

Policy Scenarios in the System Dynamics Model of Indonesia's Sugar Supply and Demand for the National Food Self-Sufficiency Strategy

Cordova Maulana Wanggai and Armand Omar Moeis

Department of Industrial Engineering

Faculty of Engineering

Universitas Indonesia

Depok, 16424, Indonesia

cordova.maulana@ui.ac.id, armand.omar@ui.ac.id

Abstract

Indonesia's national sugar market continues to face a structural imbalance between demand and supply, as reflected in high import dependency and the persistent failure to achieve sugar self-sufficiency targets. This condition is driven by limited sugarcane productivity, evolving consumption patterns, and complex interactions among actors within the national sugar industry ecosystem. This study aims to design and evaluate appropriate government policies to balance national sugar demand and supply in order to enhance self-sufficiency while maintaining price stability. A system dynamics approach is employed to capture the integrated dynamics of the sugar industry by incorporating the roles of sugarcane farmers, processing industries, government, and trading actors through the development of causal loop diagrams and stock-and-flow diagrams. The model is simulated under three main scenarios which are Business-as-Usual, Economic Boom, and Worsening Climate, with consistent testing of policy interventions in the form of import tariff adjustments and improvements in domestic sugar productivity. Simulation results indicate that, without significant policy intervention, the system tends to maintain long-term dependence on imports. Increasing domestic sugar productivity emerges as the most effective strategy for reducing the self-sufficiency gap, while import tariffs function mainly as a short-term balancing instrument.

Keywords

System Dynamics, Sugar Industry, Policy Scenarios, Supply and Demand

1. Introduction

Food security is a strategic issue that is directly related to national sovereignty, as it encompasses the availability, accessibility, stability, and quality of food for the entire population (Indonesia, 1996). Within the national legal framework, defines food security as a condition in which food is sufficiently available for the state and individuals, characterized by adequate quantity and quality, safety, nutritional value, equitable distribution, and affordability, and represents a shared responsibility between the government and society (Indonesia 2012). Food security is understood as an integrated system consisting of food availability, accessibility, and quality and safety subsystems, whose performances are interrelated.

In this context, sugar is one of Indonesia's strategic food commodities due to its dual role as a household consumption good and as a key input for the food and beverage industry (Indonesia, 2004). The government employs the Import Dependency Ratio (IDR) and the Self-Sufficiency Ratio (SSR) to assess the degree of import dependence and domestic production capacity (BPN, 2023). Empirical data indicate that sugar exhibits a high level of import dependency, signaling a structural imbalance between national sugar demand and supply (Figure 1).



Figure 1. Sugar Production and Consumption

A comparison between domestic sugar production and consumption reveals that national production capacity remains insufficient to meet domestic demand (BPS, 2023). Furthermore, the production and consumption ratio is declining year over year, with fulfillment levels far below the 90 percent self-sufficiency threshold (FAO, 2023). As a result, sugar imports function as the primary mechanism for balancing domestic supply, while simultaneously reflecting persistent structural dependence. On the demand side, population growth and rising incomes continue to drive sugar consumption, whereas on the supply side, limited sugarcane productivity, constrained cultivated area, and inefficiencies in processing industries constitute major bottlenecks (Kementerian Pertanian, 2024).

1.1 Objectives

The objective of this study is to analyse the Indonesian sugar self-sufficiency system by examining key indicators under business-as-usual and alternative scenarios to test the effectiveness of strategic policy interventions. More specifically, this study is conducted with the Government of Indonesia as the problem owner and finding out how appropriate policy modeling be designed in order to balance national sugar supply and demand with the goal of increasing the level of self-sufficiency and maintaining price stability. Furthermore, multiple alternative scenarios will be conducted to provide a better understanding of the problem owners policy strategy capabilities in keeping its goals. This study analyses the Indonesian sugar self-sufficiency system by examining key indicators under business-as-usual and alternative scenarios to test the effectiveness of strategic policy interventions.

2. Literature Review

This study is grounded in three main theoretical foundations: simulation theory, system dynamics theory, and policy theory. These theories are integrated to construct the model, analyze system behavior, and evaluate government policies under long-term uncertainty.

2.1 Simulation

Simulation as a method for imitating the operation of a real system using computer-based models to enable systematic analysis (Law and Kelton, 1991). Simulation allows researchers to understand system behavior and evaluate policy alternatives without direct intervention in the real system (Shannon, 1998).

2.2 System Dynamics

System dynamics is a method for understanding complex industrial systems that emphasizes that system behavior is determined not merely by individual components, but primarily by internal structures, including feedback loops, time delays, and nonlinear relationships among variables (Forrester, 1961). System dynamics aims to understand complex system behavior, identify structural causes of problems, and evaluate policy resistance (Sterman, 2000). In this approach, models are not only descriptive, but also explanatory and prescriptive, as they can reproduce historical behavior and assess future policy alternatives.

2.3 Policy Analysis

Policy analysis is understood as a rational and systematic process for generating information about the consequences of alternative policy options (Walker, 2000). Policy analysis is not purely technical, but also involves value judgments, trade-offs, and uncertainty (Bardach 2000). It is said that many policies fail because they do not account for feedback structures and time delays, leading to unintended outcomes (Sterman, 2000). Within the system dynamics framework, policy is conceptualized as a modification of system structure or parameters that influences long-term behavior. Heineman (1990) also argues that because human values and meaning cannot be separated from analysis, social sciences cannot attain the rigidity of physical sciences; nevertheless, policy analysis remains scientific by being transparent, empirical, consistent with existing knowledge, and verifiable.

With the three main theoretical foundations, this study builds upon it by adopting a scenario-based policy approach in which external uncertainties are explicitly incorporated into policy evaluation. Where scenarios simulations are used not as forecasts, but as analytical tools to test the robustness and effectiveness of policies under various plausible futures.

3. Methods

This study employs a system dynamics approach to model and analyze national sugar demand–supply dynamics within the context of food security. System dynamics is an appropriate and robust methodological approach for this study due to the inherently complex and interdependent nature of the Indonesian sugar industry. This approach enables the integration of these interacting variables into a coherent system structure, allowing the study to explicitly model feedback loops, time delays, and accumulations that characterize the long-term behavior of the industry. By representing causal relationships among economic, institutional, and operational factors, system dynamics provides a comprehensive understanding of how policy interventions or external shocks propagate through the future system behavior.

Key actors were identified in Indonesia’s sugar industry along with their influence on the system. Based on the actor analysis, the system diagram in Figure 2 is constructed as an initial conceptual framework for system dynamics modeling.

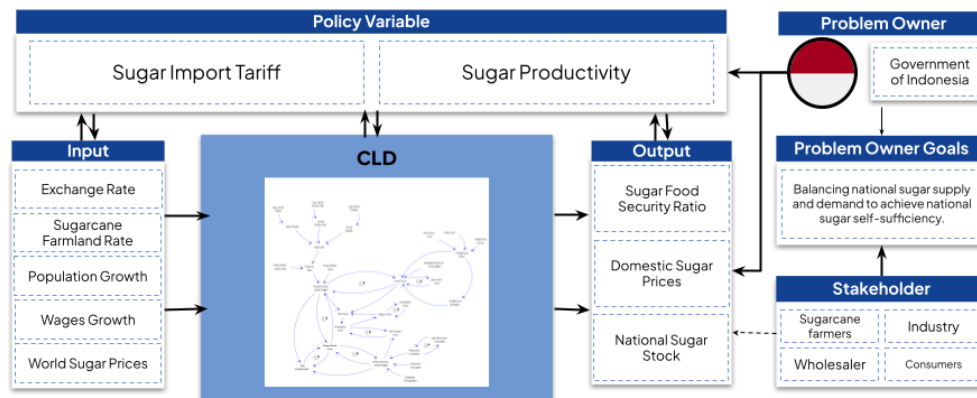


Figure 2. System Diagram

The system diagram delineates system boundaries, key actors, internal variables, external variables, and interactions among components within the national sugar industry is further developed in a causal loop diagram (CLD) of the model illustrated in Figure 3. The CLD itself is used to identify feedback structures that shape system behavior, including both reinforcing loops and balancing loops.

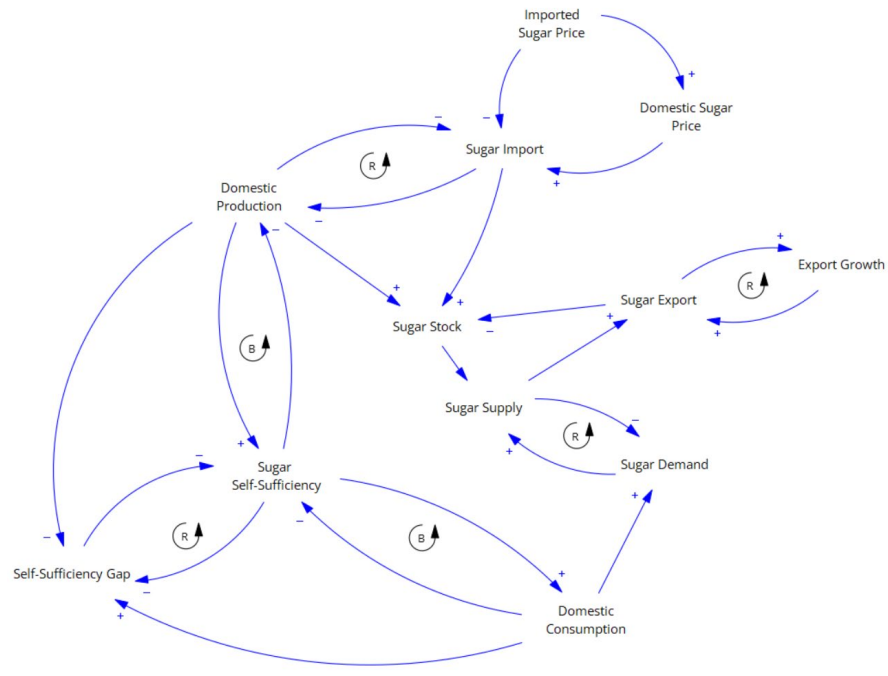


Figure 3. Causal Loop Diagram

The consumption module captures the formation of domestic sugar demand and its interaction with supply conditions. Domestic consumption positively influences total sugar demand, which in turn increases pressure on national sugar supply. Rising consumption widens the self-sufficiency gap when domestic supply growth does not keep pace. This relationship forms a reinforcing loop, where higher demand leads to greater dependency on supply sources, particularly imports, if production remains constrained.

The production module represents the domestic supply-side dynamics of the sugar system. Domestic production contributes positively to sugar stock levels, thereby increasing overall sugar supply and improving the self-sufficiency ratio. Higher domestic production reduces the self-sufficiency gap, creating a balancing effect on import dependence.

Import and export makes up the trade module regulates system imbalances through sugar imports and exports. Sugar imports increase when domestic production and stock levels are insufficient to meet demand, thereby stabilizing sugar supply in the short term. Imports are also influenced by imported sugar prices and domestic sugar prices, reflecting market and policy interactions. Sugar exports, while limited, increase when sugar stock levels exceed domestic requirements, forming a reinforcing export growth loop.

A supply and demand balance module integrates the effects of production, consumption, and trade into a single system outcome. Sugar stock acts as a central state variable, accumulating inflows from domestic production and imports and depleting through consumption and exports. The interaction between sugar supply and sugar demand determines the self-sufficiency level, which is summarized by the self-sufficiency gap indicator. This module reveals how reinforcing demand growth and constrained production interact with balancing trade flows to shape long-term system performance.

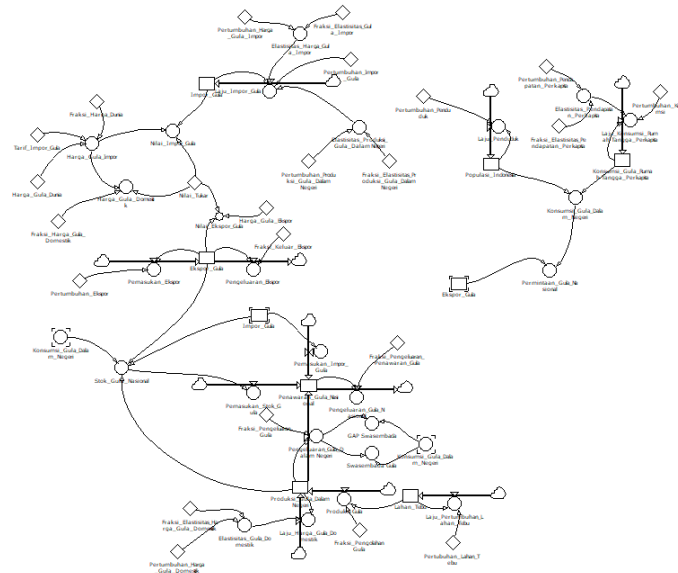


Figure 4. Stock and Flow Diagram

The developed CLD is subsequently translated into a stock and flow diagram (SFD) illustrated in Figure 4, to represent the system structure quantitatively. The SFD illustrates the accumulation of stocks, such as national sugar stock, and the flows that affect them, including domestic production, consumption, and imports.

4. Data Collection

This study employs secondary numerical data obtained from official and credible institutions to ensure data reliability, consistency, and comparability. The primary source of data is Badan Pusat Statistik (BPS), which provides nationally standardized statistical data compiled using rigorous methodologies.

Data collection was conducted by systematically compiling time-series and cross-sectional datasets from BPS publications and online data portals. To maintain data accuracy, all variables were selected based on consistent definitions and measurement units. When discrepancies or missing values were identified, data verification was performed by cross-referencing supplementary publications from relevant government agencies and international institutions.

Scenario development is then conducted to incorporate external uncertainty into policy analysis. This stage begins with the construction of a two-dimensional priority matrix based on business impact and uncertainty level. Through this matrix, external factors with high impact and significant uncertainty on the national sugar industry system are identified.

Based on this analysis, exchange rates, the rate of change in sugarcane land area, and world sugar prices are determined as critical uncertainties. These factors form the basis for the formulation of three main scenarios: Business-As-Usual, Economic Boom, and Worsening Climate, each representing different external conditions in which the input variables were altered to simulate the different scenarios (Table 1).

Table 1. Scenario Variables

Scenario	Variable Input	Effect	Description
Business As Usual	Exchange Rate	3%	Stable rupiah
	Sugarcane Land Growth	4%	Minimal expansion following historical trend
	World Sugar Price	6%	Stable world supply and demand
Economic Boom	Exchange Rate	-5%	Stronger Rupiah and cheaper imports
	Sugarcane Land Growth	7%	Encourages farmer expansion
	World Sugar Price	10%	Rupiah appreciation mitigates global price impact; lower sensitivity
Worsing Climate	Exchange Rate	15%	Economic uncertainty due to climate risks
	Sugarcane Land Growth	-8%	Productivity decline; farmers avoid risk and switch crops
	World Sugar Price	20%	Sharp increase due to disrupted global production

The developed scenarios are subsequently simulated using the system's (SFD) to analyze the evolution of key output variables over a 20-year time horizon. This simulation period is selected to capture short-term and long-term dynamics needed to be understood by the problem owners. Thus, the resulting outputs will ought to provide insights into trends, interactions among variables, and potential future trajectories,

5. Results and Discussion

5.1 Numerical Results

Simulation results indicate that national sugar demand–supply behavior is strongly influenced by system structure and external conditions. Under the Business-as-Usual scenario, the system tends to maintain long-term import dependence, as domestic production growth is insufficient to keep pace with rising demand driven by population growth and consumption increases. Consequently, the self-sufficiency gap remains relatively stagnant.

Under the Economic Boom scenario, accelerated economic growth stimulates investment in agriculture and sugar processing industries, resulting in higher sugarcane productivity and improved processing efficiency. Simulation results show that domestic sugar production grows more rapidly, reducing the gap between national production and demand. Although imports remain necessary, their relative role diminishes as domestic performance improves (Table 2).

Table 2. Simulation Result

Scenario	National Demand / Stock	Self-Sufficiency Gap	Domestic Sugar Price
Business As Usual	41440712 Ton	53.768	Rp15,414,750
Economic Boom	29253562 Ton	66.201	Rp16,108,413
Worsening Climate	52127107 Ton	42.867	Rp21,272,355

Overall, policy intervention testing confirms that improvements in domestic sugar productivity deliver the most consistent reduction in the self-sufficiency gap across all scenarios. This policy directly strengthens the system’s underlying structure by enhancing long-term production capacity. In contrast, import tariff policies function as effective short-term balancing instruments for stabilizing supply and prices, but are insufficient to drive structural transformation when applied independently.

5.2 Graphical Results

This section presents the graphical results of the simulation. The analysis compares outcomes under three conditions: Business as Usual (BAU), Economic Boom, and Worsening Climate. These scenarios reflect different structural and policy assumptions while excluding corrective strategies, allowing for an assessment of baseline system behavior and inherent dynamics (Figure 5).

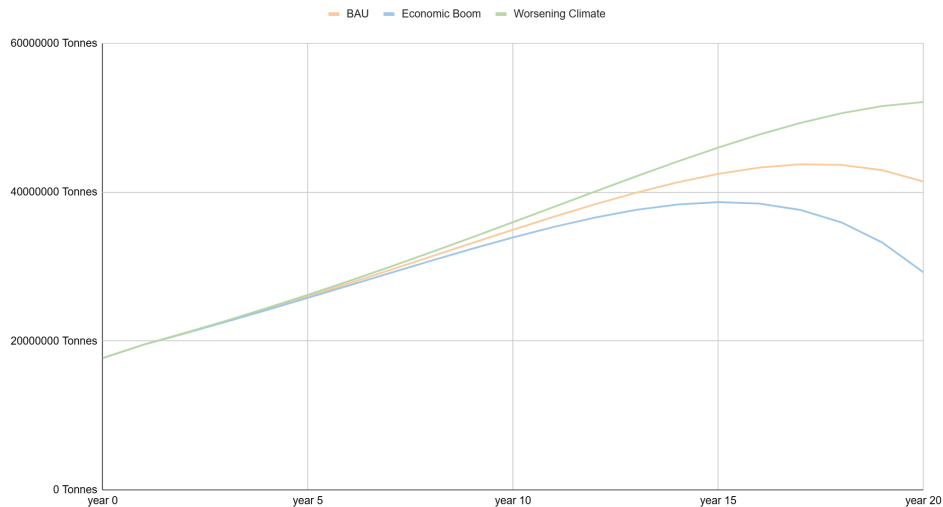


Figure 5. Simulation of National Demand / Stock

The simulation results indicate that across all scenarios examined, national sugar demand—represented in the form of stock requirements—continues to increase over time in line with population growth and rising per capita sugar consumption. This growth in demand is structural in nature and remains largely unaffected by variations in policy scenarios, implying that the system is required to continuously enhance its capacity to meet national sugar needs in a sustainable manner (Figure 6).

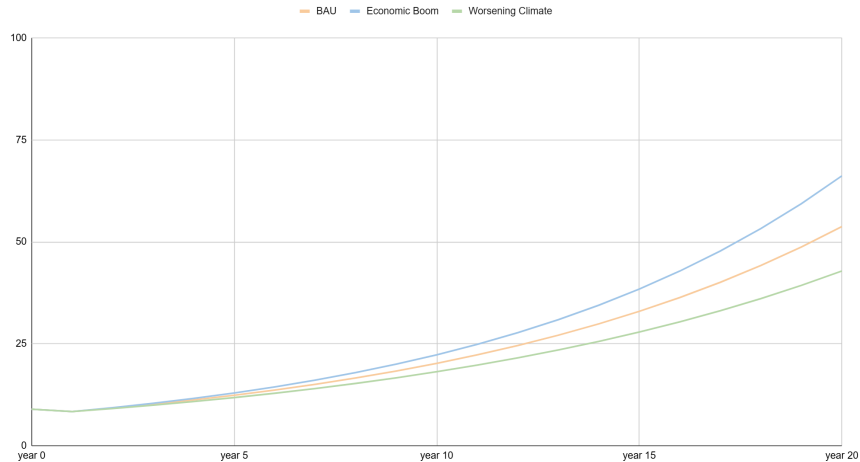


Figure 6. Simulation of Self-Sufficiency Gap

The simulation results show that the dynamics of the national sugar self-sufficiency gap are strongly influenced by differences in scenario conditions. Across all scenarios, the business-as-usual (BAU) condition tends to generate a large and persistent self-sufficiency gap, driven by increasing national sugar demand that cannot be fully met by domestic production. This finding confirms that market mechanisms alone are insufficient to steer the system toward equilibrium between national demand and supply, even not clearing 75% self-sufficiency with the economic boom scenario coming the closest.

5.3 Proposed Improvements

In addition to external scenarios, this study also tests government policy strategies through changes in policy variables within the model. The tested strategies include adjustments to import tariffs and improvements in domestic sugar productivity. Import tariff policies are modeled as parameter changes that affect import volumes and supply stability, while productivity improvements are modeled through changes in sugarcane productivity and production efficiency parameters (Table 3).

Table 3. Simulation Result

Policy	Value	Impact
Import Tariff	-40%	National sugar price
Productivity	20%	Domestic sugar production

Policy strategy testing is conducted consistently across all scenarios to assess policy effectiveness under different external conditions. Simulation results are then analyzed to evaluate policy impacts on sugar self-sufficiency levels, import requirements, and overall system stability (Figure 7).

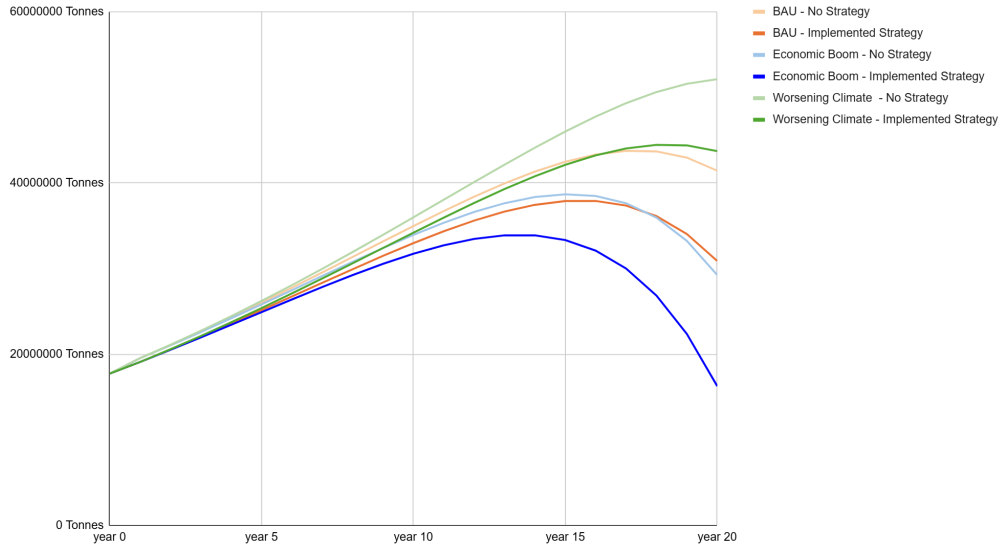


Figure 7. Strategy Implementation of National Demand / Stock

The implementation of policy strategies through adjustments in import tariffs and improvements in sugar productivity is shown to reduce pressure on the system, particularly with respect to import dependency and imbalances between domestic supply and demand. Import tariff policies function primarily as short-term control instruments that influence import volumes; however, their impact on meeting domestic demand remains limited, as they do not directly contribute to expanding national production capacity. In contrast, policies aimed at increasing sugar productivity demonstrate a more consistent and sustained effect in strengthening the system’s ability to respond to continuously growing demand (Figure 8).

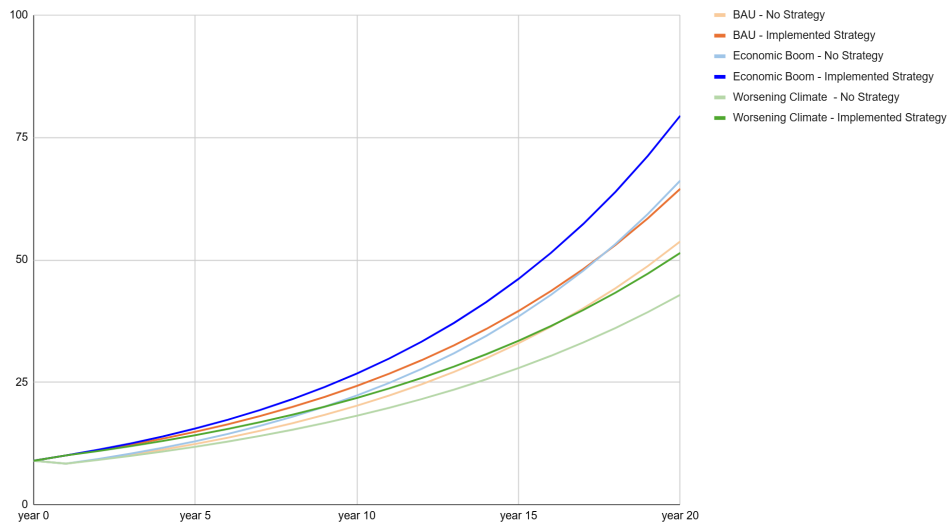


Figure 8. Strategy Implementation of Self-Sufficiency Gap

The implementation of policy strategies through import tariff adjustments and improvements in sugar productivity is shown to enhance system performance across all scenarios. These policy interventions consistently reduce the self-sufficiency gap relative to the no-policy condition, although the magnitude of improvement varies among scenarios. The Economic Boom scenario yields the most favorable outcome, in which productivity improvements significantly

boost domestic production, narrowing the self-sufficiency gap to approximately 80%, approaching the national self-sufficiency target of 90% (Table 4).

Table 4. Policy Simulation Result

Scenario	Policy	National Demand / Stock	Self-Sufficiency Gap	Domestic Sugar Price
Business As Usual	Not implemented	41440712 Ton	53.768	Rp15,414,750
	Implemented	30898902 Ton	64.522	Rp15,168,114
Economic Boom	Not implemented	29253562 Ton	66.201	Rp16,108,413
	Implemented	16274322 Ton	79.441	Rp15,850,679
Worsing Climate	Not implemented	52127107 Ton	42.867	Rp21,272,355
	Implemented	43722577 Ton	51.441	Rp20,931,997

The testing of policy interventions indicates that improvements in domestic sugar productivity generate the most significant impact in reducing the self-sufficiency gap across all scenarios. Meanwhile, import tariff policies function as effective short-term balancing instruments for maintaining supply stability, but their influence on long-term structural improvement of the system remains limited.

5.4 Validation

Model verification was done to ensure that the structure and data used in the model are able to represent the problem logically and are free from errors during the simulation process. This verification process is generally conducted through the Dimensional Consistency Test and the Integration Error Test.

Meanwhile, model validation is carried out to assess whether the developed model reasonably and plausibly represents the real system. Various methods can be applied in the validation process. In this study, six types of tests were conducted, namely: the Structure Assessment Test, Boundary Adequacy Test, Dimensional Consistency Test, Extreme Condition Test, Integration Error Test, and Behavior Reproduction Test.

6. Conclusion

This study concludes that the imbalance between national sugar demand and supply is structural in nature, driven by limited domestic productivity, consumption dynamics, and complex stakeholder interactions. Without significant policy intervention, long-term import dependence persists. Simulation results confirm that the Business-as-Usual scenario fails to improve sugar self-sufficiency, while the Economic Boom scenario offers improvement opportunities when accompanied by productivity and efficiency gains. The Worsening Climate scenario highlights the system's vulnerability to external shocks. Productivity enhancement emerges as the most effective long-term strategy for reducing the self-sufficiency gap, while import policies serve as complementary short-term stabilizers. Achieving sustainable sugar self-sufficiency therefore requires integrated, long-term, and structurally oriented policy frameworks.

References

- Badan Pangan Nasional, Panel harga pangan, Available: <https://panelharga.badanpangan.go.id/>, 2023
- Badan Pangan Nasional, Analisis komoditas pangan strategis 2023. Available: https://satudata.pertanian.go.id/assets/docs/publikasi/Analisis_Komoditas_Pangn_Strategis_2023-gab-ttd.pdf, 2023
- Badan Pusat Statistik, Statistik tebu Indonesia 2023. Available: <https://www.bps.go.id/id/publication/2024/11/29/71e6450a9b235855ffc525c9/statistik-tebu-indonesia-2023.html>, 2023

- Bardach, E., *A practical guide for policy analysis: The eightfold path to more effective problem solving*, CQ Press, 1996.
- Forrester, J.W., *Industrial Dynamics*, M.I.T. Press, 1961.
- Food and Agriculture Organization of the United Nations.. The state of food and agriculture 2023: Revealing the true cost of food to transform agrifood systems. FAO. Available: <https://openknowledge.fao.org/server/api/core/bitstreams/ea722624-2814-4cc5-ba44-90a79a2c2de5/content>, 2023.
- Heineman, R. A., Bluhm, W. T., Peterson, A. D., and Kearny, E. N., *The world of the policy analyst: Rationality, values, and politics*, Chatham House, 1990
- Kementerian Pertanian, Statistik konsumsi pangan 2024. Available: https://satudata.pertanian.go.id/assets/docs/publikasi/Buku_Statistik_Konsumsi_2024.pdf, 2024
- Kementerian Pertanian, Outlook tebu 2025. Pusat Data dan Sistem Informasi Pertanian. Available: https://satudata.pertanian.go.id/assets/docs/publikasi/OUTLOOK_TEBU_2025_sign_compressed.pdf, 2025
- Law, A. M., & Kelton, W. D., *Simulation Modeling and Analysis*, 2nd ed., McGraw-Hill, 1991.
- Patton, C. V., Sawicki, D. S., & Clark, J. J., *Basic methods of policy analysis and planning*, 3rd ed., Routledge, 2012
- Pemerintah Republik Indonesia, Undang-Undang Republik Indonesia Nomor 7 Tahun 1996 tentang Pangan, 1996
- Pemerintah Republik Indonesia, Undang-Undang Nomor 18 Tahun 2012 tentang Pangan, 2012
- Presiden Republik Indonesia, Keputusan Presiden Republik Indonesia Nomor 57 Tahun 2004 tentang Penetapan Gula sebagai Barang dalam Pengawasan. Available: <https://peraturan.bpk.go.id/Details/55702/keppres-no-57-tahun-2004>, 2004
- Shannon, R.E., Introduction to the Art and Science of Simulation, *Proceedings of the 1998 Winter Simulation Conference*, pp 7-14, Washington DC, 1998
- Sterman, J. D., *Business dynamics: Systems thinking and modeling for a complex world*. Irwin/McGraw-Hill, 4th ed., 2000
- Walker, W., *Public policy analysis: A pragmatic approach*, 2000

Biographies

Cordova Maulana Wanggai is an undergraduate student in the Industrial Engineering Department at the University of Indonesia. He is in the final year of his studies, using this research as a thesis for a requirement to receive a bachelor's degree in engineering. His research interests include Technology and Policy Modelling with System Dynamics.

Armand Omar Moeis is an Assistant Professor in the Industrial Engineering Department at the University of Indonesia. He holds a Bachelor's degree from the University of Indonesia, a Master's degree from Delft University of Technology, and a Doctoral degree from the University of Indonesia. His research expertise encompasses System Modeling, System Engineering, Industrial Simulation, System Dynamics, Advanced Modeling, and System Thinking. Armand Omar Moeis has contributed to several journal publications and conference papers.