	Partner Farmers Growth Rate (person/year)	TMD	Total milling days(days)
CVJPMtTKM	Conversion Factor JPM to TKM (ha/person)	PANP	Potential Area of Nucleus Plantation (ha)
TPF	Total Partner Farmers (person)	PRNP	Planting Rate Nuclues Plantation (ha/year)
PRPP	Planting Rate Partner Plantation (ha/year)	PFNP	Planting Fraction Nucleus Plantation (%)
CFPBMtJPM	Conversion Factor of PBM to JPM (person/IDR)	NPC	Nucleus Plantation Cultivated (ha)
PAPP	Potential Area of Partner Plantation (ha)	LRE	Livestock Route Expansion (ha)
PFPC	Partner Farmers Plantation Cultivated (ha)	GRLR	Growth Rate of Livestock Route (ha)
PFPH	Partner Farmers Plantation Harvested (ha)	LRA	Livestock Route Area (ha)
PPP	Productivity Partner Plantation (ton/ha)	NPSP	Nucleus Plantation Sugarcane Production (tons)
PPHR	Partner Plantation Harvest Ratio (%)	NPP	Nucleus Plantation Productivity (ton/ha)
TSP	Total Sugarcane Production (ton)	NPHR	Nucleus Plantation Harvest Ratio (%)
UMCR	Utilized Milling Capacity Ratio (%)	NPH	Nucleus Plantation Harvested (ha)
TIMC	Total Installed Milling Capacity (ton/year)	WCSP	WCS Production (ton)
TIPF	Total Income Partner Farmers (IDR)	SY	Sugarcane Yield (%)
NIPF	Net Income Partner Farmers (IDR)	WCSDFL	WCS Demand Fulfillment Level (%)
PC	Production Cost (IDR)	WCSC	WCS Consumption (ton/person)
SP	Subsidy Program (type)	WCSD	WCS Demand (ton)
SPr	Sugarcane Price (IDR/ton)	P	Population (person)
MCI	Milling Capacity Installed (TCD)	PGRF	Population Growth Rate Fraction (%/year)
WCSCGR	WCS Consumption Growth Rate (ton/person/year)	PGR	Population Growth Rate (person/year)
FGRWCSC	Fractional Growth Rate of WCS Consumption (%/year)	PFP	Partner Farmers Sugarcane Production (ton)

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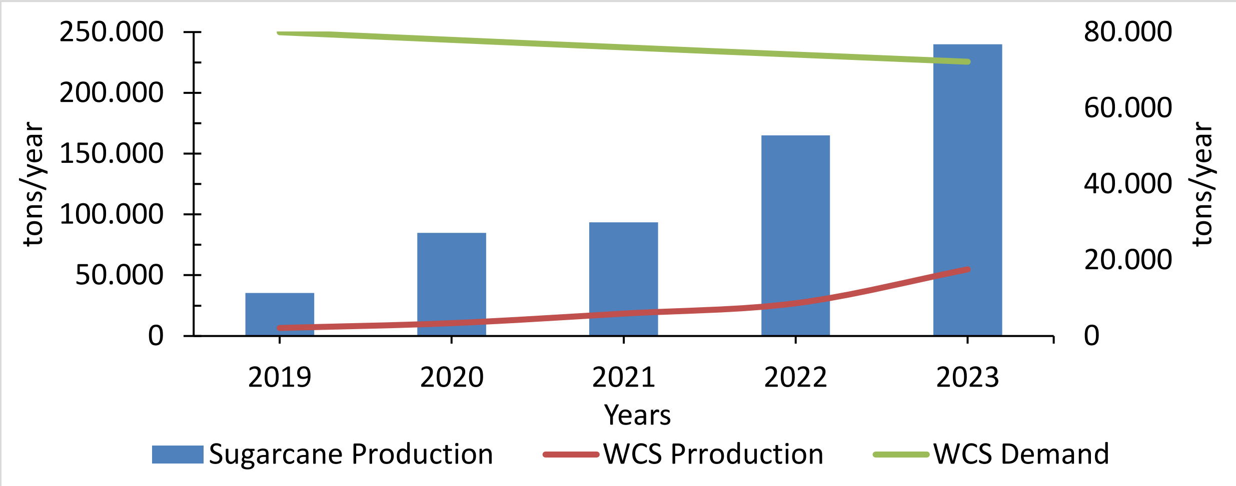

Figure 5. Simulation of total sugarcane production, WCS production, and WCS demand under existing conditions

Figure 5 presents the simulation results for 2019–2023 under existing conditions for each submodel parameter.

As shown in Figure 5, the overall WCS demand exhibits a decreasing trend of –2.52%, reflecting the combined effect of population growth and declining per capita WCS consumption. In contrast, sugarcane and WCS production display similar upward trends, as WCS output is linearly dependent on the amount of milled sugarcane supply.

Model validation was carried out through a quantitative assessment of the agreement between the predicted results and the actual data. The scatter plots comparing the actual data with the predicted values are illustrated in Figure 6(a) - 6(c). Based on this figure, the distribution of points in the plantation and production submodels lies close to the ideal line, indicating good predictive capability. However, several prediction points in the demand submodel deviate from the ideal line because the model produces predicted values that underestimate the actual data.

Meanwhile, Table 3 presents the validation results using Theil's test. The analysis of Theil's coefficient values in the table shows that most of the prediction errors in the

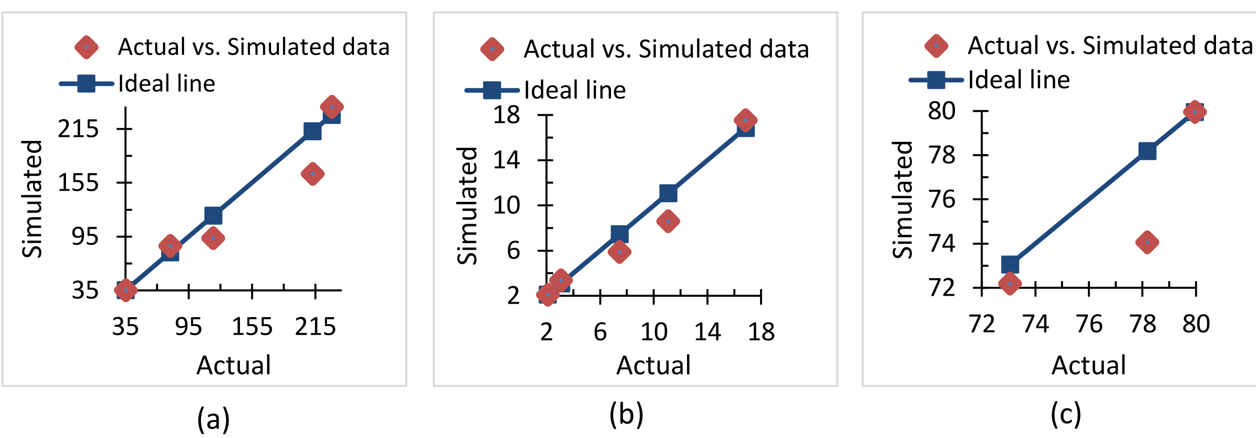

Figure 6. Scatter plots comparing actual data with simulated results (in thousand tons): (a) Plantation submodel, (b) Production submodel, and (c) Demand submodel

plantation and production submodels originate from the U^c components, with values of 0.762 and 0.791, respectively. In contrast, the contributions of systematic errors (U^m and U^s) are relatively small, indicating that the errors in both submodels are primarily due to noise.

Table 3. Theil's test results

Parameter	U^m	U^s	U^c
Sugarcane production	0.206	0.032	0.762
WCS production	0.207	0.002	0.791
WCS demand	0.611	0.004	0.385

On the other hand, the demand submodel indicates that most errors originate from the U^m component, with a value of 0.611, suggesting systematic discrepancies between the predicted and actual data. However, as this submodel aims to estimate the long-term behaviour of WCS demand, short-term differences are disregarded, allowing the overall model to effectively understand, predict, and support policy formulation for improving system performance.

Model Simulation

Policy Interventions are required to increase sugarcane supply and expand PT SMS's utilized capacity to meet the WCS demand of Eastern Indonesia. The policy scenarios analyzed are as follows:

a) Scenario 1

Scenario 1 involves increasing the sugarcane price from IDR 500,000/ton under existing conditions to IDR 540,000/ton, considering the average inflation rate of 2.63% over the period from 2023 to 2025.

b) Scenario 2

The company's current subsidy program for partner farmers includes free seedlings for new planting areas. Scenario 2 introduces new subsidy types, specifically machinery rental and fertilizer costs, tailored to meet farmers' needs and build on past experiences with subsidies. This scenario assumes the removal of ratoon sugarcane that has been cultivated for five years since planting.

c) Scenario 3

The existing sugarcane yield is 7.31%, while the target set in Presidential Regulation *(Perpres)* No. 40 of 2023 is 8.05%. Therefore, Scenario 3 is designed to increase the sugarcane yield by 50% of the gap between the current condition and the national target, resulting in a yield of 7.68% in this scenario. This target is considered realistic and conservative for PT SMS, reflecting gradual improvement toward the national target.

d) Scenario 4

Scenario 4 expands livestock crossing routes within the nucleus estate from 70 ha to 210 ha, based on the needs of livestock farmers identified through field interviews. This intervention aims to reduce crop damage caused by animals entering the plantation. The scenario assumes an increase in nucleus estate productivity from 48.82 ton/ha to 67.91 ton/ha, calculated as 50% of the gap

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toward the national productivity target of 87 ton/ha (Presidential Regulation No. 40 of 2023).

e) Scenario 5

Scenario 5 employs an integrative approach that combines technical, agronomic, and economic aspects, representing the combination of Scenarios 2, 3, and 4 to promote holistic improvement. This approach aligns with the good milling sugarcane cultivation principles as stipulated in Regulation of the Minister of Agriculture (*Permentan*) No. 53 of 2015.

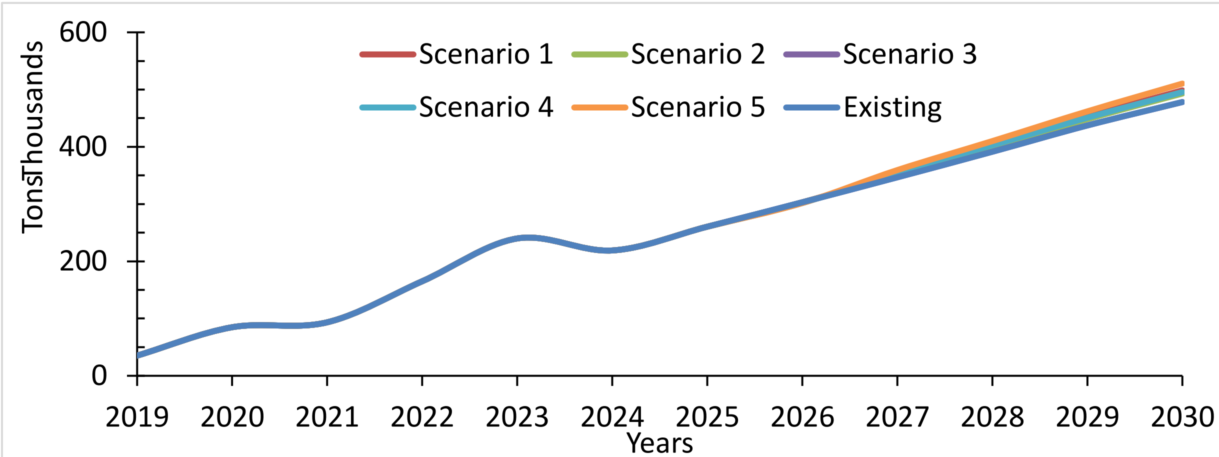

Figure 7. Simulated sugarcane production under different intervention scenarios

The impact of various intervention scenarios was analyzed based on the model simulation results. As shown in Figure 7, Scenarios 1, 2, 4, and 5 all demonstrated an increase in sugarcane production compared to the existing condition from the beginning of the intervention implementation. Meanwhile, Scenario 3 did not show any improvement over the existing condition, resulting in sugarcane production of only 478,165.75 tons in 2030, with a milling utilization rate of 63.76%, as it focused solely on improving sugarcane yield without increasing raw material production. Scenario 1, based on price increases, achieved an average annual production growth of 2.38% relative to the existing condition, resulting in 498,604.16 tons of sugarcane production in 2030, with a milling utilization rate of 66.48%. Scenarios 2 and 4 achieved average annual increases of 1.67% and 2.39%, producing 493,028.49 tons and 495,533.82 tons, with milling utilization rates of 65.74% and 66.07%, respectively.

Scenario 5, the integrative approach, yielded the highest performance, with an average annual growth of 4.06% compared to the existing condition, resulting in 510,396.56 tons of sugarcane and achieving a milling utilization rate of 68.05% by 2030. This improvement is attributed to an enhancement in overall model performance, a finding that confirms that integrating various cultivation methods and technologies into a single package is a more effective and efficient strategy for increasing sugarcane and sugar yields [27].

The increase in sugarcane production affects the amount of WCS produced by PT SMS. The predicted WCS demand and production under each intervention scenario are presented in Figure 8. Based on the figure, all

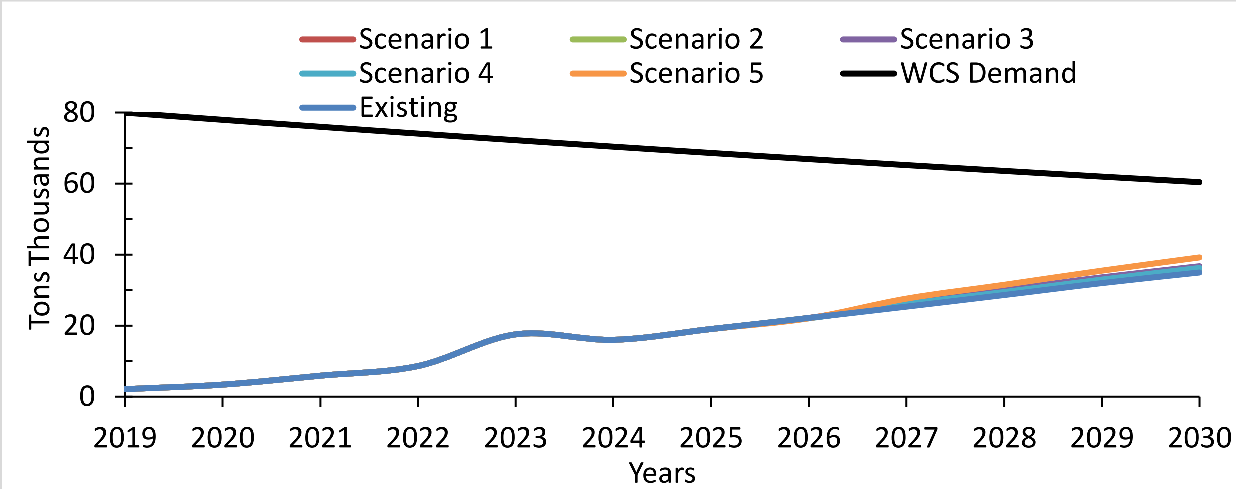

Figure 8. Simulated WCS demand and WCS production under different intervention scenarios

alternative intervention scenarios show annual increases in WCS production. At the same time, WCS demand for Eastern Indonesia continues to decline at a rate of -2.52% per year, resulting in a projected demand of 60,389.21 tons in 2030. Despite these production improvements, none of the alternative scenarios will be able to meet the WCS demand in 2030 fully. However, Scenario 5 achieves the highest performance, with an average annual increase of 8.32%, producing 39,198.46 tons and fulfilling 64.91% of total demand. Scenario 3 yields a growth rate of 4.05%, resulting in 36,723.13 tons and meeting 60.81% of demand. This improvement is primarily driven by the increase in sugarcane yield, which exhibits a strong correlation with WCS production.

Scenarios 1, 2, and 4 demonstrate more moderate improvements, with average annual increases of 2.38%, 1.67%, and 2.39%, resulting in WCS outputs of 36,447.96, 36,040.38, and 36,223.52 tons, respectively. These production levels correspond to WCS demand fulfillment rates of 60.36%, 59.68%, and 59.98%. In contrast, the simulation under existing conditions produces only 34,953.92 tons of WCS, indicating that without policy interventions, the capacity to meet WCS demand in 2030 would reach only 57.88%. These findings reinforce those of the previous study [28], which emphasizes that intervention strategies—whether through price incentives, subsidies, or technical and institutional improvements—can sustainably enhance the productivity and efficiency of WCS production systems.

Managerial Implications

The procurement of raw materials to increase WCS production at PT SMS was carried out through five intervention scenarios. Based on the analysis, the most effective scenario in achieving the goal of enhancing WCS production was Scenario 5, which combines Scenarios 2, 3, and 4. The managerial implications of this scenario highlight the importance of synergy among stakeholders. In 2026, the expansion of livestock corridors within the nucleus estate and the introduction of new types of subsidies will take place, leading to the initiation of periodic ratoon stubble clearing in sugarcane fields that have reached 4–5 years of age since the initial planting (plant cane). In addition, efforts will be made to strengthen human resource competencies and implement Good Agricultural Practices (GAP) in accordance with sugarcane cultivation guidelines, both by partner farmers and the company, to achieve a sugarcane recovery rate of 7.68% by 2027. Consequently, by 2030, sugarcane production is projected to increase by 6.74% compared to the existing conditions, reaching 510,396.56 tons with a milling capacity utilization rate of 68.05%. Similarly, WCS production shows a 12.14% increase, reaching 39,198.46 tons and fulfilling 64.91% of the total WCS demand.

CONCLUSION

This study has successfully analysed the existing condition of the sugarcane raw material procurement system at PT SMS. The results of the analysis show that the sources of raw material are the nucleus estate and partner farms. However, these sources remain insufficient to meet the raw material needs for WCS demand in Eastern Indonesia. The system dynamics model demonstrated consistency with actual data, making it useful for understanding real system behaviour and formulating policies to improve its performance. The selected scenario to enhance the model's performance is Scenario 5, which is a combined scenario implemented through the expansion of subsidy types to include seedlings, machinery rental costs, and fertilizers; an increase in the sugarcane recovery rate to 7.68%; and expands livestock crossing routes within the nucleus estate from 70 ha to 210 ha. Under this scenario, the amount of sugarcane-based raw material projected to be produced in 2030 increases by 6.74% compared to the existing condition, reaching 510,396.56 tons, with the factory's milling capacity utilization rising to 68.05%. This enhancement results in 39,198.46 tons of WCS production, representing a 12.14% increase from the existing condition, thereby meeting 64.91% of the WCS demand in Eastern Indonesia. In future research, model development could be enhanced by incorporating stochastic factors to better represent the uncertainties inherent in the real-world system

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Complementary Subtitles:

APPENDIX

Table 1 Model Parameters

No	Parameter	Value	Unit
	Initial simulation year (*t=0*)	2019	year
		Plantation Submodel	
1	Nucleus Plantation Cultivated ($NPC_{t=0}$)	764.85	ha
2	Planting Fraction Nucleus Plantation ($PFNP_t$)	TIME; 2020; 1; {122.10; 31.66; 6.45; -33.81; ≥2024:19.06}	%
3	Nucleus Plantation Productivity (NPP_t)	TIME; 2019; 1; {≤2023:23.00; 80.63; 37.91; 47.69; 48.82; ≥2024:48.82}	ton/ha
4	Nucleus Plantation Harvest Ratio ($NPHR_t$)	TIME; 2019; 1; {15.49; 11.27; 23.25; 19.50; 77.09; ≥2024:19.50}	%
5	Livestock Route Area ($LRA_{t=0}$)	70	ha
6	Potential Area of Nucleus Plantation (PANP)	5,500	ha
7	Potential Area of Partner Plantation (PAPP)	11,881	ha
8	Partner Farmers Plantation Cultivated ($PFPC_{t=0}$)	950.11	ha
9	Productivity Partner Plantation (PPP_t)	TIME; 2019; 1; {55.83; 67.32; 61.63; 82.13; 66.08; ≥2024:66.08}	ton/ha
10	Partner Plantation Harvest Ratio ($PPHR_t$)	TIME; 2019; 1; {61.35; 92.06; 62.04; 75.05; 87.17; ≥2024:75.05}	%
11	Total Partner Farmers ($TPF_{t=0}$)	1,004	person
12	Cost of Land Tax (CLT)	105,000	IDR/ha
13	Depreciation Cost (DC)	1,072,000	IDR/ha
14	Fertilizer Cost (FC)	1,530,000	IDR/ha
15	Pesticide Cost (PC)	840,000	IDR/ha
16	Planting Labor Cost (PLC)	1,500,000	IDR/ha
17	Harvesting Labor Cost (HLC)	120,000	IDR/ton
18	Machine Rental Cost (MRC)	1,200,000	IDR/ha
19	Seedling Cost (SC)	2,500,000	IDR/ha
20	Subsidy Program (SP)	Seedling	type

No	Parameter	Value	Unit
21	Conversion Factor JPM to TKM (CFJPMtTKM)	0.99	ha/person
22	Conversion Factor of PBM to JPM (CFPBMtJPM)	5.42×10^{-5}	person/IDR
23	Sugarcane Price (SPr)	500,000	IDR/ton
	Production Submodel		
1	Milling Capacity Installed (MCI)	5,000	TCD
2	Total Milling Days (TMD)	150	days
3	Sugarcane Yield (SY_t)	TIME; 2019; 1; {5.98; 3.99; 6.31; 5.22; 7.31; ≥2024:7.31}	%
	Demand Submodel		
1	Population ($P_{t=0}$)	12,053,265	person
2	Population Growth Rate Fraction (PGRF)	1.38	%/year
3	WCS Consumption ($WCSC_{t=0}$)	6.63×10^{-3}	ton/person
4	WCS Consumption Growth Rate (WCSCGR)	-3.84	%/year

Table 2 Model Variables

No	Variable	Equations	Unit
	Plantation Submodel		
1	Planting Rate Nuclues Plantation ($PRNP_t$)	$PFNP_t$x NPC_{t-1}	ha/year
2	Nucleus Plantation Cultivated (NPC_t)	NPC_{t-1}+ $PRNP_t$	ha
3	Nucleus Plantation Harvested (NPH_t)	NPHR x NPC_t	ha
4	Growth Rate of Livestock Route (GRLR)	LRE	ha
5	Livestock Route Area ($LRA_{t=1}$)	LRA_{t-1}+ LRE	ha
6	Nucleus Plantation Sugarcane Production ($NPSP_t$)	NPH_t x NPP_t	ton
7	Total Income Partner Farmers ($TIPF_t$)	$PFSC_t$ x SPR	IDR

No	Variable	Equations	Unit
8	Production Cost (PC_t)	(CLT + DC + FC + PC) x $PFPC_t$ + (PLC + MRC + SC) x $PRPP_t$) + (HLC x $PrTKM_t$) – (SC x $PRPP_t$)	IDR
9	Net Income Partner Farmers ($NIPF_t$)	$TIPF_t$ – BPM_t	IDR
10	Partner Farmers Growth Rate ($PFGR_t$)	CFPBMtJPM x $\frac{NIPF_{t-1}}{TPF_{t-1}}$	person/year
11	Total Partner Farmers (TPF_t)	$TPF_{t-1} + PFGR_t$	person
12	Planting Rate Partner Plantation ($PRPP_t$)	CFJPMtTKM x ($TPF_t - TPF_{t-1}$)	ha/year
13	Partner Farmers Plantation Cultivated ($PFPC_t$)	$PFPC_{t-1} + PRPP_t$	ha
14	Partner Farmers Plantation Harvested ($PFPH_t$)	PPHR x $PFPC_t$	ha
15	Partner Farmers Sugarcane Production ($PFSC_t$)	$PFPH_t$ x PPP	ton
16	Total Sugarcane Production (TSP_t)	$NPSP_t + PFSC_t$	ton
		Production Submodel	
1	WCS Production ($WCSP_t$)	TSP_t x SY	ton
2	Total Installed Milling Capacity (TIMC)	MCI x TMD	ton/year
3	Utilized Milling Capacity Ratio ($UMCR_t$)	$\frac{TSP_t}{TIMC}$ x 100%	%
		Demand Submodel	
1	WCS Consumption Growth Rate ($WCSCGR_t$)	WCSCGR x $WCSC_{t-1}$	ton/person/year
2	WCS Consumption ($WCSC_t$)	$WCSC_{t-1} + WCSCGR_t$	ton/person
3	Population Growth Rate (PGR_t)	PGRF x P_{t-1}	person/year
4	Population (P_t)	$P_{t-1} + PGR_t$	person
5	WCS Demand ($WCSD_t$)	$WCSC_t$ x P_t	ton
6	WCS Demand Fulfillment Level ($WCSDFL_t$)	$\frac{WCSP_t}{WCSD_t}$ x 100%	%