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Influence of a Conflict in the Strait of Hormuz on Indonesia's Fertilizer Production: A System Dynamics Approach

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Abstract

This study presents a System Dynamics model integrating maritime chokepoint risk in the Strait of Hormuz with mineral-fertilizer supply-chain dynamics, applied to PT Pupuk Indonesia. The problem addressed is that Indonesia's compound-NPK production depends on imported sulfur, phosphate, and potassium, leaving it exposed to a disruption of the Strait of Hormuz through which most of its sulfur supply transits. A continuous-time stock-and-flow model of four raw-material subsystems with first-order sourcing delays, a normalized logistic production response, and a downstream agricultural submodule is validated structurally, parametrically, behaviorally, and under extreme conditions, then analyzed across 2,000 Monte Carlo runs. Under a 180-day total blockade, urea remains fully insulated by domestic gas while NPK is drawn to a critical near-miss trough of 64% as the sulfur buffer falls to 21 equivalent days. Blockade duration and sulfur dependency dominate risk, with 20% of scenarios reaching production halt by day 240, while buffers exceeding 180 days preserve output above 97%. A combined strategy of extended strategic buffer and accelerated alternative sourcing sustains output across all scenarios. We quantify working-capital, fiscal-subsidy, and real-option dimensions and propose a Strategic Sulfur Reserve of about 180 days of consumption as the principal policy contribution for strengthening national food-security resilience.

Keywords: System Dynamics; Strait of Hormuz; fertilizer supply chain; sulfur dependency; geopolitical risk; food security

1. INTRODUCTION

The global fertilizer industry operates within an intricate web of geopolitical dependencies and maritime logistics that shape food security outcomes for billions, especially during extraordinary outbreaks such as COVID-19 [1], [2]. Indonesia has experienced such an impact when experiencing the first effects of the Russo-Ukrainian War [3]. The Strait of Hormuz transits roughly 21 million barrels of crude per day and approximately 45% of seaborne sulfur trade [3, 4]. There is a very significant Hormuz-attributable share of global oil and LNG, and they flag fertilizer-specific transmission channels (urea and other inputs) as sensitive to chokepoint disruptions [4], [5], [6].

PT Pupuk Indonesia (Persero) oversees capacity exceeding 14.65 million ton/yr across subsidiaries including Pupuk Kalimantan Timur, Petrokimia Gresik, Pupuk Sriwidjaja, and Pupuk Iskandar Muda [7], [8]. While urea benefits from abundant domestic gas, compound NPK requires imported phosphorus, potassium, and, critically, sulfur [9]. The Gulf region supplies sulfur to some countries, including Indonesia, 60% of whose sulfur supplies come from this region [10]. Sulfur is a key feedstock in phosphate fertilizer production because phosphoric acid, a core intermediate, is typically produced via sulfuric acid digestion of phosphate rock [11], [12].

System Dynamics (SD) [13], [14], [15] captures feedback, delays, and nonlinearity, and has been applied to supply-chain disruption [16], [17], energy security [18], [19], and strategic-mineral resilience [20]. This study contributes: (i) the first SD model, to our knowledge, integrating a maritime chokepoint variable into a mineral-fertilizer chain, mapped onto resilience dimensions; (ii) methodological rigor via a continuous logistic production response, explicit first-order delays, a stated integration scheme, and four-dimensional validation; (iii) a 2,000-run Monte Carlo with probabilistic envelopes and tornado ranking; and (iv) downstream food-security and upstream economic (working-capital, subsidy, real-option) extensions.

Understanding this exposure requires situating Indonesia within the global fertilizer trade. Compound NPK fertilizer, unlike urea, cannot be produced from domestic natural gas alone: it requires phosphate rock, potassium salts, and sulfur, the last of which is the feedstock for the sulfuric acid used to digest phosphate rock into phosphoric acid [21], [22], [23]. Indonesia imports essentially all of its phosphate rock and potassium, is very dependent on them [24], and a substantial share of its sulfur originates from Gulf suppliers whose shipments transit the Strait of Hormuz. Consequently, a single chokepoint event can throttle an entire branch of national fertilizer output even when ammonia and urea capacity remain fully operational, producing a divergence between the two product lines that a conventional cost-based analysis would overlook [25].

The strategic importance of the Strait of Hormuz extends well beyond crude oil. Because a large share of globally traded sulfur and refined petrochemical products also passes through this single waterway, a disruption there transmits simultaneously across energy and agricultural-input markets, compounding the shock experienced by import-dependent economies [26], [27], [28]. For Indonesia, an archipelagic nation whose food security rests on sustained rice output, and whose rice yields are in turn tightly coupled to fertilizer availability [29], [30], [31], this exposure is not merely an industrial concern but a national resilience question. Recent geopolitical episodes, including the Russo-Ukrainian war and

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renewed tension in the Persian Gulf, have already demonstrated how rapidly fertilizer and feedstock prices can escalate when a critical corridor is threatened [32], [33], [34].

Prior research has examined supply-chain disruption from several angles. Studies of the COVID-19 pandemic documented systemic fragility in globally intertwined supply networks, while quantitative reviews catalogued methods for assessing supply-chain resilience [35], [36], [37]. System Dynamics in particular has been applied to maritime disruption, as in analyses of the Suez Canal blockage, and to critical-commodity risk, as in models of the rare-earth-element supply chain [38], [39], [40]. However, these efforts either treat generic freight flows or focus on minerals unrelated to food production; none integrates a maritime chokepoint variable directly into a mineral-fertilizer production chain, and none is calibrated to the Indonesian context in which urea is insulated by domestic gas while compound NPK remains critically exposed through imported sulfur. This constitutes the research gap addressed here.

Accordingly, the objective of this study is to develop and validate a System Dynamics model that quantifies how a Strait of Hormuz disruption propagates through PT Pupuk Indonesia's raw-material inventories to NPK production and, ultimately, to national food security, and to evaluate mitigation strategies under uncertainty. To do so, the model couples four raw-material stocks with first-order sourcing delays, a normalized logistic production response, and a downstream agricultural submodule, and is run across 2,000 Monte Carlo simulations to derive probabilistic envelopes, a tornado sensitivity ranking, and a comparative evaluation of six mitigation configurations.

2. RESEARCH METHODOLOGY

2.1. Background and Resilience Framework

Maritime chokepoints generate disproportionate consequences through war-risk premiums, route diversion, and congestion [41], [42]. Feyrer [43] estimated a 10% distance increase reduces trade 5–8%, with risks borne asymmetrically by import-dependent nations. The 2022 supply shock revealed substantial fragility in fertilizer and food-systems buffers, with disruptions in potash and urea capacity exemplifying vulnerabilities in just-in-time (JIT) supply chains [44]. In Indonesia, a gas-price rise correlates with a severe rice-output decline [45]. We structure the analysis using four resilience dimensions: robustness (function under stress), redundancy (buffer stocks), agility (adaptive speed), and resourcefulness (financial absorption). Figure 1 maps SD model components onto these dimensions.

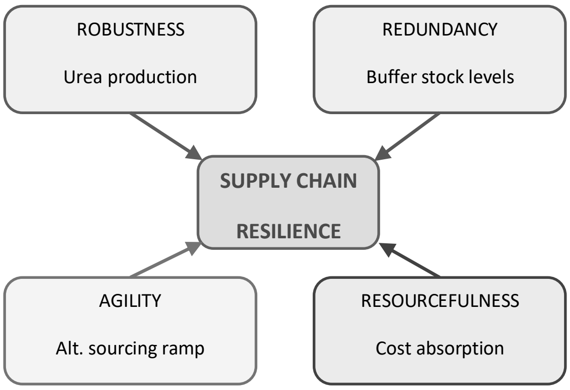

Figure 1. SD model components mapped onto four resilience dimensions.

2.2. Supply-Chain Architecture

Natural gas dominates urea costs and is sourced domestically under long-term agreements, insulating urea from chokepoint risk [4], [46]. Rock phosphate is almost all imported. Indonesia brought in about 1.4 Mt in January–November 2025, with more than 60% originating from Jordan, and Pupuk Indonesia signed a January 2026 MoU with Algeria's Somiphos for up to 1 Mt/yr [47]. Potassium is likewise fully imported from outside Gulf region, namely from Canada and Laos. The binding constraint is sulfur which is imported primarily via Hormuz Strait [48]. This becomes a strong basis for us to apply a Hormuz dependency parameter $\delta H = 0.75$ in the simulation.

2.3. System Dynamics Model

Figure 2 shows the causal structure. The dominant reinforcing loop R1 (sulfur depletion cascade) propagates a blockade through inventory, sulfuric acid, and NPK output; R2 amplifies cost; balancing loops B1 (alternative sourcing) and B2 (demand adjustment) equilibrate [15]. Figure 3 shows the stock-and-flow topology.

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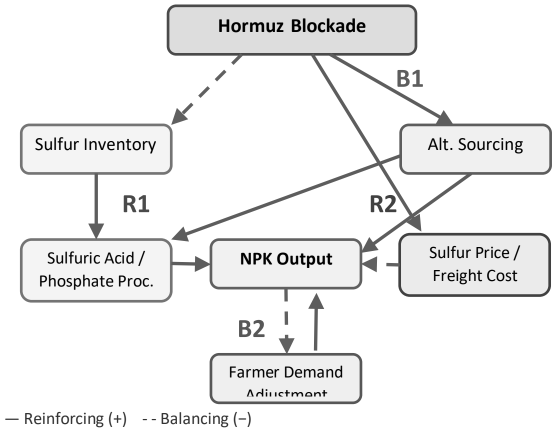

Figure 2. Causal loop diagram with reinforcing (R1–R2) and balancing (B1–B2) loops.

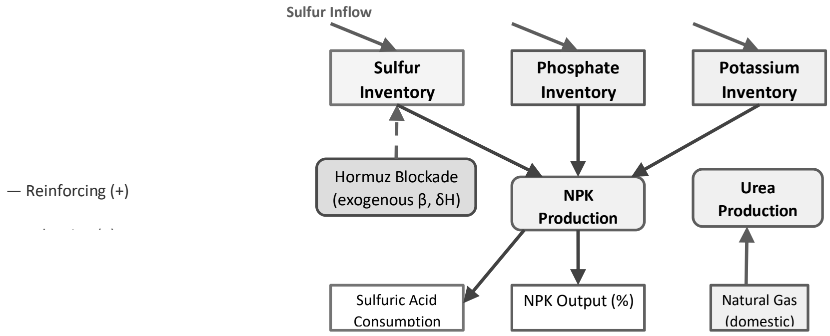

Figure 3. Stock-and-flow diagram of the raw-material system.

The model integrates four inventories (natural gas, sulfur, phosphate, and potassium) using the Euler method with Δt = 0.25 d (verified to be stable under step-halving to 0.125 d) over a 540-day horizon. Stocks are measured in units of equivalent consumption-days; flows are measured as fractions of normal daily consumption. Each imported stock obeys $dS_i/dt = \text{Inflow}_i - \text{NPK}(t)$, with consumption proportional to production. Sulfur inflow is

$$Inflow_S(t) = [1 - \delta_H \cdot \beta(t)] + A(t) + \sigma_{dom}, \quad (1)$$

where $\delta_H = 0.75$ is Hormuz dependency, $\beta(t) \in [0, 1]$ is blockade intensity (permitting partial or leaky blockades; $\beta = 0$ outside the blockade window), σ_{dom} is domestic recovery, and $A(t)$ is alternative supply following a first-order material delay whose activation scales with disruption severity:

$$\frac{dA}{dt} = \frac{[A*\cdot\beta(t) - A(t)]}{\tau_A} \quad (2)$$

with policy ramp target A* and delay constant τ_A = 50 d (most-likely value; Monte Carlo samples 30–80 d). Production availability uses a normalized logistic in place of a binary step. Writing $\sigma(S) = 1/(1 + \exp[-(S - S_{safe})/w])$ with safety threshold S_{safe} = 15 d and width w = 8 d, the availability is

$$f(S) = \frac{\sigma(S) - \sigma(0)}{1 - \sigma(0)} \quad (3)$$

normalized so that $f(0) = 0$ exactly (production ceases at zero stock) while $f \rightarrow 1$ for ample inventory; the raw logistic alone would imply a spurious around 13% residual output at empty stock. Plants thus throttle gradually as stock approaches the safety band. NPK output follows Liebig's minimum across imported inputs,

$$NPK(t) = \min[\, f(S_S), f(S_P), f(S_K) \,] \cdot U(t), \quad (4)$$

where $U(t) = 1$ if gas availability meets the 70% ammonia turndown and 0 otherwise; domestic gas supply keeps U = 1 throughout all scenarios.

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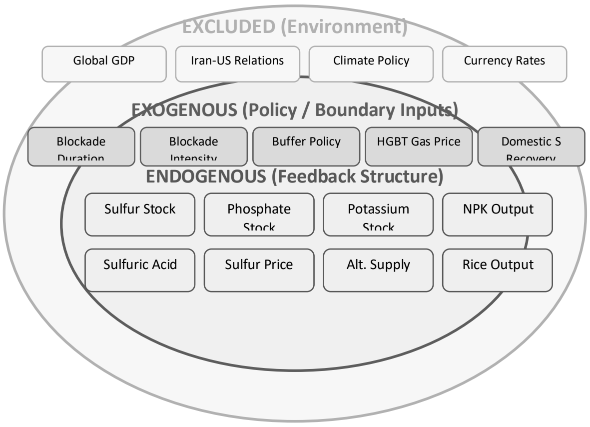

Figure 4. Model boundary: endogenous, exogenous, and excluded variables.

Validation. Structural: the four-stock boundary captures binding constraints; ammonia/sulfuric-acid intermediates are instantaneous conversions given hour-to-day residence times. Figure 4 gives the boundary diagram. Note that all Environment factors (Global GDP, Iran-US Relations, Climate Policy, and Currency Rates) are excluded. Parameter: each value carries a min–likely–max range (Table I) propagated by Monte Carlo. Note that the distributions are all triangular. Behavioral: under no blockade, the model holds a stable equilibrium (100% output, constant inventory), matching 2022–2023 levels. Extreme-condition: a 100% permanent cutoff drives sulfur stock and NPK output monotonically to zero—exactly zero under Eq. (3), while urea persists; a zero-blockade case stays at equilibrium. Both are logically correct.

Table 1. Model parameters with uncertainty ranges.

Parameter	Min	Likely	Max
Sulfur buffer (d)	120	150	200
Phosphate buffer (d)	180	210	260
Potassium buffer (d)	150	180	230
Hormuz dependency δH	0.65	0.75	0.85
Blockade duration (d)	90	180	365
Alt. sourcing target A*	0.00	0.05	0.18
Alt. delay τA (d)	30	50	80
Shutdown cost (M$)	9.0	12.6	16.0

3. RESULT AND DISCUSSION

Deterministic baseline. Under a complete 180-day blockade with no mitigation (Figure 5), the three imported materials diverge in their dependencies. Sulfur drains at approximately 0.70 d/day from a 150-day buffer to a critical trough/local minimum near 21 days (just above the safety threshold) before recovering, because the blockade duration is shorter than the full depletion time. This is a near-miss, not a clean halt: survival depends on timely reopening.

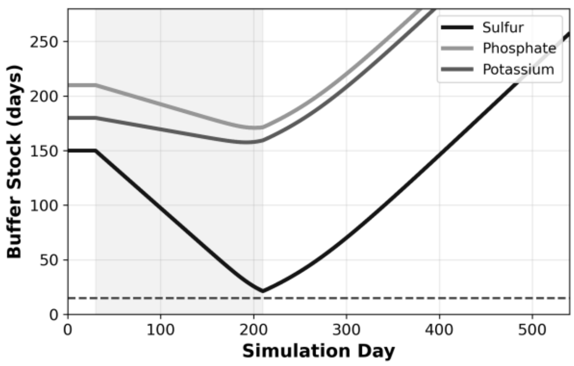

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Figure 5. Raw-material stock depletion under a 180-day blockade (continuous model).

Production. Figure 6 shows urea holding 100% throughout while NPK degrades gradually to a 64% trough at day 210 (blockade end) before recovering. The smooth decline reflects operational throttling absent in a binary model. Partial-blockade tests (50–100% intensity) place the resilience-to-failure transition in the 75–90% band.

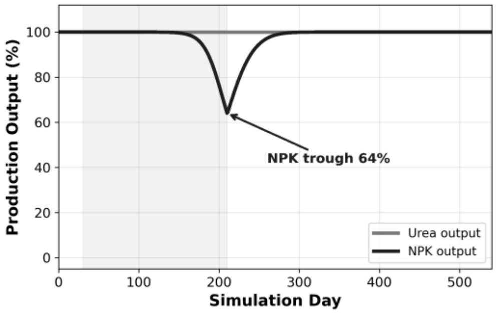

Figure 6. Urea (insulated) versus NPK (import-dependent) output.

Stochastic analysis. Across 2,000 Monte Carlo runs sampling Table I with only limited spontaneous substitution, the sulfur envelope (Figure 7) shows wide dispersion driven by blockade duration. Halt (NPK < 50%) before day 180 is negligible (0.1% of runs), but 20% of scenarios reach halt by day 240, with the 10th-percentile case at day 220. The deterministic 180-day case thus sits near the median-adverse boundary rather than a worst case.

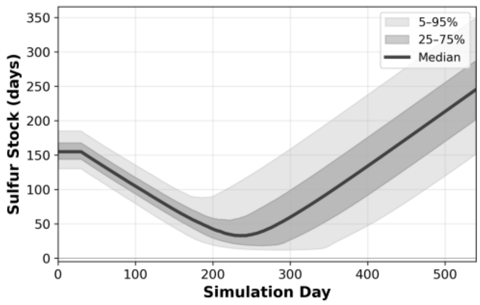

Figure 7. Monte Carlo sulfur-stock probability envelope (2,000 runs).

Sensitivity. The tornado diagram (Figure 8) ranks blockade duration and Hormuz dependency as dominant, followed by initial buffer; sourcing target and ramp speed are smaller levers. A buffer sweep shows 90–120-day buffers halt (NPK troughs 27–35%), 150 days is a stressed near-miss (64%), and more than 180 days keep NPK above 97%.

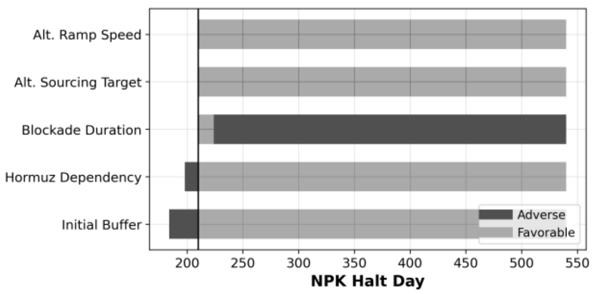

Figure 8. Tornado ranking of parameter influence on the NPK halt threshold.

Economics. Sulfur prices ramp 150% (to US$500/t) within 60 days, and freight reaches 2.5× baseline. Scoped to Pupuk Indonesia's own sulfur requirement of 150 kt/yr (411 t/d) [48], a 150-day buffer at US$150/t represents US$9 M of inventory; extending to 210 days at stressed prices raises this to US$43 M, an incremental US$34 M of working capital. This is a striking result: the reserve that removes most halt risk costs a small fraction of the avoided loss, since a single shutdown event alone is modeled at US$9–16 M and a sustained NPK shortfall carries national food-security consequences. The fiscal burden falls not on inventory but on the delivered fertilizer price: absorbing the raw-material increase via subsidy expands the fertilizer budget, while passing it through risks the farmer demand response reported in Section I [45].

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Mitigation Scenarios. Six configurations (Figure 9) span supply-side, demand-side, and structural levers. The combined buffer-plus-sourcing strategy is most robust (minimum sulfur 114 days), with synergy exceeding the sum of parts because the extended buffer provides time for the sourcing delay to reach target. Demand-shift (lower-sulfur grades) and DAP/phosphoric-acid import bypass elevate the trough at low capital cost.

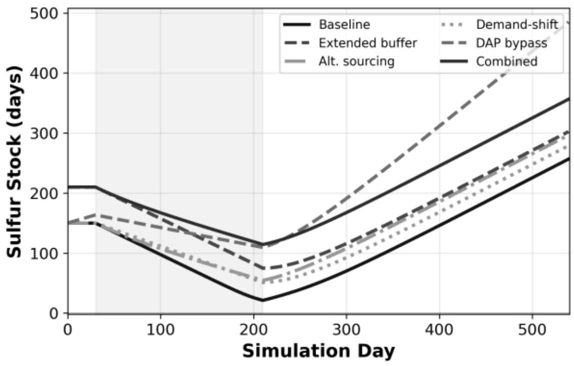

Figure 9. Expanded mitigation scenario matrix (sulfur stock).

Table 2. Mitigation outcomes under a 180-day blockade.

Scenario	Mechanism	Min sulfur
Baseline	150-day buffer	21 d (near-miss)
Extended buffer	210-day buffer	75 d
Alt. sourcing	+30% ramp	55 d
Demand-shift	Low-S grade	51 d
DAP bypass	Import P interm.	~109 d
Combined	Buffer + sourcing	~114 d (robust)

Policy. (1) Diversify mining via blended equity JV and long-term offtake (Canada potash/sulfur; Algeria/Morocco phosphate). (2) Institutionalize the HGBT US$6/MMBtu gas price in durable, WTO-consistent regulation. (3) Establish pre-negotiated standby sulfur offtake with explicit triggers, volumes, and penalties. (4) Create a Strategic Sulfur Reserve targeting 180 days at full consumption, which the sensitivity analysis keeps NPK above 97%. (5) Pursue green ammonia (GAIA), enabling 10% minimum loads versus 70% conventional, as a long-horizon structural hedge.

Comparison with prior studies. These findings both corroborate and extend the existing System Dynamics literature on supply-chain disruption. Li et al. modeled the Suez Canal blockage and likewise found that chokepoint closures produce strongly nonlinear performance losses once buffers are exhausted; our results reproduce this threshold behavior but locate the critical transition specifically in the 75-90% blockade-intensity band for Indonesian NPK. Keilhacker and Minner, modeling the rare-earth supply chain, identified diversification and strategic stockpiling as dominant mitigations, consistent with our tornado ranking in which buffer size and sourcing responsiveness dominate. Unlike these generic or non-food commodity studies, however, our model isolates a divergence between two co-produced fertilizer lines, urea and NPK, driven entirely by feedstock origin, a distinction absent from freight-centric disruption models and directly relevant to food-security policy. Relative to Ivanov's pandemic simulation, which emphasized demand-side ripple effects, the present study foregrounds an upstream feedstock constraint and quantifies its downstream agricultural consequence, thereby linking the maritime-logistics and food-security literatures within a single validated model.

4. CONCLUSION

A validated, continuous-time SD model shows that under a 180-day Hormuz blockade, urea is fully insulated while NPK is drawn to a critical 64% near-miss trough/nadir as sulfur falls to 21 equivalent days. Monte Carlo analysis identifies blockade duration and sulfur dependency as dominant drivers, with 20% of scenarios reaching halt by day 240. The tornado analysis further isolates initial buffer size and alternative-sourcing responsiveness as the principal controllable levers, indicating where policy investment yields the greatest marginal resilience. Buffers below 135 days risk a halt; more than 180 days of reserves preserve output above 97%, and a combined buffer-plus-sourcing strategy sustains production across all simulated conditions. Given that Pupuk Indonesia's own analysis links sustained fertilizer price shocks to a potential 2-million-tonne national rice production shortfall [45], building resilience by diversification, a Strategic Sulfur Reserve, contingent sourcing, and a green-ammonia transition is a food-security imperative beyond industrial policy. Beyond the specific case of PT Pupuk Indonesia, the modeling framework demonstrates how System Dynamics can translate a single geopolitical chokepoint into quantified, time-resolved production and food-security risk, offering a transferable decision-support tool for other import-dependent economies. Future work should incorporate spatially explicit crop data, endogenous price feedback, and correlated parameter uncertainty to refine the economic estimates presented here. However, we are attaching only publicly available data, and the results should not reflect any government policies.

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