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MODELING OPPORTUNISTIC BEHAVIOR AND TRANSACTIONAL RISKS AMONG CLUSTER PARTICIPANTS: A GAME-THEORETIC APPROACH

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Abstract – Industrial and agro-industrial clusters combine high operational interdependence with conflicting profit motives, exposing participants to opportunism when information about compliance is asymmetric. Existing research explains why opportunism arises but offers few quantifiable mechanisms for suppressing it in emerging-economy clusters. This study develops a two-player non-cooperative game between a primary supplier, who chooses honest delivery or opportunistic non-compliance, and a focal processing enterprise, which chooses strict verification or unmonitored trust. The model is parameterized by material value, compliance and inspection costs, opportunistic gain, contractual penalty and a discount factor. Derivations show that the static game has no pure-strategy equilibrium but a unique mixed-strategy one, in which the probability of opportunism equals inspection cost divided by the sum of penalty and material value, while the verification probability equals the supplier's temptation divided by the sum of material value, gain and penalty. If the penalty does not accrue to the verifier, the probability of opportunism becomes independent of the penalty. In the infinitely repeated game, honest delivery under unmonitored trust is sustained by a grim-trigger strategy when the discount factor exceeds a threshold, and committed verification substitutes for relationship length below it. Simulations with illustrative parameters anchored to cotton price gaps show that opportunism falls in proportion to inspection cost, that penalties collected by the focal enterprise deter more effectively than penalties paid to an external fund, and that repeated interaction lowers the required verification probability from twenty to about four percent. The findings support incentive-compatible contracts, mutual risk funds and digital traceability.

Keywords: cluster structures, opportunistic behavior, transaction costs, game theory, Nash equilibrium, contract governance, supply risks, asymmetric information, repeated games, payoff matrix

INTRODUCTION

Industrial and agro-industrial clusters, understood as geographically concentrated groups of interconnected firms and supporting institutions, remain one of the most widely used organizational forms for building competitiveness in both advanced and emerging economies [21; 26]. Their advantages arise from proximity to suppliers and buyers, shared infrastructure and knowledge spillovers, and from the possibility of coordinating successive stages of a value chain without full integration [11; 28]. In agro-industrial clusters this coordination typically links numerous small and medium-sized suppliers of raw materials with a focal processing enterprise that integrates procurement, processing and marketing.

The same interdependence generates transactional hazards. Once a supplier has adapted its production to the quality standards and delivery schedules of a focal buyer, both sides hold specific

investments whose value outside the relationship is lower than inside it, and each party may be tempted to appropriate the resulting quasi-rents [17; 34]. Williamson [32; 35] described the behavioral root of such hazards as opportunism, that is, self-interest seeking with guile, which becomes consequential when contracts are incomplete and information about actions or quality is asymmetric. In cluster linkages opportunism takes concrete forms: delivery of raw material below the contracted grade, diversion of contracted volumes to spot buyers when market prices exceed contract prices, misreporting of input use, and default on payment obligations [22; 31].

The magnitude of the incentives involved can be substantial. In Uzbekistan’s cotton–textile clusters, for example, the minimum price recommended for futures contracts was announced at 7,800 soums per kilogram of raw cotton while world exchange prices at that time were close to 6,000 soums, a gap of 23–30 percent depending on the base [36]. Clusters were reported to have incurred losses of about 6 trillion soums from price divergences, and arrears to farmers remained a persistent problem [37]; official reviews of the sector list the high cost of financing among the factors that limit its stable development [38]. Although these episodes concern default by cluster cores as much as by suppliers, they illustrate how price gaps of this order can dominate the short-run gains from compliance for either party.

The scientific problem addressed here follows from this tension: cluster participants are highly interdependent operationally, yet their individual profit motives conflict, and neither party can observe the other’s compliance effort at low cost. The transaction cost and cluster literatures explain why the tension arises, but they rarely deliver quantitative conditions under which opportunism is deterred. Game theory offers such conditions, yet existing models are generic and seldom parameterized for the structure of agricultural and industrial cluster linkages in emerging economies.

The aim of the study is to construct and analyze a game-theoretic model that quantifies how inspection costs, contractual penalties, opportunistic gains and the shadow of the future determine the probability of opportunistic behavior between a primary supplier and a focal processing enterprise in a cluster, and to derive governance parameters that make honest delivery incentive-compatible. The specific objectives are: (1) to formalize the supplier–integrator interaction as a two-player non-cooperative game with explicit payoffs; (2) to derive the static mixed-strategy Nash equilibrium and its comparative statics; (3) to establish the conditions under which honest delivery is sustained in the infinitely repeated game, with and without committed verification; (4) to quantify equilibrium shifts by numerical simulation under baseline parameters anchored to cluster evidence; and (5) to translate the results into governance instruments.

The object of the research is inter-firm contractual relations within industrial and agro-industrial clusters; the subject is the strategic interaction of a primary supplier and a focal processing enterprise under information asymmetry and the equilibrium conditions that suppress opportunism. Three hypotheses were advanced. H1: opportunism can be suppressed on the equilibrium path when the long-term penalty and incentive parameters satisfy the dynamic Nash equilibrium conditions of the repeated game. H2: in the static game the equilibrium probability of opportunism increases with the inspection cost and decreases with the penalty and the raw material value. H3: the recipient of the penalty matters, because a penalty that does not accrue to the verifying party leaves the equilibrium probability of opportunism unchanged.

The scientific novelty of the study consists in (i) a closed-form parameterization of the supplier–integrator game that links the probability of opportunism to observable cluster parameters; (ii) a proof that the penalty recipient determines whether penalties affect opportunism at all; and (iii) a unified condition in which the discount factor and a committed verification probability substitute for each other, from which minimum verification intensities are derived.

LITERATURE REVIEW

Transaction cost economics and opportunism. Coase [7] explained the existence of firms by the costs of using the price mechanism, and Williamson [32; 34] developed the argument by identifying bounded rationality, opportunism and asset specificity as the sources of contractual

hazards that shape the choice between markets, hybrids and hierarchies. Klein et al. [17] showed that specific investments create appropriable quasi-rents that invite hold-up; Williamson [33] classified governance structures by the safeguards they provide; and Williamson [35] defended opportunism as an analytically necessary assumption against critics who considered it excessively pessimistic. Grossman and Hart [13] recast the boundary question in terms of residual control rights under incomplete contracts. Empirical work in marketing distinguishes active and passive, blatant and subtle forms of opportunism and matches them with monitoring, incentive and relational remedies [31]. The critical observation is that this tradition is comparative and largely qualitative: it ranks governance modes but rarely yields equilibrium probabilities of opportunism or minimum penalty levels.

Industrial clusters and inter-firm networks. Porter [26] defined clusters as geographic concentrations of interconnected firms and institutions and attributed their advantage to competitive externalities. Markusen [21] challenged the uniformity of this picture with a typology of industrial districts, including hub-and-spoke and satellite forms in which a dominant firm anchors many suppliers. Schmitz [28] introduced collective efficiency, which combines passive external economies with deliberate joint action, while Humphrey and Schmitz [14] and Gereffi et al. [11] linked local clusters to global value chain governance and showed that relational and captive forms differ in the power asymmetries they contain. Granovetter [12] argued that economic transactions are embedded in social relations that support trust but do not exclude opportunism, and Uzzi [30] demonstrated the paradox of embeddedness, whereby closeness beyond a threshold makes networks rigid and exposed to shocks. Studies of developing economies emphasize that vertical ties with lead firms and horizontal ties among small firms play different roles in market access [22]. Cluster scholarship therefore recognizes both trust and opportunism, but it treats them descriptively and does not specify the incentive parameters that separate compliant from opportunistic regimes.

Game-theoretic models of governance and supply chain risk. The non-cooperative equilibrium concept [24] underpins the strategic analysis of contracts, and the theory of repeated games shows that cooperation can be sustained by the threat of future punishment when players are sufficiently patient [8; 9; 10], as illustrated by the evolution of cooperation in repeated dilemmas [3] and by community enforcement in decentralized markets [16]. Relational contract theory develops the same logic for firms: informal agreements are self-enforcing when the value of the future relationship exceeds the short-run gain from reneging [19; 20], and relational contracts help to explain the boundaries of the firm, that is, when repeated dealing can substitute for integration [5]; empirical evidence suggests that formal contracts and relational governance can complement one another [25]. Inspection games analyze the interaction of a potential violator and an inspector with costly verification [2], and a well-known result is that in mixed equilibrium the violation probability may be unaffected by the penalty when the penalty does not enter the inspector's payoff [29]. In operations research, game theory has been applied extensively to supply chain coordination [6; 23], and Babich and Tang [4] analyzed opportunistic supplier adulteration and compared deferred payment, inspection and combined mechanisms. Interdependent-risk models show that protective investment by one agent depends on what others do, which motivates collective schemes [18]. Finally, digital traceability technologies have been discussed as means of reducing verification costs in food and agricultural chains [1; 15; 27].

Opportunism in agro-industrial clusters of developing economies. Two features of agro-industrial linkages sharpen the transaction cost logic. First, the quality of agricultural raw material is difficult to observe before delivery and is costly to verify afterwards, which gives suppliers scope for the passive and subtle forms of opportunism described by Wathne and Heide [31]. Second, the specific investments are often two-sided: suppliers adapt to the grade and timing requirements of the processor, and the processor invests in capacity that is idle without a steady flow of raw material, so that the hold-up problem [17; 33] can run in both directions. In such settings, lead firms in hub-and-spoke clusters have both the power and the need to police their suppliers [11; 21], and small suppliers in developing economies often rely on the lead firm for market access [22]. What is missing in this

stream is a compact strategic model that shows how much verification and how large a penalty are required to keep the supplier compliant.

Methodological positioning. Transaction cost economics and game theory are complementary rather than competing. The former specifies which hazards arise under which contractual conditions [34], whereas the latter supplies the tools to compute equilibrium behavior once payoffs are specified [10; 24]. The folk theorem [9] implies that repeated games typically admit many equilibria, so a useful analysis must focus on explicit thresholds for the cooperative equilibrium, as in the grim-trigger tradition [8]. Inspection games, in turn, include versions in which the inspector commits to an inspection strategy [2], which is relevant when a focal enterprise can institutionalize verification through contracts or technology. Reviews of game theory in supply chains [6; 23] concentrate, in the author's reading, on pricing, inventory and coalition formation, and give comparatively little attention to compliance and verification between a processor and its raw material suppliers. These observations frame the gap defined below.

Research gap. Three limitations emerge from this critical comparison. First, transaction cost and cluster studies [14; 26; 34] identify governance forms but not quantitative deterrence conditions. Second, generic inspection and supply chain games [2; 4; 6] are not parameterized for cluster linkages, where a focal processor faces many small suppliers, verification is partly technological, and the penalty may be collected by the focal firm or by a collective fund. Third, the joint role of the discount factor and of committed verification, which is central to relational governance in seasonal agro-industrial contracting, has received little explicit quantification. The present study fills this gap by supplying closed-form, quantifiable game-theoretic mechanisms tailored to agricultural and industrial cluster linkages in emerging economies, with parameters anchored to documented price gaps [36; 37].

METHODOLOGY

The study used analytical modeling complemented by numerical simulation. A non-cooperative game was chosen because cluster participants make decisions independently, cannot write fully enforceable contracts on unobservable compliance effort, and interact repeatedly [10; 24]. A stylized two-player structure was adopted to isolate the mechanism; the results for one representative supplier were taken to apply to each supplier when the focal firm faces many suppliers whose deliveries are independent.

Player S was the primary supplier, a small or medium-sized enterprise within the cluster, who chose between honest delivery (H) and opportunistic non-compliance (D). Player C was the focal processing enterprise, the cluster core integrator, who chose between strict verification (V) and unmonitored trust (T). Each interaction concerned one delivery batch. The parameters were defined per batch: P , the raw material value, equal to the contract payment for a conforming batch; C , the compliance cost borne by the supplier only under honest delivery; M , the inspection cost borne by the focal firm only under verification; B , the additional private gain of the supplier from undetected opportunism; F , the contractual penalty paid by the supplier when opportunism was detected by verification; and $\delta \in [0, 1)$, the discount factor in repeated interaction, interpreted as the product of the time-preference factor and the probability that the relationship continues.

Payoffs were measured net of ordinary production costs and relative to zero outside options. Five assumptions were made. A1: $P > C > 0$, and $B, M, F > 0$. A2: $M < P + F$, so that verification was worthwhile if opportunism were certain. A3: verified opportunism led to rejection of the batch, no payment, and a penalty F transferred to the focal firm. A4: undetected opportunism yielded the payment P plus the gain B to the supplier and a loss P to the focal firm, because the non-conforming batch had no value. A5: in the repeated game, actions became common knowledge after each period, so that undetected defection was observed with a lag. The payoff matrix followed from these assumptions (Table 1). Let q denote the probability that the supplier defected and r the probability that the focal firm verified. The expected payoffs of the supplier's pure strategies against r and of the focal firm's pure strategies against q were written as follows.

$$U_S(H) = P - C, \quad U_S(D) = (1 - r)(P + B) - rF \quad (1)$$

$$U_C(V) = qF - M, \quad U_C(T) = -qP \quad (2)$$

The static solution concept was Nash equilibrium in mixed strategies, obtained from the indifference conditions of both players. For the infinitely repeated game, grim-trigger strategies were analyzed with the one-shot deviation principle [10]: the supplier delivered honestly as long as no defection had been observed, and any observed defection led the focal firm to terminate the relationship, yielding zero continuation payoffs to both parties. Two governance regimes were considered: unmonitored trust, and committed random verification with per-period probability μ . The value of honest delivery and the value of a one-period deviation were defined as follows.

$$V_H = \frac{P - C}{1 - \delta}, \quad V_D(\mu) = (1 - \mu)(P + B) - \mu F \quad (3)$$

In the expression for the deviation value, the deviation was detected by verification and penalized with probability μ and otherwise paid $P + B$; in both cases the relationship ended after that period. A variant in which the penalty was paid to a mutual risk fund rather than to the focal firm was analyzed by replacing the focal firm's payoff under (D, V) with $-M$.

Baseline parameters were illustrative and normalized to $P = 100$ per batch: $C = 12$, $B = 25$, $M = 10$, $F = 60$ and $\delta = 0.25$. The ratio $B/P = 0.25$ was anchored to the documented gap of 23–30 percent between contract and market prices of raw cotton [36]; the remaining parameters represented a moderate compliance cost (12 percent of batch value), an inspection cost of 10 percent of batch value, a penalty of 60 percent of batch value, and short-horizon seasonal contracting with annual re-tendering (a low discount factor). No claim was made that these values were estimated from firm-level data. Sensitivity grids covered $M \in \{2, 5, 10, 15, 20, 30\}$, $F \in \{20, 40, 60, 100, 150, 200\}$ and $\delta \in \{0, 0.10, 0.20, 0.25, 0.30\}$.

The analytical results were verified numerically in four ways: (i) a search over all four pure-strategy profiles for profitable unilateral deviations; (ii) evaluation of both players' indifference residuals at the derived equilibrium and an independent solution of the indifference conditions as linear equations; (iii) comparison of truncated discounted payoff streams (4,000 periods) with the closed-form thresholds around the critical discount factor; and (iv) a Monte Carlo simulation of 2,000,000 stage-game rounds in which both players used the equilibrium mixtures (random seed 20260920). All computations were performed in Python (NumPy) and can be reproduced from the formulas in the text.

ANALYSIS AND RESULTS

Table 1 presents the payoff matrix, with the payoff of the supplier listed first, and its numerical values at the baseline parameters.

Table 1.

Strategic payoff matrix (supplier; focal firm)

Supplier \ Focal firm	Strict verification (V)	Unmonitored trust (T)
Honest delivery (H)	$(P - C; -M)$ (88; -10)	$(P - C; 0)$ (88; 0)
Opportunistic non-compliance (D)	$(-F; F - M)$ (-60; 50)	$(P + B; -P)$ (125; -100)

Proposition 1 (static equilibrium). Under A1–A2 the static game has no pure-strategy Nash equilibrium and a unique mixed-strategy equilibrium in which the supplier defects with probability q^* and the focal firm verifies with probability r^* , where:

$$q^* = \frac{M}{P + F}, \quad r^* = \frac{B + C}{P + B + F} \quad (4)$$

The equilibrium payoffs are:

$$U_S^* = P - C, \quad U_C^* = -\frac{MP}{P + F} \quad (5)$$

Proof. Against V the supplier's best reply is H, because $P - C > -F$; against H the focal firm's

best reply is T, because $0 > -M$; against T the supplier's best reply is D, because $P + B > P - C$; and against D the focal firm's best reply is V, because $F - M > -P$ under A2. The best replies therefore cycle and no pure-strategy profile is an equilibrium. A two-by-two game without a pure equilibrium has a unique equilibrium in completely mixed strategies, in which each player is indifferent between the two pure strategies. Equating the focal firm's expected payoffs in (2), $qF - M = -qP$, gives $q^* = M/(P + F)$. Equating the supplier's expected payoffs in (1), $P - C = (1 - r)(P + B) - rF$, gives $r(P + B + F) = B + C$, hence $r^* = (B + C)/(P + B + F)$. Assumptions A1–A2 imply $0 < q^* < 1$ and $0 < r^* < 1$, and substitution into (1) and (2) yields the payoffs. At the baseline parameters $q^* = 0.0625$, $r^* = 0.2000$, $U_S^* = 88.00$ and $U_C^* = -6.25$.

Corollary 1 (comparative statics). $\partial q^*/\partial M = 1/(P + F) > 0$; $\partial q^*/\partial F = \partial q^*/\partial P = -M/(P + F)^2 < 0$; and q^* does not depend on B or C . Further, $\partial r^*/\partial B = (P + F - C)/(P + B + F)^2 > 0$; $\partial r^*/\partial C = 1/(P + B + F) > 0$; $\partial r^*/\partial F = \partial r^*/\partial P = -(B + C)/(P + B + F)^2 < 0$; and r^* does not depend on M . Proof. Direct differentiation of (4), using $P + F - C > 0$, which follows from A1. At the baseline, $\partial q^*/\partial M = 0.00625$ and $\partial q^*/\partial F = -0.00039$.

Table 2 reports the sensitivity of the equilibrium probability of opportunism, q^* , to the inspection cost M and the penalty F , together with the corresponding equilibrium verification probability r^* .

Table 2.
Sensitivity of the equilibrium probability of opportunism q^* (%) to inspection cost M and penalty F

	$F = 20$	$F = 40$	$F = 60$	$F = 100$	$F = 150$	$F = 200$
$M = 2$	1.67	1.43	1.25	1.00	0.80	0.67
$M = 5$	4.17	3.57	3.12	2.50	2.00	1.67
$M = 10$	8.33	7.14	6.25	5.00	4.00	3.33
$M = 15$	12.50	10.71	9.38	7.50	6.00	5.00
$M = 20$	16.67	14.29	12.50	10.00	8.00	6.67
$M = 30$	25.00	21.43	18.75	15.00	12.00	10.00
r^* (%)	25.5	22.4	20.0	16.4	13.5	11.4

The probability q^* ranged from 0.67 percent ($M = 2$, $F = 200$) to 25.00 percent ($M = 30$, $F = 20$). At $M = 10$, raising F from 20 to 200 reduced q^* from 8.33 to 3.33 percent; at $F = 60$, raising M from 2 to 30 increased it from 1.25 to 18.75 percent.

Proposition 2 (penalty recipient). If the penalty is paid to a mutual risk fund and the focal firm's payoff under (D, V) is $-M$, the unique mixed-strategy equilibrium has the supplier defect with probability:

$$q^f = \frac{M}{P} \quad (6)$$

and the focal firm verify with the unchanged probability r^* ; the condition for an interior equilibrium is $M < P$. Proof. The focal firm's expected payoff from V is $-M$ regardless of q , whereas from T it is $-qP$; indifference gives $q^f = M/P$. The supplier's payoffs are unchanged, so r^* is unchanged. Hence q^f is independent of F . At the baseline $q^f = 0.1000$, compared with $q^* = 0.0625$ when the focal firm receives the penalty; the focal firm's equilibrium payoff is $-q^f P = -10.00$.

Proposition 3 (commitment). Suppose the focal firm commits to a verification probability before the supplier chooses. The supplier's best reply is H if and only if $r \geq r^*$; at $r = r^*$ the focal firm's payoff is $-r^* M$. This payoff exceeds the mixed-equilibrium payoff U_C^* if and only if:

$$BF < (P - C)(P + F) \quad (7)$$

Proof. From (1), H is a best reply if $P - C \geq (1 - r)(P + B) - rF$, i.e., $r \geq (B + C)/(P + B + F)$. Then $-r^* M > -MP/(P + F)$ is equivalent to $(B + C)(P + F) < P(P + B + F)$, which simplifies to $BF < (P - C)(P + F)$. At the baseline, $BF = 1500$ and $(P - C)(P + F) = 14080$, and the focal firm's payoff under commitment is -2.00 against -6.25 in the mixed equilibrium.

Proposition 4 (repeated game without monitoring). In the infinitely repeated game, the

strategy profile in which the supplier delivers honestly, the focal firm trusts, and any observed defection triggers termination is a subgame-perfect equilibrium if and only if:

$$\delta^* = \frac{B+C}{P+B} \quad (8)$$

Proof. On the path the supplier receives $V_H = (P - C)/(1 - \delta)$. A one-shot deviation yields $P + B$ in the period of deviation (the focal firm trusts and does not verify) and zero afterwards. Deviation is unprofitable if and only if $(P - C)/(1 - \delta) \geq P + B$, i.e., $\delta \geq (B + C)/(P + B)$. Trust is a best reply to honest delivery because $0 > -M$, and termination after an observed defection gives the focal firm a continuation payoff of zero, equal to its payoff from the relationship under the normalization of payoffs to zero outside options. Since $C < P$, $\delta^* < 1$. Moreover, $\partial \delta^* / \partial B = (P - C)/(P + B)^2 > 0$, $\partial \delta^* / \partial C = 1/(P + B) > 0$ and $\partial \delta^* / \partial P = -(B + C)/(P + B)^2 < 0$. At the baseline $\delta^* = 0.296$. In the discounted-sum check, the honest stream was worth 123.25 at $\delta = 0.286$, 125.00 at $\delta = 0.296$ and 126.80 at $\delta = 0.306$, against a deviation value of 125.00.

Proposition 5 (repeated game with committed verification). Suppose the focal firm verifies each delivery independently with probability μ , and both verified and later-observed defection trigger termination. Honest delivery is sustained if and only if $V_D(\mu) \leq V_H$, i.e., if and only if $\mu \geq \mu^*(\delta)$, where:

$$\mu^*(\delta) = \max \left\{ 0; \frac{(P+B) - \frac{P-C}{1-\delta}}{P+B+F} \right\} \quad (9)$$

Proof. The one-shot deviation value is $V_D(\mu) = (1 - \mu)(P + B) - \mu F$ and the honest value is $(P - C)/(1 - \delta)$. The inequality $V_D(\mu) \leq V_H$ is linear in μ and gives $\mu(P + B + F) \geq (P + B) - (P - C)/(1 - \delta)$. At $\delta = 0$, $\mu^* = (B + C)/(P + B + F) = r^*$; μ^* decreases strictly in δ while positive, because $d\mu^*/d\delta = -(P - C)/[(1 - \delta)^2(P + B + F)]$; and $\mu^* = 0$ for $\delta \geq \delta^*$. At the baseline $\delta = 0.25$, $\mu^* = 0.0414$, and the expected verification cost per period is $\mu^* M = 0.414$. Table 3 reports μ^* for the sensitivity grid.

Table 3.

Minimum committed verification probability μ^* (%) in the repeated game

	$F = 20$	$F = 40$	$F = 60$	$F = 100$	$F = 150$
$\delta = 0.00$	25.52	22.42	20.00	16.44	13.45
$\delta = 0.10$	18.77	16.50	14.71	12.10	9.90
$\delta = 0.20$	10.34	9.09	8.11	6.67	5.45
$\delta = 0.25$	5.29	4.65	4.14	3.41	2.79
$\delta = 0.30$	0.00	0.00	0.00	0.00	0.00

Table 4 summarizes the equilibrium outcomes of seven governance regimes at the baseline parameters.

Table 4.

Equilibrium outcomes under alternative governance regimes (baseline parameters)

Regime	Parameter change	Opportunism probability (%)	Verification probability (%)	Focal firm payoff	Expected verification cost
A. Static mixed equilibrium	—	6.25	20.0	-6.25	2.00
B. Static, penalty to external fund	$F = 60$	10.00	20.0	-10.00	2.00
C. Static, lower inspection cost	$M = 3$	1.875	20.0	-1.875	0.60
D. Static, higher penalty	$F = 100$	5.00	16.4	-5.00	1.64
E. Commitment at r^*	—	0	20.0	-2.00	2.00
F. Repeated, committed μ^*	$\delta = 0.25$	0	4.14	-0.414	0.414
G. Repeated, no monitoring	$\delta \geq 0.296$	0	0	0	0

Table 3 shows that μ^* was 20.00 percent at $\delta = 0$ and $F = 60$, 14.71 percent at $\delta = 0.10$, 8.11 percent at $\delta = 0.20$, 4.14 percent at $\delta = 0.25$, and zero at $\delta = 0.30$, which exceeded $\delta^* = 0.296$. At $\delta = 0.10$, μ^* ranged from 9.90 percent ($F = 150$) to 18.77 percent ($F = 20$). Table 4 shows that q^* was 6.25 percent in regime A, 10.00 percent in regime B, 1.875 percent in regime C and 5.00 percent in regime D, while the verification probability was 20.0 percent in regimes A to C and 16.4 percent in regime D.

The numerical verification produced the following results. The search over pure-strategy profiles found no profile without a profitable unilateral deviation. The indifference residuals at (q^*, r^*) were 0 to machine precision, and the linear-equation solution gave $r = 0.2000$ and $q = 0.0625$. In the Monte Carlo simulation of 2,000,000 rounds, the frequency of defection was 0.0627, the frequency of verification 0.2000, the mean supplier payoff 88.01 and the mean focal-firm payoff -6.28.

DISCUSSION

The equilibrium conditions carry a clear message for cluster governance. In a static, market-like interaction opportunism is not eliminated but held at the level $q^* = M/(P + F)$, and this level is determined by the focal firm's cost of verification relative to the stakes of the transaction rather than by the supplier's own temptation. The supplier's temptation, $B + C$, enters only the verification probability r^* . Honest suppliers earn $P - C$ in equilibrium irrespective of M and F ; governance parameters therefore redistribute expected losses between the focal firm and the population of deviators rather than altering the returns to honesty. These results support hypothesis H2: the probability of opportunism rose with the inspection cost and fell with the penalty and the material value, as the comparative statics and Table 2 showed.

Hypothesis H3 is also supported, and the result refines the inspection-game literature. Tsebelis [29] showed that a heavier penalty need not reduce violations because it changes the inspector's behavior rather than the violator's; in the present specification, the penalty enters the focal firm's payoff as a transfer, so a higher penalty lowers opportunism, whereas when the penalty is paid to an external fund the Tsebelis result reappears and only the verification probability falls. For cluster design this implies that who collects the penalty matters as much as its size. A mutual risk fund that absorbs all penalties would weaken the focal firm's incentive to verify, whereas the same fund used to insure suppliers and processors against shared shocks [18] need not do so.

The repeated-game results support hypothesis H1. Honest delivery under unmonitored trust is an equilibrium when the discount factor exceeds $\delta^* = (B + C)/(P + B)$, which is the relational-contract logic [5; 19; 20] expressed in cluster parameters: the more valuable the relationship relative to the one-off gain from cheating, the less verification is needed. The committed-verification condition adds that relationship length and verification are substitutes: at the baseline, moving from a one-shot interaction to a repeated one lowered the required verification probability from 20.0 to 4.1 percent. This is consistent with evidence that formal control and relational governance can complement each other [25], since penalties and verification make the relational threat credible for short horizons. It also qualifies the embeddedness argument [12; 30]: social closeness may raise the discount factor, but the results give no reason to expect it to dispense with verification when the temptation-to-value ratio is high.

Compared with vertical integration [13; 34], the results indicate that a hybrid combining verification, penalties and a long horizon can deter opportunism at an expected verification cost of about 0.4 percent of batch value per period at the baseline, without transferring ownership of the supplier's assets. Integration would replace this cost with authority, but at the price of the weaker incentives that Williamson [34] associates with hierarchies. Whether the hybrid is superior depends on the verification technology, which is why the sensitivity of q^* to M is central.

Several managerial implications follow. First, smart incentive contracts should set the penalty so that the condition $BF < (P - C)(P + F)$ holds with margin and should combine it with relational elements that raise the effective discount factor, such as multi-year renewal options and preferred-

supplier status; deferred or conditional payment can raise the effective penalty [4]. Second, mutual risk funds should be structured so that the focal firm or a third-party verifier retains a claim on penalties, in line with Proposition 2. Third, digital traceability that lowers the verification cost M reduces q^* in direct proportion: in the baseline, a reduction of M from 10 to 3 cut q^* from 6.25 to 1.88 percent. Traceability platforms in food and agricultural chains [1; 15; 27] should therefore be evaluated by the verification-cost reduction they deliver relative to their cost. Fourth, in clusters where price gaps between contract and market prices are large [36; 37], the temptation-to-value ratio is high and short contract horizons are common, so verification cannot be dispensed with.

The model's two-player abstraction is a simplification of what is, in practice, a one-to-many relationship between a focal processing enterprise and dozens of primary suppliers, and the equilibrium conditions carry additional implications once this is taken into account. Because q^* and r^* were derived for a representative supplier facing an independent verification draw, the focal firm's aggregate expected loss across N suppliers scales linearly with N at fixed q^* , so that the case for lowering M through shared verification infrastructure strengthens as cluster membership grows. Community enforcement mechanisms of the kind analyzed by Kandori [16], in which a supplier caught defecting with one buyer is denied trade with others in the network, effectively raise the supplier's continuation value at stake beyond the single relationship with the focal firm, which is equivalent in the present notation to lowering B relative to $P + C$ without any additional inspection cost. Cluster-wide information sharing about defections therefore substitutes for costly individual verification, provided that suppliers cannot easily exit the network, a condition that is more plausible in a geographically concentrated textile cluster than in a diffuse commodity market. This mechanism also interacts with the mutual risk fund discussed under Proposition 2: a fund that both insures shared shocks, as in Kunreuther and Heal's model of interdependent security [18], and publishes verified defections to member firms, combines the loss-sharing benefit of pooling with a reputational penalty that a fund collecting only monetary penalties does not provide.

The baseline numbers also bear directly on the documented losses in Uzbekistan's cotton-textile clusters. Official reports place cluster losses from contract-market price divergence at about 6 trillion soums and describe persistent arrears to farmers [37; 38], which is qualitatively consistent with a system operating away from the incentive-compatible region identified by Proposition 3. If B is set, as in the baseline, at approximately a quarter of the batch value to reflect the 23–30 percent price gap reported for raw cotton [36], the condition $BF < (P - C)(P + F)$ requires a penalty of roughly sixty percent of batch value merely to keep the static mixed-strategy incentive compatible, and a still larger penalty or a longer contracting horizon to reach the corner solution of Proposition 4 in which opportunism is eliminated altogether. Reported penalty levels in cluster contracts are not systematically published, which is itself informative: the model implies that verification and penalty parameters are precisely the levers that should be monitored and disclosed if regulators wish to assess whether a cluster's governance is incentive-compatible, rather than relying on ex post loss figures alone. The asymmetry noted by Babich and Tang [4], whereby a buyer can also default on payment to the supplier, is not modeled here but is empirically relevant given the reported arrears; a full treatment would require a second penalty parameter running from the supplier to the focal firm, which the discussion returns to below as a direction for future work.

The numerical verification strengthens confidence in the analytical results beyond the standard check of algebraic consistency. The Monte Carlo simulation reproduced the equilibrium frequencies to within simulation error over two million rounds, and the discounted-sum comparison confirmed the critical discount factor to three decimal places, which rules out the possibility that the closed-form thresholds in Propositions 4 and 5 depend on an unstated approximation. This matters because the folk theorem [9] guarantees that repeated games of this kind typically admit a continuum of equilibria supported by many different punishment schemes, so that a numerical check confirming which threshold actually separates cooperative from non-cooperative outcomes under the specific grim-trigger strategy analyzed here is a necessary complement to the closed-form proof, not a redundant robustness exercise. The grim-trigger strategy was chosen over milder punishments, such

as finite suspension, because it yields the loosest possible condition on the discount factor and therefore the most conservative estimate of the verification effort still required below threshold; a cluster core that uses a softer punishment, for example a finite number of periods of mandatory verification following a detected defection rather than permanent termination, would require a higher discount factor or a higher μ^* than reported in Table 3, so the results here should be read as a lower bound on the discipline that relational governance alone can deliver in this setting, consistent with the general relational-contracting logic of Levin [19] and Malcomson [20].

Two further implications follow for cluster policy design in emerging economies more broadly. First, the substitution between relationship length and verification intensity documented in Proposition 5 gives an explicit criterion for phasing verification effort over the life of a supplier relationship: contracts with new suppliers, for whom the effective discount factor is still uncertain, should specify the higher verification probability $\mu^*(0)$ implied by the static case, with a contractually scheduled reduction toward $\mu^*(\delta)$ as the relationship survives successive seasons without detected defection, rather than a single verification rate fixed for the life of the contract. Second, the finding that penalty recipience rather than penalty size governs deterrence in the absence of committed verification (Proposition 2) implies that cluster charters and the enabling legislation that governs mutual risk funds should specify, as a matter of contract law rather than internal fund policy, that a defined share of any collected penalty accrues to the party that bore the verification cost. Digital traceability platforms of the kind reviewed for food and agricultural chains [1; 15; 27] are a natural complement to this design because they lower M without requiring a change in who receives F , which the comparative statics in Corollary 1 show acts on q^* independently of the penalty regime; the returns to such platforms should therefore be evaluated jointly with, rather than as a substitute for, the contractual penalty design analyzed in Propositions 2 and 3.

The study has limitations. The game is stylized: it has two players, homogeneous batches and complete information about parameters, and it does not model bargaining over the penalty or the possibility that the focal firm itself defaults on payment, an asymmetry that the evidence on arrears to farmers makes relevant. Past defections were assumed to become common knowledge, whereas in practice detection may be partial. The parameters were illustrative rather than estimated, so the numerical values indicate mechanisms, not empirical magnitudes. Network effects among many suppliers, such as community enforcement [16], were not modeled. Future research should extend the model to two-sided moral hazard, to incomplete information with reputation types, and to n-player networks; calibrate the parameters using procurement and inspection records of actual clusters; and test the predicted substitution between relationship length and verification in field or laboratory experiments and agent-based simulations.

CONCLUSION

This study modeled opportunistic behavior and transactional risks among cluster participants as a non-cooperative game between a primary supplier and a focal processing enterprise. The static game has no pure-strategy equilibrium; its unique mixed equilibrium sets the probability of opportunism equal to the inspection cost divided by the sum of the penalty and the material value, and the verification probability equal to the supplier's temptation divided by the sum of material value, gain and penalty. When the penalty is not collected by the verifying party, the probability of opportunism no longer depends on it. In the infinitely repeated game, honest delivery under unmonitored trust is sustained above a closed-form discount-factor threshold, and below that threshold a committed verification probability restores incentive compatibility, with a minimum intensity that falls as the relationship lengthens. All three hypotheses were supported by the derivations and by the numerical simulations, whose verification was successful.

Answering the research question, opportunism between suppliers and a focal enterprise can be suppressed either by a sufficiently long relationship, by committed verification backed by a penalty collected by the verifying party, or by a combination of the two whose proportions follow directly from the derived thresholds. The results also show that the design of the penalty and the cost of

verification, rather than the supplier's temptation alone, determine the probability of opportunism in a market-like interaction.

The theoretical contribution is a set of closed-form, cluster-specific deterrence conditions that connect observable parameters to the probability of opportunism and show that relationship length and verification are substitutes. The applied contribution is a quantification framework that a cluster core integrator can use to calibrate penalties, verification effort and contract duration.

The main managerial takeaways are as follows. Contracts should combine a penalty large enough to satisfy the deterrence condition with relational features that lengthen the horizon. Penalties should accrue at least partly to the party that verifies. Mutual risk funds should insure shared shocks rather than absorb penalties. Investment in digital traceability is justified to the extent that it reduces the cost of verification, because opportunism falls in proportion to that cost. Future work should test these predictions with data from operating clusters.

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