

Why Manufacturing Maturity Models Fail Upstream: A System Dynamics Perspective on Bio-industrial Manufacturing Using Causal Loop Diagrams

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Abstract—Existing digital maturity models assume that organizations progress through sequential stages of capability development. However, this assumption does not adequately explain digital transformation in fragmented upstream bio-industrial supply chains, where logistics, financing, and regulatory constraints shape digital capability. This study investigates why conventional digital maturity models fail to explain persistent low digital maturity among Indonesia's palm oil, timber, and pulp suppliers. A qualitative system dynamics approach was used to develop a Causal Loop Diagram (CLD) by synthesizing evidence from 55 digital maturity models and contextualizing the model with operational evidence from Indonesian bio-industrial supply chains. The analysis identifies three reinforcing feedback loops driven by logistics inefficiencies, compliance financing, and data monopolization, together with one balancing loop that may accelerate smallholder exclusion under the European Union Deforestation Regulation (EUDR). Based on these findings, four policy leverage points are prioritized, beginning with transport improvement and compliance financing before broader data governance reforms. The study extends digital maturity research by explaining digital capability through interconnected supply chain feedback rather than linear organizational progression and offers practical guidance for upstream digital transformation.

Keywords—DMMs, CLD, System dynamics, Bio-industrial supply chain, EUDR

I. INTRODUCTION

Digital transformation has become a strategic imperative for manufacturing organizations, enabling improvements in operational efficiency, resilience, and sustainability through Industry 4.0 technologies such as the Internet of Things (IoT), cloud computing, and big data analytics [1], [2], [7]. To support this transition, numerous Digital Maturity Models (DMMs) assess organizational capabilities across strategy, technology, culture, and processes while prescribing maturity roadmaps [4], [5]. However, most DMMs assume that digital capability progresses linearly through internal strategic commitment and financial investment,

overlooking structural constraints beyond organizational boundaries [4], [5], [7].

This assumption does not hold in fragmented upstream supply chain nodes, which produce raw materials through independent oil palm smallholders and community timber growers before supplying downstream processing, manufacturing, and export. Their digital capability is constrained by governance structures, logistics inefficiencies, unequal power relationships, and international regulations [70], [72]. These challenges have intensified under the European Union Deforestation Regulation (EUDR) (Regulation EU 2023/1115), which mandates deforestation free traceability through a verified Due Diligence Statement (DDS) containing GPS coordinates or polygon boundaries for every export lot [3]. Although digital transformation has advanced in downstream operations, Indonesia's 2.4 million independent smallholders, managing approximately 40% of the national oil palm area, and millions of community forest owners continue to rely on weak data infrastructure, paper-based records, and inaccurate land mapping, resulting in persistently low digital maturity [70].

This study addresses the following research question: How do structural supply chain feedback mechanisms prevent upstream bio industrial suppliers from progressing through conventional digital maturity pathways, and under what conditions does regulatory pressure improve capability or produce exclusion? Existing studies provide limited insight because they assess firms in isolation and overlook dynamic interactions across the value chain. To address this limitation, this study applies System Dynamics (SD) and Causal Loop Diagrams (CLDs) to model the feedback loops, delays, and power relationships governing capability development. Key concepts are defined upon first use: feedback loops are closed causal structures; reinforcing loops (R) amplify change; balancing loops (B) counteract change and stabilize systems; absorptive capacity is an organization's ability to recognize, assimilate, and apply external knowledge [6]; and leverage points are strategic locations where small interventions produce substantial long term system change [9] - [13].

This study makes two contributions. First, it reconceptualizes digital maturity as a dynamic outcome of value chain governance and resource dependence by

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translating the static dimensions of 55 peer reviewed DMMs into a signed, feedback based causal model. Second, it contextualizes this model within Indonesia's palm oil sector (e STDB, ISPO, and the National Dashboard) and forestry and pulp and paper sector (SVLK under UUCK and SIPUHH) to identify and prioritize policy leverage points for governments and industry stakeholders operating under resource constraints.

II. LITERATURE REVIEW

To explain the structural determinants of capability development, this study integrates Global Value Chain (GVC) Governance Theory and Resource Dependence Theory (RDT) [74]. GVC theory classifies governance into market, modular, relational, captive, and hierarchical forms according to transaction complexity, information codifiability, and supplier capability. As traceability requirements become more stringent, governance shifts toward captive or hierarchical forms in which led firms define compliance requirements while suppliers operate with limited strategic autonomy [70], [75]. Complementing this perspective, RDT explains how asset specificity, resource dependence, and bargaining power shape organizational capability through unequal control of critical resources [76].

These perspectives explain how governance structures, resource dependence, and institutional pressure interact to influence capability development. Unequal bargaining power enables downstream firms to capture a disproportionate share of the economic and reputational value generated by digital traceability, while upstream suppliers absorb most compliance costs, constraining investment capacity [70], [72], [76].

Meanwhile, coercive regulations and normative certification standards act as institutional pressures that either strengthen capability development or reinforce supplier exclusion depending on absorptive capacity and external support [3], [70].

Based on these theories, the proposed causal model comprises five constructs: Upstream Digital Maturity Capability, the ability to generate, manage, and transmit verified digital records; Downstream Surplus Capture, the concentration of traceability related economic and reputational value among downstream firms; Information Asymmetry, unequal access to operational, compliance, and market information; Capability Support, financial, technical, and institutional assistance provided by governments, downstream firms, or nongovernmental organizations; and Traceability Compliance Gap, the mismatch between regulatory requirements and upstream digital capability.

Existing DMMs primarily assess organizational readiness rather than the structural mechanisms governing capability evolution. The Smart Industry Readiness Index (SIRI) evaluates Industry 4.0 readiness through the dimensions of Process, Technology, and Organization and provides benchmarking together with implementation priorities, but its assessment remains focused on firm level capabilities [8]. Similarly, the Technology Organization Environment (TOE) based maturity model incorporates environmental conditions but represents them as static assessment dimensions rather than interacting system relationships [5]. As summarized in Table I, the proposed CLD complements these models by explicitly representing feedback interactions among governance, logistics, compliance financing, data governance, and institutional pressure rather than static maturity assessment.

Table I.
Comparison Of Existing Digital Maturity Models And The Proposed Causal Loop Approach

Aspect	SIRI Model	TOE Digital Maturity Model	Proposed Causal Loop Approach
Primary objective	Assess Industry 4.0 readiness and prioritize digital transformation	Assess digital maturity using Technology, Organization, and Environment dimensions	Explain why upstream suppliers remain trapped in low digital maturity
Unit of analysis	Individual manufacturing firm	Individual organization	Upstream bio-industrial supply chain
Capability perspective	Sequential readiness progression	Progressive organizational maturity	Dynamic capability shaped by feedback interactions
Analytical perspective	Static organizational assessment	Static organizational assessment	Dynamic systems analysis
Treatment of external factors	Limited consideration of supply chain interactions	Environmental factors included as assessment dimensions	Logistics, compliance financing, governance, and regulation modeled as interacting feedback mechanisms
Primary output	Readiness score and implementation roadmap	Digital maturity level and organizational recommendations	Feedback loops and prioritized policy leverage points
Applicability to fragmented upstream bio-industrial supply chains	Limited, assumes established IT/OT infrastructure and capital.	Limited, overlooks resource dependence and bargaining power.	Designed for fragmented upstream bio-industrial systems

III. METHODOLOGY

A. Literature Selection and Causal Model Development

A systematic literature review was conducted following the PRISMA protocol [5]. Peer reviewed articles published between 2016 and 2022 were retrieved from Scopus and Web of Science using Boolean combinations of keywords related to digital transformation ("Digital Transformation", "Digitalization"), maturity assessment ("Digital Maturity Model", "Maturity Model", "Capability Model", "Readiness Assessment"), and Industry 4.0 manufacturing ("Industry 4.0", "Manufacturing", "Supply Chain"). After restricting the search to Q1 and Q2 journals (SCImago Journal Ranking), 55 Digital Maturity Models (DMMs) were selected for analysis [14]–[68].

Following Kim and Andersen [12], the selected studies were analyzed through open, axial, and selective coding. Open coding extracted 146 unique capability variables (in Appendix A); axial coding consolidated related variables into generalized constructs (e.g., IT connectivity, sensor deployment, and ERP integration into Upstream Digital Maturity Capability); and selective coding translated static maturity dimensions into signed causal relationships by identifying explicit and implicit cause effect statements reported in the literature [18], [29].

B. Model Boundary

The CLD boundary encompasses the key socioeconomic, operational, and regulatory interactions

linking upstream producers and downstream processors. Endogenous variables include Upstream Digital Maturity Capability, Value Capture, Retained Margin, Digital Investment, Data Integration, Information Asymmetry, Downstream Surplus Capture, Workforce Competence, Organizational Learning, Traceability Compliance Gap, and Capability Support. Exogenous drivers comprise EUDR implementation, international commodity prices, and national land administration, while household consumption, trade negotiations, and hardware specifications are excluded to preserve model parsimony.

C. Structural Validation

The proposed CLD was compared against independent empirical evidence to verify that each signed causal relationship reflected observed interactions within Indonesian bio industrial supply chains. Validation drew on three complementary studies: (1) RSPO audit reports and spatial sourcing patterns from 87 certified palm oil mills in Sumatra and Kalimantan, representing 360 mill years of operational data [70]; (2) a mixed methods study of SVLK implementation and economic feasibility among 121 community forest farmers in Banten Province [72]; and (3) analyses of timber transport productivity and logistics in North Sumatra industrial forests [73].

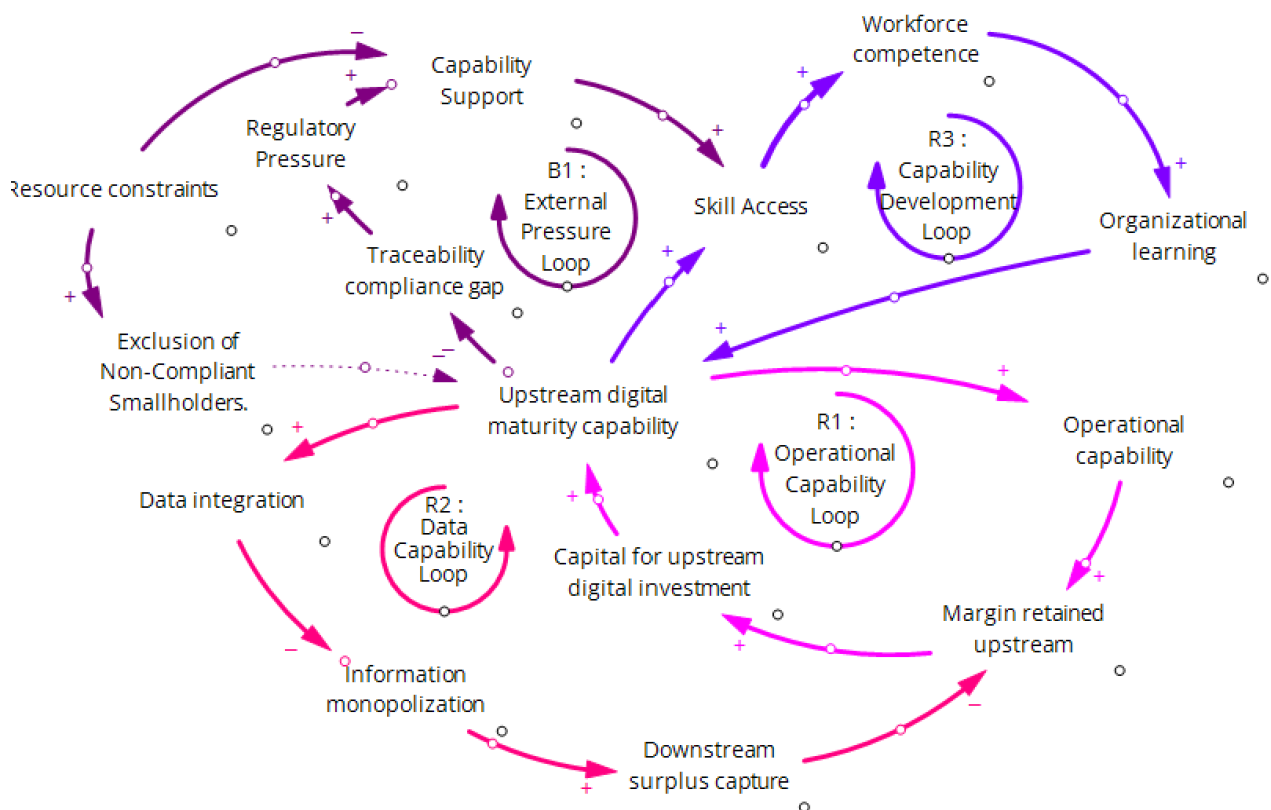


Figure 1. Causal loop diagram of upstream digital maturity

Note: Solid arrows indicate direct causal relationships with positive (+) or negative (-) polarity. The dotted arrow denotes an indirect system level relationship.

Table II.
Literature Grounding Of Causal Relationships In the Proposed Causal Loop Diagram

Loop	Causal Relationship	Sign	Supporting DMM Literature	Causal Structure Explanation
R1 Operational Capability Loop	Operational capability → retained margin	+	[14], [15], [16], [17], [18], [45]	Higher operational capability improves process efficiency, product quality (e.g. FFA remains < 3%), and resource utilization, enabling firms to retain greater economic value from their operations.
	Retained margin → digital investment	+	[14], [18], [22], [32], [45], [52], [67]	Greater retained financial resources increase the organization's capacity to invest in digital technologies, infrastructure (e.g., smartphones, mapping applications), and organizational improvements required for Industry 4.0.
	Capital for Digital investment → Upstream DM Capability	+	[15]–[68]	Investments in digital technologies, workforce development, and organizational processes strengthen overall digital capability and increase organizational maturity.
	Upstream DM Capability → operational capability	+	[16], [20], [23], [34], [40], [46], [64]	Digital capability (e.g., e-STDB GPS mapping, barcoded logs) enhances operational visibility, process integration, automation, and decision making, further improving operational performance and completing the reinforcing feedback loop.
R2 Data Capability Loop	Upstream Digital Maturity Capability → data integration	+	[23], [34], [40], [49], [61], [67]	Higher digital maturity enables integrated data management (plot-level polygon mapping and log-tracking data) across organizational processes, improving information availability and consistency.
	Data integration → information monopolization	–	[27], [34], [64]	Upstream data is uploaded to proprietary refiner portals or the National Dashboard, concentrated under refiner/exporter control
	Information monopolization → Downstream surplus capture	+	[27], [34], [44]	Downstream actors exploit information asymmetry, utilizing compliance data to secure premium market access while keeping FFB/timber purchase prices stagnant.
	Downstream surplus capture → Retained margin	–	[18], [29], [34]	Concentration of compliance value downstream drains economic margins from upstream producers, who receive no price premiums for data.
R3 Capability Development Loop	Upstream Digital Maturity Capability → skill access	+	[22], [28], [42], [51], [62]	Certified and digitally active producers gain access to technical assistance, training workshops, and cooperative extension services.
R3 Capability Development Loop	Skill access → workforce competence	+	[22], [42], [51], [62]	Increased training improves the digital literacy of smallholders and cooperative administrators (e.g., managing e-STDB or SVLK logs)
R3 Capability Development Loop	Workforce competence → organizational learning	+	[22], [42], [51], [62]	Increased workforce competence accelerates organizational learning and improves the effective use of digital technologies.

Loop	Causal Relationship	Sign	Supporting DMM Literature	Causal Structure Explanation
	Organizational learning → Upstream Digital Maturity Capability	+	[22], [42], [51], [62], [67]	Continuous organizational learning enhances technology adoption, process improvement, and long-term digital capability, reinforcing organizational maturity.
B1 External Pressure Loop	Upstream Digital Maturity Capability → traceability compliance gap	–	[5], [21], [33], [41], [64], [67]	Higher upstream digital capability directly reduces the compliance gap by enabling plot-level geolocation and legal land verification
	Traceability compliance gap → regulatory pressure	+	[3], [24], [70]	A wider traceability gap under EUDR increases regulatory scrutiny, threat of audit failure, and market entry denial
	Regulatory pressure → capability support	+	[70], [72]	Coercive pressure from EUDR/SVLK forces refiners and public bodies to facilitate compliance (e.g., APBN funding for SVLK, BPDPKS-funded registration).
	Capability support → skill access	+	[22], [28], [72]	Funding and technical assistance expands upstream training programs, cooperative capacity building, and digital tool access

IV. FINDINGS AND DISCUSSION

A. Loop R1: The Operational Capability Trap

Operational capability provides the financial basis for digital upgrading because improvements in logistics, inventory management, and traceability enable organizations to retain more value for subsequent investment in digital technologies and organizational development [18], [29]. This relationship assumes that producers can capture the economic returns generated by operational improvements. In fragmented upstream palm oil supply chains, however, value capture is constrained by biological characteristics and supply chain arrangements that lie beyond the control of individual smallholders.

Independent smallholders cultivate between 3.8 and 6.0 million hectares, accounting for approximately one third to two fifths of Indonesia's oil palm area, yet most rely on local collectors to access processing mills [70]. Fresh fruit bunches must be processed within 24 to 48 hours after harvest because free fatty acid content increases rapidly after harvesting, particularly when fruit is damaged during handling and transportation [69], [70]. Dynamic modeling further shows that bruised fruit exceeds acceptable quality thresholds more quickly than intact fruit [69]. Since collectors consolidate harvests over several days and manual loading increases physical damage, mills apply quality-based price deductions that are largely absorbed by independent smallholders [69], [70].

Reduced retained income limits investment in smartphones, GPS based plot mapping, mechanized loading equipment, and electronic cultivation registration through e STDB, all of which could improve logistics efficiency and reduce dependence on intermediaries. As a result, operational constraints continue to restrict digital investment, while limited digital capability reduces opportunities to improve operational performance. Digital upgrading therefore depends not only on organizational investment but also

on whether upstream producers can retain sufficient value to finance continued capability development. This finding suggests that value capture is a prerequisite for digital maturity in fragmented upstream supply chains, a condition that remains largely implicit in conventional digital maturity models.

B. Loop R2: Downstream Information Concentration

Data integration creates value only when organizations can control, verify, and use information to support decision making and continued digital investment [34], [64]. Existing digital maturity models therefore associate greater analytical capability with sustained capability development, but they largely assume that the organizations generating digital information also retain its value. In fragmented supply chains, however, data generation and data ownership are often separated, making information governance a determining factor in how digital capability evolves.

The implementation of the EUDR illustrates this separation. In October 2024, PT Wilmar Nabati Indonesia completed Indonesia's first palm oil export through the National Dashboard, a government traceability platform coordinated by the Coordinating Ministry for Economic Affairs and operated by PT Surveyor Indonesia, after meeting the legality and traceability requirements for the European market [71]. Compliance requires exporters to collect plot level polygon data from supplying smallholders through proprietary digital applications. Although smallholders generate spatial information through their land and production activities, the verified Due Diligence Statement that enables market access remains under downstream control. The economic value created through regulatory compliance is therefore retained primarily by exporters, who can reinvest these returns to strengthen their digital infrastructure, while upstream producers receive limited returns from the information they provide.

This arrangement alters the pathway through which digital capability develops. Capability grows where information ownership can be translated into financial

returns that support continued investment, rather than where the information originates. As downstream firms expand their analytical capabilities, upstream producers remain dependent on external platforms for compliance and market access, reinforcing existing capability disparities across the supply chain. Digital maturity therefore depends not only on the availability of information but also on who controls its governance and captures its economic value, extending conventional digital maturity models beyond technology adoption toward information ownership and value distribution.

D. Loop R3: The Capability Erosion Loop

Organizational capability depends on sustained investment in workforce development, organizational learning, and technical support to support continued digital advancement [22], [28], [42], [51], [61], [62], [67]. This perspective emphasizes capability development but gives less attention to the conditions required to preserve existing capability over time. In fragmented upstream production systems, institutional support and financial resources determine not only whether capability can be developed but also whether it can be maintained.

The community timber sector in Indonesia illustrates this dependency. SVLK serves as the baseline requirement for access to European markets and provides the institutional foundation for compliance with the EUDR [72]. A mixed methods study of community forest farmers in Banten Province found that self-funded SVLK certification was not economically viable because audit and surveillance costs exceeded the financial returns generated through certification [72]. Certification remained sustainable only while government support covered these recurring costs. Once this support ended, many farmers were unable to maintain surveillance audits, resulting in the loss of active certification despite having previously achieved compliance [72].

The loss of certification extends beyond market access because it also weakens the institutional capability required for future digital transformation. Organizational records, land documentation, audit procedures, and compliance experience gradually deteriorate, reducing readiness for more demanding traceability requirements such as polygon-based verification under the EUDR. As institutional capability declines, opportunities for training, technical assistance, and market participation also diminish, further limiting future investment. Digital maturity therefore depends not only on developing new capability but also on sustaining existing capability. This finding suggests that capability maintenance is a prerequisite for long term digital progression in fragmented upstream supply chains, a condition that remains largely implicit in conventional digital maturity models.

E. Loop B1: The Regulatory Exclusion Trap

Regulatory pressure is expected to accelerate digital capability by increasing the cost of noncompliance and encouraging investment in traceability and process improvement [5], [21], [33], [41], [64], [67]. This balancing effect, however, depends on organizations having sufficient absorptive capacity to respond to regulatory requirements. Where financial resources, infrastructure, and institutional readiness remain limited, regulation can restrict market participation instead of stimulating capability development.

The Indonesian timber and palm oil sectors illustrate this constraint. In North Sumatra, poor road conditions, steep terrain, and long transportation distances make

the continuous chain of custody required under the EUDR difficult to achieve without substantial increases in cost or quality loss [73]. Consequently, downstream buyers often reduce compliance risk by sourcing from large concession holders rather than dispersed community producers. A similar pattern exists in the palm oil sector. Although independent smallholders contribute approximately one third of regional production, they account for only about 7 percent of certified mill intake and have limited participation in segregated, and identity preserved supply chains required for EUDR compliance [70]. This challenge is further compounded by land legality, with approximately one quarter of smallholder plantations located within State Forest areas where legal documentation is often unavailable [70].

These conditions shift the function of regulation from capability development to market selection. Compliance increasingly favors producers that already possess the operational, institutional, and financial capacity to satisfy regulatory requirements, while upstream smallholders lose access to the market opportunities, learning processes, and financial returns needed to strengthen their own digital capability. Regulatory pressure therefore promotes digital transformation only when absorptive capacity already exists. In fragmented upstream supply chains, it can instead reinforce existing capability disparities by limiting participation in higher value markets.

F. Prioritized Leverage Points for Intervention

Meadows' hierarchy of leverage points suggests that interventions become more influential as they move from operational parameters toward information flows and system rules [13]. The proposed intervention sequence reflects this progression. Early interventions strengthen the operational and financial conditions required for digital transformation, while later interventions address the governance structures that determine how capability and value are distributed across the supply chain. This sequencing recognizes that institutional reforms are unlikely to succeed unless upstream producers first possess the capacity to participate in them.

The initial priority is to restore operational viability by improving harvest handling through cooperative managed consolidation hubs coordinated with local plantation offices (Dinas Perkebunan). Strengthening retained income provides the financial foundation for subsequent digital investment. This is followed by financing mechanisms that sustain SVLK and Indonesian Sustainable Palm Oil certification, including the use of Palm Oil Plantation Fund Management Agency (BPDP) export levy funds to support electronic cultivation registration through e STDB, certification, and audit costs. These interventions strengthen the resources required to maintain digital capability before introducing broader institutional reforms.

Higher leverage interventions focus on information governance and system rules. Allocating a data generation premium through the National Dashboard recognizes upstream producers as contributors to regulatory compliance rather than only data providers, creating incentives for continued participation in digital traceability. At the deepest level, a federated governance model that enables cooperatives to retain ownership of polygon data changes the rules governing information access and value distribution across the supply chain. Unlike operational improvements, these interventions

reshape the institutional conditions that influence long term capability development, making their effectiveness dependent on the operational and financial capacity established through earlier action.

V. CONCLUSION

This study advances digital maturity research by conceptualizing digital capability as a system level outcome shaped by interactions across fragmented upstream bioindustry supply chains. The proposed causal loop diagram complements conventional digital maturity models by explaining how supply chain relationships, institutional conditions, and governance structures influence capability development beyond the boundaries of individual organizations.

The framework contributes theoretically by extending digital maturity research from organizational assessment toward system behavior, providing a basis for examining how feedback relationships shape digital capability over time. Practically, it offers a systems-based perspective for designing digital transformation strategies that prioritize structural constraints alongside organizational capability, enabling policymakers and industry stakeholders to identify interventions with greater long-term influence on supply chain transformation.

This study is limited to a qualitative causal loop diagram that specifies the direction of causal relationships without quantifying their strength. Consequently, the proposed feedback structure should be interpreted as a dynamic hypothesis rather than predictive evidence. Future research should validate the model using primary field data and extend it into quantitative system dynamics or agent-based models to evaluate the effects of alternative intervention strategies under different policy and operational scenarios.

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