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Reliability Screening and Signaling Investment in Cross-Border Supply Chains: The Pricing Effects of Blockchain Capability

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Abstract. Cross-border disruption is unavoidable, yet foreign retailers often cannot observe suppliers' recovery capability before contracting. This study analyzes auditable blockchain capability investment as both a productive input and a signal of supplier reliability. We develop a manufacturer-led Stackelberg game with asymmetric information that separates exogenous disruption, type-dependent baseline recovery, and investment-driven recovery. Backward induction yields closed-form pricing, demand, and complete-information investment decisions, after which we characterize minimum-cost separation, imitation by the low-reliability type, and the channel-efficiency boundary. A higher perceived delivery probability raises wholesale and retail prices as well as demand, but wholesale price merely responds to the belief induced by investment and is not an independent signal. A digital-cost advantage allows the high-reliability manufacturer to separate credibly, although a larger reliability gap may strengthen imitation incentives and increase the required investment. Because the manufacturer captures only part of the reliability gains accruing to the retailer, signaling investment can correct channel underinvestment until it exceeds the channel optimum. Universal subsidies may stimulate both adoption and imitation, whereas performance-contingent cost sharing better preserves screening incentives. The results inform supplier certification, reliability pricing, digital subsidies, and disruption-risk sharing.

Keywords: blockchain capability, signaling game, cross-border supply chain, supply reliability, channel efficiency

1. Introduction

Cross-border orders pass through booking, customs, port handling, main-haul transport, destination clearance, and last-mile delivery. Route diversions, congestion, extreme weather, inspections, and documentation errors can delay any stage. UNCTAD's 2025 review [1] describes persistent route restructuring, freight volatility, and port disruption. Since individual firms cannot eliminate many of these shocks, operational differentiation rests on post-disruption recovery: switching carriers or ports, correcting electronic documents, coordinating customs and insurance, and restoring delivery

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within an acceptable window. The central governance problem is therefore not simply how to prevent disruption, but how to identify and build recovery capability.

That capability is privately known. Manufacturers observe their backup resources, partners, exception routines, and data quality; retailers with limited history see only quotations, promises, and partial records. Undervaluing a reliable supplier weakens investment incentives, whereas overvaluing an unreliable one creates stock-outs, refunds, platform penalties, and reputational loss. The operating and capital-market costs of disruptions are well documented by Hendricks and Singhal [2, 3]. Distance, institutional differences, and verification costs make one-off audits and self-reported delivery rates particularly weak screening devices in cross-border trade.

Permissioned blockchain can convert latent recovery capability into an auditable action. Manufacturers, carriers, customs agents, and retailers may record order milestones, document status, custody transfers, exceptions, and route substitutions, while smart contracts automate rebooking, insurance notice, or settlement. The technology does not prevent geopolitical shocks or port closure; in this model it reduces data inconsistency and response delay, thereby increasing recovery and final delivery. Node integration, data cleaning, process redesign, and continuous audit are costly, and manufacturers with mature logistics and data systems can typically build the same auditable capability at lower cost.

Three literatures motivate the model. Disruption research studies diversification, buffers, backup capacity, insurance, and contingent sourcing [4, 11], and more recent work examines strategic suppliers, learning bias, and competitive emergency sourcing [12-14]. Signaling theory establishes how costly actions reveal private type [15-18], while supply-chain studies analyze performance measures, guarantees, quality investment, trustworthiness, and information leakage [19-23]. Research on electronic-market transparency and blockchain addresses traceability, anti-counterfeiting, financing, deep-tier finance, smart contracts, and platform design [24-33]. What remains underdeveloped is the joint determination of productive investment, supplier screening, and vertical pricing when the same auditable investment both improves fulfillment and changes beliefs.

We therefore ask how posterior reliability affects wholesale price, retail price, and demand; when productive blockchain investment can sustain a separating equilibrium; and whether investment above the manufacturer's private optimum necessarily destroys channel value. The model embeds signaling in a manufacturer-led pricing game and distinguishes an investment signal from a price response to belief. It also combines the low type's imitation constraint, the high type's participation constraint, and the channel optimum. This framing shows when blockchain capability is a credible productive signal, when proof becomes excessive, and how subsidy, cost sharing, and nonfulfillment liability redistribute adoption and screening incentives.

2. Model setup

2.1. Research setting and supply chain structure

Consider a vertical channel with one cross-border manufacturer M, one foreign retailer R, and an end market. M produces and organizes logistics; R imports and sells. M's baseline ability to mobilize backup carriers, alternative ports, document correction, and interorganizational coordination is private information. R cannot observe type directly but can observe an investment x in auditable blockchain capability, including node coverage, document coverage, exception records, process automation, and route-trigger functions. Figure 1 maps the channel, external disruption, and auditable information flows.

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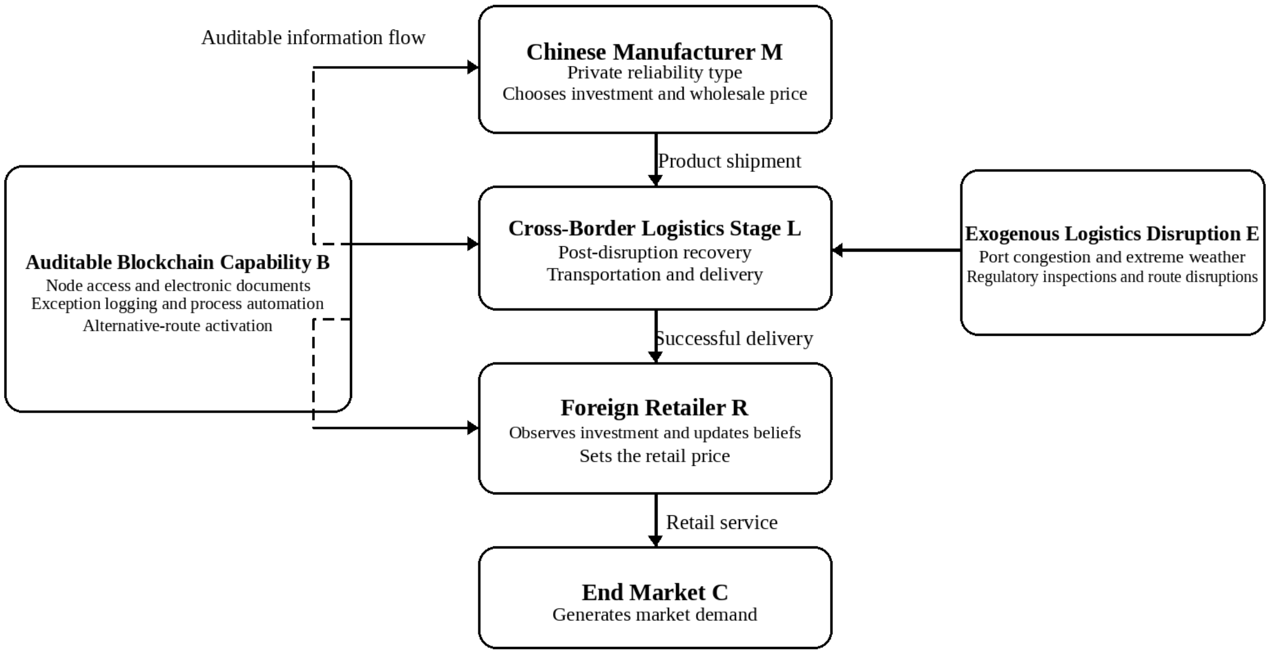

Figure 1. Cross-border supply chain structure, risks, and auditable information flows

Under the benchmark contract, payment occurs only after successful delivery. The unit cost is the net incremental cost of delivered units, with recoverable value from failed delivery netted out. Actual delivery probability therefore scales the manufacturer's realized operating return but does not enter the first-order condition for wholesale price. This assumption isolates the signaling role of investment; prepayment, unrecoverable production cost, or explicit shortage penalties could make price informative.

2.2. Reliability, blockchain capability, and market demand

M has type $\theta \in \{H,L\}$. After an exogenous disruption, the high type has a higher baseline recovery rate. Before trade, M chooses observable investment x. Investment does not change disruption probability; it improves conditional recovery, so final delivery probability combines baseline capability and the recovery effect of x, as in Equation (1).

$$q_\theta(x) = 1 - \delta\,[1 - r_\theta - \gamma x] = q_\theta^0 + \eta x$$
$$\Delta q \equiv q_H^0 - q_L^0 = \delta(r_H - r_L) > 0 \tag{1}$$

Both baseline delivery probabilities lie in (0,1), with $q_H^0 > q_L^0$. Investment effectiveness is positive and the upper bound $\bar{x}$ keeps delivery probabilities feasible. Cost is convex, and $k_H \le k_L$ captures the high type's stronger data, partner, and process foundations. After observing x, R forms posterior belief μ(x) and perceived delivery probability $\hat{q}$. These assumptions support single crossing and interior solutions.

Demand is $D=a-bp+v\hat{q}$, where $a,b,v>0$ and $A=a-bc>0$. Reliability raises market availability and expected service, so R prices on perceived delivery probability, whereas M values orders using actual delivery probability. Profits are given in Equation (2), and Table 1 defines the notation.

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$$\begin{aligned} \pi_R &= \hat{q}(p-w)\left(a-bp+\nu\hat{q}\right) \\ \pi_{M\theta} &= q_\theta(x)(w-c)\left(a-bp+\nu\hat{q}\right)-\frac{k_\theta x^2}{2} \end{aligned} \tag{2}$$

Table 1. Principal notation and economic interpretation

Symbol	Economic interpretation	Symbol	Economic interpretation
$\theta \in \{H, L\}$	Manufacturer's private reliability type	λ	Prior probability of the high type
δ, r_θ	Exogenous disruption probability and baseline recovery rate	$x, \overline{x}$	Blockchain investment and its upper bound
q_θ^0, η	Baseline delivery probability and investment effectiveness	k_θ	Type-specific investment-cost coefficient
$\mu(x), \hat{q}$	Posterior belief and perceived delivery probability	Δq	Baseline reliability gap between high and low types
w, p	Wholesale price and retail price	a, b, v	Market size, price sensitivity, and preference for reliability
c, A	Net unit cost and effective market size	h	Retailer's per-unit nonfulfillment loss

2.3. Decision sequence and equilibrium concept

Figure 2 shows the sequence. Nature selects type; M observes it and chooses x; R observes x and updates beliefs; M sets wholesale price w; R sets retail price p; demand, disruption, recovery, delivery, and settlement follow. We solve for pure-strategy perfect Bayesian equilibria and use the intuitive criterion to assess pooling outcomes. Even if R updates again after observing w, both types rank wholesale-price/belief pairs identically, so w cannot separate types independently of x.

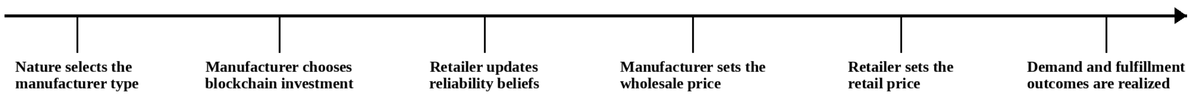

Figure 2. Sequence of decisions

3. Benchmark equilibrium and the reliability premium

3.1. Channel pricing and posterior-belief transmission

Backward induction gives a unique pricing subgame. R's profit is strictly concave in p, and M anticipates R's best response when choosing w. Because actual delivery probability only multiplies M's operating return under the benchmark settlement rule, it does not affect the wholesale-price first-order condition. The resulting w^*, p^*, and D^* are shown in Equation (3).

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$$\begin{aligned} w^*(\hat{q}) &= c + \frac{A + v\hat{q}}{2b} \\ p^*(\hat{q}) &= c + \frac{3(A + v\hat{q})}{4b} \\ D^*(\hat{q}) &= \frac{A + v\hat{q}}{4} \end{aligned} \quad (3)$$

Proposition 1. For given x and q̂, the pricing equilibrium is unique. A higher q̂ raises w^*, p^*, and D^*. Conditional on the posterior induced by x, both manufacturer types rank wholesale prices identically; wholesale price is therefore a response to reliability beliefs, not an additional type signal.

$$U_\theta(x;\mu) = \frac{q_\theta(x)\left[A + \nu\hat{q}(x,\mu)\right]^2}{8b} - \frac{k_\theta x^2}{2}$$

$$V_R(\hat{q}) = \frac{\hat{q}\left(A + \nu\hat{q}\right)^2}{16b}$$

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3.2. Complete-information investment and type heterogeneity

With public type, investment has only productive value. Assuming the investment payoff is strictly concave and marginal return is negative at x̄ ensures a unique interior optimum. Substituting actual delivery probability into the investment-stage payoff in Equation (4) yields the quadratic first-order condition and the economically relevant smaller root in Equation (5).

$$\begin{aligned} x_\theta^{CI} &= \frac{M_\theta - \sqrt{\Omega_\theta}}{6\nu^2\eta^3} \\ M_\theta &= 8bk_\theta - 2\nu\eta^2(2A + 3\nu q_\theta^0) \\ \Omega_\theta &= M_\theta^2 - 12\nu^2\eta^4(A + \nu q_\theta^0)(A + 3\nu q_\theta^0) \end{aligned} \quad (5)$$

Proposition 2. Each type has a unique complete-information optimum x_θ^{CI}. It increases with baseline delivery capability, effective market size, consumers' valuation of reliability, and investment effectiveness, and decreases with the investment-cost coefficient. If $q_H^0 > q_L^0$ and $k_H \leq k_L$, then $x_H^{CI} > x_L^{CI}$.

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4. Signaling equilibrium for supply reliability

4.1. Single crossing and the low type's incentive to imitate

Under asymmetric information, x affects both actual delivery and R's inference. The derivative in Equation (6) is positive, so the high type's payoff advantage increases with investment: the model satisfies strict single crossing. This ordering is necessary but not sufficient for separation because imitation, high-type participation, and the investment bound must also be satisfied.

$$\frac{\partial[U_H(x;\mu)-U_L(x;\mu)]}{\partial x} = \frac{\Delta q v\eta\left[A+v\hat{q}(x,\mu)\right]}{4b} + (k_L - k_H)x > 0 \tag{6}$$

On the truthful low-type path, L chooses x_L^{CI}. If it seeks the high-type assessment, it reoptimizes investment under μ=1. Its imitation payoff is strictly concave, and equating it to truthful payoff gives the cubic in Equation (7). The separation threshold is the unique upper root on the declining branch of the imitation payoff.

$$P_L(x) = a_3x^3 + a_2x^2 + a_1x + a_0 = 0, \quad \begin{cases} a_3 = v^2\eta^3 \\ a_2 = v\eta^2\left(vq_L^0 + 2B_H\right) - 4bk_L \\ a_1 = \eta B_H\left(B_H + 2vq_L^0\right) \\ a_0 = q_L^0 B_H^2 - 8bH_L \end{cases} \tag{7}$$

If imitation is already unprofitable at x_H^{CI}, the minimum separating investment equals the high type's productive optimum. Otherwise H raises investment to the upper root that leaves L indifferent. Separation also requires this threshold not to exceed H's maximum willingness to pay or $\bar{x}$.

4.2. Existence conditions for a separating equilibrium

Proposition 3. A minimum-cost separating equilibrium exists if and only if the investment required to deter L does not exceed the maximum investment H is willing and able to undertake.

In equilibrium, L chooses x_L^{CI} and H chooses the smallest feasible separating investment. Figure 3 shows the intersection of L's imitation constraint with H's incentive-compatible interval. Deterring imitation alone is insufficient: a certification threshold can be so demanding that the reliable supplier prefers pooling at a lower assessment.

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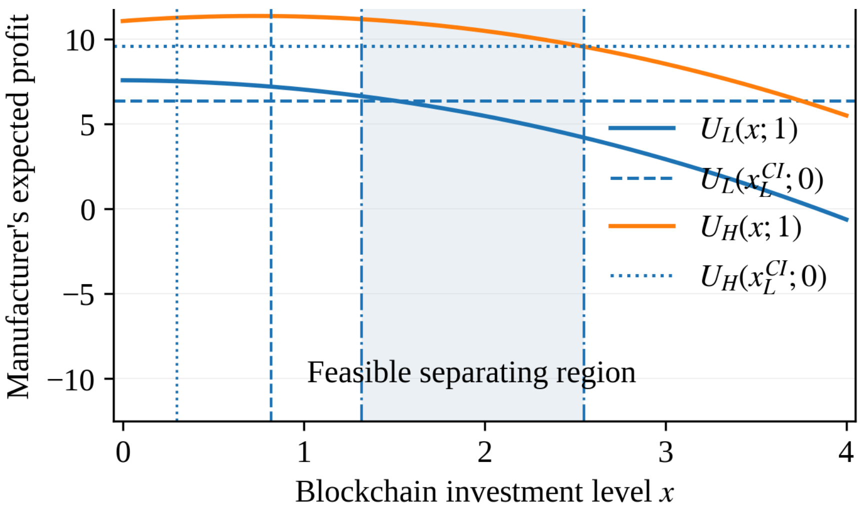

Figure 3. Imitation constraint of the low type and incentive-compatible range of the high type

$$A=8, b=1, v=4, q_L^0=0.5, q_H^0=0.75, C=0.05, k_H=1.5, k_L=3, \overline{x}=4$$

4.3. Determinants of the separation threshold

When L's imitation constraint binds, let F be imitation payoff minus truthful payoff and choose the declining upper root. Implicit differentiation gives Equation (8): the separation threshold rises with the baseline reliability gap, falls with L's investment cost, and is independent of the prior under full separation.

$$\begin{aligned} \frac{\partial x_{det}^S}{\partial \Delta q} &= -\frac{vq_L\left(x_{det}^S\right)\left[A+vq_H^0+v\eta x_{det}^S\right]}{4bF_x}>0 \\ \frac{\partial x_{det}^S}{\partial k_L} &= \frac{\left(x_{det}^S\right)^2-\left(x_L^{CI}\right)^2}{2F_x}<0 \\ \frac{\partial x_{det}^S}{\partial \lambda} &= 0 \end{aligned} \tag{8}$$

A larger reliability gap can therefore make screening harder. It raises H's operating advantage, but also enlarges the price, demand, and profit premium that L captures when mistaken for H. By contrast, higher data-integration and audit costs for L directly reduce imitation. The irrelevance of the prior is specific to pure separation; priors may matter under partial pooling or dynamic reputation.

4.4. Pooling equilibria and the retailer's value of information

Pooling is supportable under sufficiently pessimistic off-path beliefs, but the intuitive criterion eliminates a pooling outcome when a deviation benefits only H and remains unattractive to L even under the most favorable belief. We therefore use minimum-cost separation as the main equilibrium and pooling as a benchmark for the value of information.

$$IV_R(x)=\lambda V_R(q_H)+(1-\lambda)V_R(q_L)-V_R(\bar{q})=\frac{\lambda(1-\lambda)(\Delta q)^2\nu\left[2A+\nu\left(3q_L(x)+(1+\lambda)\Delta q\right)\right]}{16b}>0 \tag{9}$$

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For fixed x, the retailer's information value is given in Equation (9). It is strictly positive when the prior is interior, the reliability gap is positive, and consumers value reliability. Investment does not change the baseline gap, but it raises average delivery and transaction scale, increasing the value at stake in misclassification. Thus H may pay the verification cost while R captures part of the pricing, demand, and stockout benefits.

5. Channel efficiency and governance instruments

5.1. Signaling investment and channel efficiency

Separating investment may exceed H's private complete-information optimum without reducing channel profit. M captures only part of the reliability gain through wholesale margin and successful delivery, whereas R also benefits from higher demand, better pricing, and fewer shortages. Maximizing joint profit yields the channel optimum in Equation (10).

$$x_\theta(m) = \frac{M_\theta^{(m)} - \sqrt{(M_\theta^{(m)})^2 - 12m^2\nu^2\eta^4(A+\nu q_\theta^0)(A+3\nu q_\theta^0)}}{6m\nu^2\eta^3}, \quad m \in \{2,3\} \tag{10}$$

Proposition 4. Accurate identification increases R's profit. Under complete information, x_θ^{CI} is below the channel-optimal investment. Hence signaling investment between the private and channel optima corrects under investment; only the portion above the channel optimum is a net efficiency loss.

Figure 4 summarizes the boundary. Extra investment is not waste merely because it serves a signaling purpose. Cost sharing should reflect the channel value created by reliability, not reimburse every dollar above the manufacturer's private optimum.

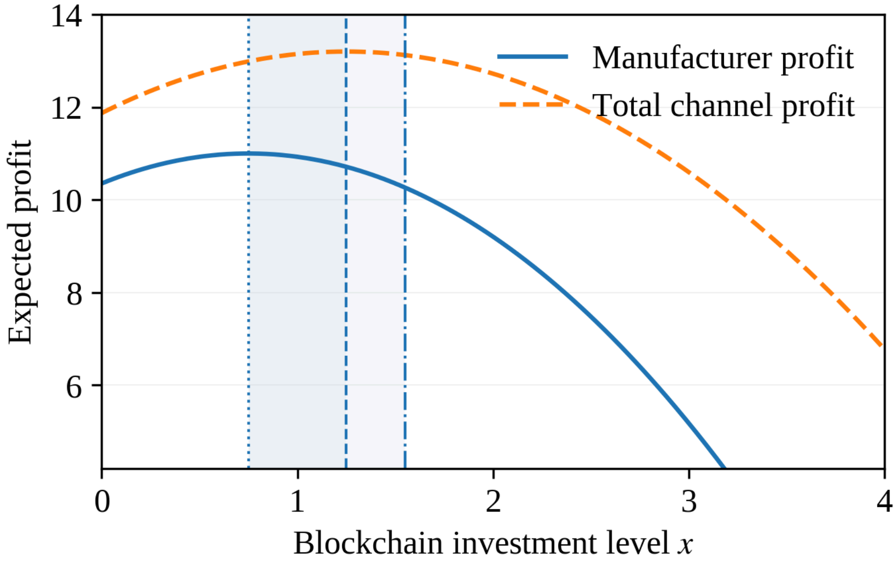

Figure 4. Relative positions

$$A = 8, b = 1, \nu = 4, q_L^0 = 0.5, q_H^0 = 0.75, C = 0.05, k_H = 1.5, k_L = 3, \overline{x} = 4$$

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5.2. Subsidy design and screening effectiveness

Now consider cost support from a government, platform, or retailer. A universal subsidy reduces both types' investment costs and therefore promotes productive adoption while also making imitation cheaper. Performance-contingent cost sharing reimburses verified recovery outcomes and, in the extension, lowers H's effective cost on the separating path without lowering L's off-path imitation cost.

Universal support is appropriate for shared interfaces, identities, and basic data standards, but subsidies based only on software spending or node counts need not improve information quality. Tying reimbursement to document consistency, response time, route activation, and final delivery strengthens H's participation while preserving the imitation barrier. Figure 5 contrasts these effects; its advantage disappears if performance measures are easily manipulated.

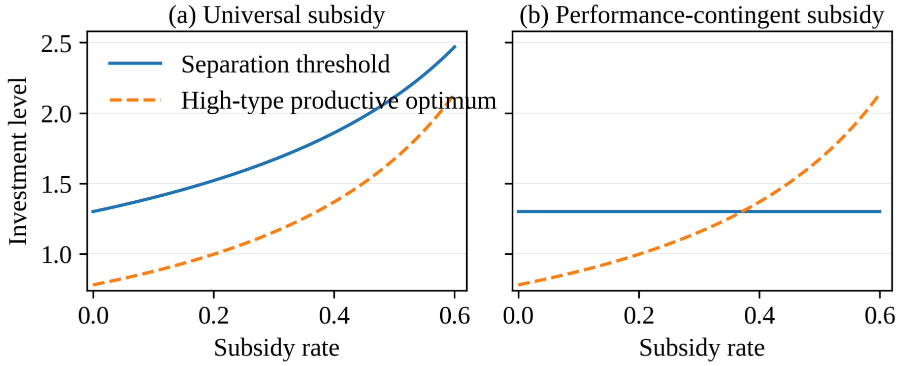

Figure 5. Different effects of universal and performance-contingent subsidies on signaling distortions

$$A = 8, b = 1, v = 4, q_L^0 = 0.5, q_H^0 = 0.75, C = 0.05, k_H = 1.5, k_L = 3, \overline{x} = 4$$

5.3. Nonfulfillment losses and investment incentives

To represent refunds, platform penalties, and reputation loss, let R incur per-unit non-fulfillment loss h. Solving the extended pricing game gives closed-form decisions, and the cross-partial in Equation (11) shows that greater liability does not monotonically strengthen investment incentives.

$$\frac{\partial^2 U_\theta^h}{\partial x \partial h} = \frac{\eta}{4q^2} \left\{ q^2 \left[A + v(2q-1) \right] - bh(1-q^2) \right\}$$
$$\overline{h}(q) = \frac{q^2 \left[A + \nu(2q-1) \right]}{b(1-q^2)} \tag{11}$$

Proposition 5. Universal subsidies affect productive investment and imitation simultaneously, so their net signaling effect is ambiguous. Performance-contingent cost sharing expands H's separation region without reducing L's imitation cost. When h is low, greater liability raises the transaction value of reliability; above a threshold, the channel limits exposure through higher prices and lower demand, weakening M's incentive to invest.

Figure 6 illustrates the threshold. Liability should therefore be coordinated with cargo insurance, flexible delivery windows, backup routes, shared inventory, and joint exception response rather than increased in isolation.

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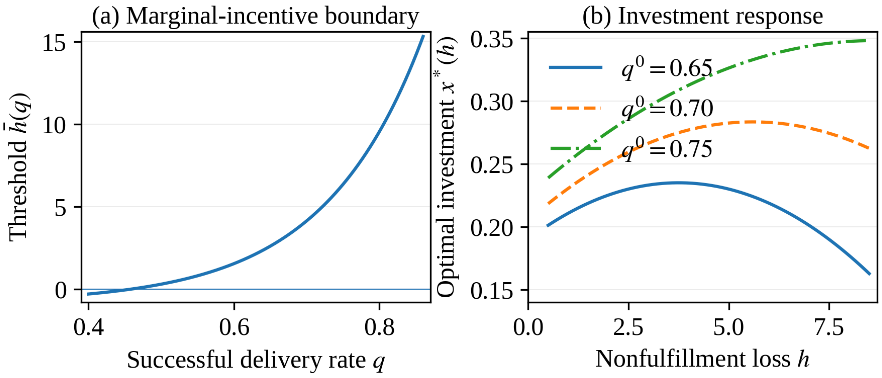

Figure 6. Threshold effect of the retailer's nonfulfillment loss on optimal investment

$$A = 8, b = 1, \nu = 4, q_L^0 = 0.5, q_H^0 = 0.75, C = 0.05, k_H = 1.5, k_L = 3, \overline{x} = 4$$

6. Managerial implications

6.1. Improving supplier certification and channel pricing with dynamic fulfillment evidence

Supplier certification should evaluate dynamic fulfillment evidence rather than software acquisition or a one-time certificate. Retailers, platforms, and auditors can score document-correction time, custody completeness, alternative-port activation, backup-capacity coverage, exception closure, and recovered delivery across repeated orders. Such evidence makes static imitation harder and helps buyers distinguish a reliability premium from bargaining power. Procurement should therefore evaluate price jointly with recovery records, inventory exposure, and downstream market value.

6.2. Designing cost sharing and digitalization subsidies around channel benefits

Reliable suppliers may bear interface, audit, and coordination costs while retailers share the benefits of fewer shortages and stronger demand. Minimum purchase commitments, post-audit interface rebates, recovery bonuses, and shared maintenance can transfer part of that value back to the supplier. Support should target the incremental channel benefit of reliability; redundant nodes, duplicate audits, and ceremonial records beyond the channel optimum should be eliminated.

6.3. Distinguishing infrastructure support, performance incentives, and risk liability

Policy should separate basic-access support from screening incentives. Common standards and identity infrastructure can receive broad support, whereas financing terms, platform traffic, rebates, and purchase commitments should depend on verified recovery performance. Liability clauses should distinguish controllable delay, concealed information, and exogenous shocks and should be paired with insurance, alternative routes, flexible windows, shared inventory, and joint response mechanisms.

7. Conclusion

This study models auditable blockchain capability as a productive signal in cross-border supply chains. By separating exogenous disruption, type-dependent baseline recovery, and investment-

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driven recovery, the model integrates investment, belief updating, wholesale pricing, and retail pricing in one dynamic game.

Four results follow. Reliability beliefs raise wholesale price, retail price, and demand, but wholesale price does not signal independently of investment. A high type with a digital-cost advantage can separate, although a wider reliability gap may also increase imitation rent and the required threshold. Because the manufacturer does not internalize the retailer's full benefit, moderate signaling investment can correct channel underinvestment; only investment beyond the channel optimum is wasteful. Universal subsidies may promote both adoption and imitation, whereas verifiable performance-contingent cost sharing better balances adoption, screening, and efficiency.

The results rely on settlement after successful delivery, a single manufacturer-retailer dyad, and one-dimensional auditable capability. Prepayment, unrecoverable production cost, shortage penalties, supplier competition, inventory choice, dynamic reputation, data falsification, oracle reliability, and privacy governance may alter the mechanism. Future work can extend the contract and competition structure and calibrate the model with electronic documents, exception-response times, route substitutions, and recovered-delivery records.

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