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Dynamic joint investments in supply chains
under information asymmetry

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**Dynamic joint investments in supply chains
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Per AGRELL¹ and Roman KASPERZEC²

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Abstract

Supply chain management involves the selection, coordination and motivation of independently operated suppliers. However the central planner's perspective in operations management translates poorly to vertically separated chains, where suppliers may have rational myopic reasons to object to full information sharing and centralized decision rights. Particular problems occur when a downstream coordinator demands relation-specific investments (equipment, cost improvements in processes, adaptation of components to downstream processes, allocation of future capacity etc) from upstream suppliers without being able to commit to long-term contracts. In practice and theory, this leads often to a phenomenon of either underinvestment in the chain or costly vertical integration to solve the commitment problem. A two-stage supply chain under stochastic demand and information asymmetry is modelled. A repeated investment-production game with coordinator commitment in supplier's investment addresses the information sharing and asset-specific investment problem. We provide a mitigation of the hold-up problem on the investment cost observed by the supplier and an instrument for truthful revelation of private information by using an investment sharing device. We show that there is an interior solution for the investment sharing parameter and discuss some extensions to the work.

Keywords: supply chain management, investment, information.

JEL Classification: M11, L24

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1 Introduction

As the product life cycle is decreasing under shrinking or constant margins, an urgent problem for industrial supply chains is how to assure upstream product development, process improvements and capacity provision with incomplete or short-term contracts. Second or third-tier suppliers face considerable risk in undertaking relation-specific investments in a more volatile business climate, where the return on investment not only is a question of information dissemination but also a result of a risk allocation between supply chain partners.

As seen in theory as well as in practice, the properties of this allocation mechanism exposed to the inevitable agency problems in decentralized decision making influence heavily the viability and the profitability of the organization. The hold-up problem, i.e. the non-reimbursement of a specific sunk investment by a buyer, is not only an artifact of opportunistic behavior that could be ignored in a "trusting" climate. The supplier may serve multiple clients, the investment may be undertaken before the downstream product is defined or a large part of the investment may be unverifiable opportunity costs from internal resource time or through declined orders. Simplistic solutions using out-of-equilibrium results are moreover sensitive to any exogenous shocks in ownership, financial structure or regulation, potentially changing tacit agreements in an unfavorable direction. The problem studied is truly related to supply chain management along its definition as an inter-firm coordination activity, more than to the intrafirm centralized perspective of operations management. The relevance is highest in industries with far going decentralization (vertical separation) and short product life cycles, such as the high-technology telecommunications industry, electronics or toys. However, the results can also be extended to service industries in cooperation with information industries, such as fast-food or software industry interacting with media producers (cf. Kultti and Takalo, 2002).

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The objective of the paper is to study the possibility of using investment sharing as a commitment and coordination device under asymmetric information and contractual incompleteness with risk of double moral hazard i.e. from buyer's and seller's side simultaneously. The idea, already evoked in Agrell, Lindroth and Norrman (2004), to use direct participation in upstream investments to gain information and to signal commitment, has both theoretical and practical relevance. As an anecdotal example consider the onsite supplier contracts at the MCC Smart plant in Hambach. The suppliers, that provide 85% of the process value added, are in terms of information and physically integrated in the process with considerable relation-specific investments as a consequence. As the coordinating party MCC is mainly engaged in downstream activities related to communication and sales, the relationship could easily degenerate to a rent-sharing battle given the asymmetric information on capacity and costs. On the one hand, the suppliers are paid only at sell-through of the vehicles, which allocates all inventory risk to them in spite of not controlling the downstream channel. This risk, in combination with the overall business risk attached to an innovative product and a new business model, would potentially limit the willingness of the suppliers to undertake relation-specific investments. An alternative could have been to use existing facilities to serve the demand during the introduction phase, thereby limiting the investment risk. On the other hand, the supplier integration and joint product development process is an integral part of the MCC Smart business model. The viability of the project prohibits the use of long contracts to allocate all risk to the coordinator, having too limited capital leverage to carry. It also requires levers to safeguard the highly leveraged coordinator against collective or individual attempts to acquire rents in the chain by using bargaining power. The implemented solution to these moral hazard problems, the investment hold-up by MCC and the rent hold-up by the suppliers, is found in an investment sharing mechanism where MCC amortizes the relation-specific investments through a leasing contract over ten years. In our notation where the capital opportunity cost is likely to be different from the fiscal depreciation rate, we can express this as an investment sharing with an interior solution. The sharing provides some guarantees against hold-up by MCC, as well as information about the cost structure to MCC.

The paper makes reference to two streams of literature, the industrial organization stream on joint investments in supply chains and the agency work and game theoretical work on hold-up problems.

Hennart (1991) provides empirical support to the transaction cost approach to joint ventures as commitment devices, using the example of Japanese

investments in the United States. Park and Russo (1996) give a comprehensive overview of the conflicting commitment and incentive problems in joint ventures, showing empirical evidence of failures at inadequate levels of investment sharing. Too high participation shifts risks to downstream and potentially distorts incentives for process and cost efficiency upstream, creating lock-in situations that may be suboptimal. Too low or no sharing of the investment may signal a lack of commitment and open for speculation about the credibility of the non-contractual engagement to reimburse the full cost, consequently lowering the incentives for specific investments by agency problems. In our model we explicitly address these findings by making the direct sharing costly already at the investment stage through information access and by modelling the anticipated hold-up risk as endogenously determining the investment and production game.

The literature on hold-up and commitment signals dates before Williamson (1983), although its formal treatment has profited from the information economics and the agency theoretical breakthroughs in the 1980ies. In the normative economics literature the hold-up problem has long been acknowledged as an important and challenging instance of contractual design failure under agency problems. Grout (1984) showed that incomplete contracts lead to welfare losses in investment problems, framing the problem in a renegotiation scenario. In the agency literature, Tirole (1986) addressed the investment problem under asymmetric information, showing that ex post settlements provide incentives to maintain information to lower the hold-up risk. Rogerson (1992) proved a series of contractual solutions to the general hold-up problem under commitment and various information structures. Several interesting works have continued the incomplete contracts to find solutions for specific structures. Smirnov and Wait (2001) consider the problem of sequential investments in a horizontal relationship as a second best solution to the hold-up problem. As the successive investments are only possible after the project has been undertaken, the hold-up for the follower is reduced. However authors show that the timing decision in itself can provide a hold-up problem that lowers the supply chain surplus. Gul (2001) shows that the asymmetric information in itself, i.e. the unobservable investment, can be used to leverage the hold-up problem by implementing certain disclosure policies. However, in this work the investment is made by the buyer in anticipation of a sequence of bids from the seller. On the same lines, Gonzales (1999) argues for the private information as a rent guarantee for the investor, protecting against hold-up and hence providing incentives for investments in the interest of the chain. Although the setting in Gonzales (1999) is one of screening where the agent moves first, the findings

are consistent with those of the current paper. The screening framework is further extended in Gonzales (2001) for the case where the agent's type is gradually revealed in a dynamic game and renegotiation is possible.

Our setting is similar to that of Pitchford and Snyder (2004) where the authors show that the classic hold-up problem can be solved by moving from a static to a dynamic framework. The agent invests in small increments that are observable by the principal who reimburses the increments *ex post* to continue the game. Rather than modelling an infinite horizon of periods of equal length with discounting, as in this paper, Pitchford and Snyder (2004) use a single period subdivided in an infinite number of subperiods and a probability of exit.

Agrell et al. (2004) show for a three-stage chain with exogenously given coordination instruments that information revelation about investment is not a Nash-equilibrium of the investment-production game in a one-shot two-period setting under decentralized decision making and asymmetric information: S invests opportunistically and without disclosure, the chain underperforms in terms of production quantities leading to coordination losses in terms of joint surplus.

Whereas the latter concentrates on the outcomes of a two-period investment-production game under different coordination regimes, coordination by different members of the chain and asymmetric information, this work examines the outcome of an infinitely repeated game under downstream coordination and information asymmetry. However, the same double postcontractual moral hazard is present: (i) the manufacturer does not reimburse the supplier the specific and sunk investment cost in the first period if information is disclosed or observable. The hold-up increases the manufacturer's short-term rent but violates the supplier's reservation utility *ex post*. The supplier anticipates this hold-up and invests privately to extract a smaller, yet undisputed information rent. (ii) If the manufacturer subsidizes the investment cost with a non-recoverable payment in the first period the supplier has an incentive to exercise a hit-and-run, i.e. collecting the investment premium without undertaking the investment and then refusing production in the second period. This effect is due to the lack of verifiability of the investment. As a consequence, the manufacturer refrains from reimbursing a too high amount in the first period without verifiability, even if this entails a cost for the chain.

The contributions to the positive supply chain literature come from the explicit results for combined industrial settings (no commitment due to high product risk, short product life, high specific investments and no financial possibilities to integrate vertically) that has been commonly observed and

commented. We provide proofs to support joint investment practices to signal commitment under asymmetric information. It also provides an additional viewpoint on the rent sharing game in the supply chain, empirically far from the extreme allocations found in stylized models. The paper also contributes to the economics research on games with repeated, irreversible investments under information asymmetry. Our results extend earlier static results and complement dynamic results from other specifications of the investment and production game.

The paper is organized as follows: Section 2 presents the stylized model, the dynamic game and the action space, section 3 characterizes the Nash equilibria in the game, section 4 derives some results for the outcomes, section 5 presents a numerical illustration and some conclusions in section 6 close the paper.

2 The Model

The model represents a decentralized two-tier supply chain producing a single product for sale on the final market. The supply chain consists of one independent entity at each tier: an manufacturer M (she) and a supplier S (he). The manufacturer M, downstream in the chain, develops the product and serves the market demand for it. S provides components, assembles the product on M's order and delivers it to M. M is price taker, with a price p , on a competitive market with stochastic, stationary demand D . The downstream price p and the distribution of D are common knowledge. Neither S nor M have outside opportunities reflecting the situation resulting from relation-specific investment which has only negligible value outside the relationship. Production and sales of the product take place during two periods for each product generation¹. Thereafter a new product generation is introduced since the industry is assumed to be highly innovative.

In the first period of each product generation S may undertake an investment leading to a decrease of marginal costs in the second period. The investment cost A is drawn from a uniform distribution² with support on $[A_{low}, A_{high}]$ such that $A_{low} > 0$. The type of distribution and the interval $[A_{low}, A_{high}]$ are common knowledge. Products or investments from the previous generation have no value in the subsequent one³.

¹The periods in the generations can be interpreted as an initial launch period, during which capacity investments must be made to meet a second maturity period.

²The choice of distribution is without loss of generality and only to obtain tractable analytical results.

³Value of equipment and final products from different product generations, e.g. GSM

S has private information about its cost function $C_t(\cdot)$, $t = 1, 2$. The investment decision cannot be observed⁴ by M, nor the actual investment cost A . S's first period cost function $C_1(\cdot)$ is defined as:

$$C_1(Q_1, \delta) = cQ_1 + \delta A \quad (1)$$

where $c > 0$ is the unit cost of production, Q_1 is the actual production of the first period and $\delta \in \{0, 1\}$ a binary variable. $\delta = 1$ indicates that investment A is undertaken, $\delta = 0$ else.

The second period cost function is

$$C_2(Q_2, \delta) = (c - \delta c') Q_2 \quad (2)$$

with δ being the indicator of previous period's investment, Q_2 the second period's production quantity and $0 < c' < c$ the decrease of unit costs through investment.

For each product generation S's the two-period utility⁵ is

$$U_{Sg}(\cdot) = v_1 Q_1 - C_1(Q_1, \delta) + v_2 Q_2 - C_2(Q_2, \delta) \quad (3)$$

Thereby v_i , $i = 1, 2$, denote the unit wholesale price M pays S for production in the first and second period. S maximizes his horizon utility which is the infinite sum of all two-period utilities or generation utilities $U_{Sg}(\cdot)$, $g = 0, \dots, \infty$.

$$\max_{\delta} U_S(\cdot) = \sum_{g=0}^{\infty} U_{Sg}(\cdot) \quad (4)$$

Without loss of generality, fixed costs other than those of the specific investment are ignored at any stage, as the focus is on the profit contribution of a particular decision⁶. S's reservation utility \underline{U}_S is normalized to zero.

For each product generation M's two-period utility is

$$U_{Mg}(\cdot) = (p - v_1)Q_1 + (p - v_2)Q_2 \quad (5)$$

standards or configurations are often without value in subsequent production.

⁴Investments may concern allocation or training of internal staff, dedication of processes, declined orders to safeguard capacity or cost-increasing operating choices to e.g. adapt to the partner's routines.

⁵We ignore within-period discounting, assuming either that prices and costs are given in real terms, or alternatively, that the duration of each generation is fairly short.

⁶Fixed costs may intervene in the infinite game only as participation constraints.

Thereby we assume that $p > v_i \geq c$. She maximizes her horizon utility which is the infinite sum of all generation utilities $U_{Mg}(\cdot), g = 0, \dots, \infty$.

$$\max_{Q,v} U_M(\cdot) = \sum_{g=0}^{\infty} U_{Mg}(\cdot) \quad (6)$$

M's reservation utility \underline{U}_M is normalized to zero.

M sequentially decides upon the order quantities for the two periods of each product generation, Q_1 and Q_2 . Since the focus of the model lies on strategic interactions concerning investment we refrain from introducing an explicit decision rule for order quantities which may be e.g. newsboy-type as in e.g. Agrell et al. (2004). For our model we simply assume that there are two optimal order quantities, Q^* and Q^{**} with $Q^{**} > Q^* > 0$, which can be sold on the market: Q^* if no investment has been undertaken and Q^{**} in case of investment. Q^* and Q^{**} are common knowledge. From this assumption follows that M will order Q^{**} if she knows that investment has been undertaken in the previous period and Q^* else.

From $C_2(\cdot) = (c - \delta c')Q_2$ follows that $c'Q_2$ are cost savings from investment. If $c'Q_2 \geq A_{high}$ every investment opportunity would be profitable and the solution trivial. Therefore we introduce the assumption of a non-trivial investment policy $c'Q^{**} < A_{high}$. Denote $\tilde{A}^* = c'Q^*$ as the highest acceptable investment cost under the quantity Q^* and $\tilde{A}^{**} = c'Q^{**}$ under the quantity Q^{**} , respectively with $\tilde{A}^{**} > \tilde{A}^*$. The two limits are used for the investment decision $A \leq \tilde{A}^*$ or $A \leq \tilde{A}^{**}$.

Both S and M are assumed to be riskneutral, rational and opportunistic. The coordination of the supply chain is exercised to M by sequentially proposing S single-period contract as a take-it-or-leave-it offer⁷. In case of weak indifference, the coordinating option is supposed to prevail.

In order to overcome the double deadlock, the threats of hold-up and hit-and-run, commitment to future cooperation has to be signalled with other means than long contracts. Investment sharing is one of the coordinator's possible instrument to reassure the upstream chain against downstream hold-ups, whereas (costly external) investment cost verifiability protects the downstream coordinator against upstream hit-and-run strategies.

⁷This corresponds to the practice among Original Equipment Manufacturers (OEM) developing, marketing and distributing products and services to be manufactured by Contract Manufacturers (CM).

2.1 Investment sharing and investment cost verifiability

In order to model M's direct commitment in S's relation-specific investment a sharing parameter $\eta \in [0, 1]$ is introduced. Here investment sharing means that M contributes the fraction η of S's investment cost in the first and reimburses the remaining $(1 - \eta)$ in the second period. $\eta = 0$ means that M bears no investment costs at all in the first period, whereas $\eta = 1$ that M completely reimburses the investment costs in the first period.

Due to the lack of verifiability of investment M is exposed to the threat of hit-and-run. In order to implement investment sharing M requires an audit or review, revealing information about whether the investment was undertaken and an estimate of its necessary cost.

The verifiable investment cost function $A(\eta)$ has the following properties:

- (i) $A(\eta) > 0 \forall \eta$ (positive investment),
- (ii) $\frac{dA(\eta)}{d\eta} \geq 0 \forall \eta \in [0, 1]$ and $\exists \eta$ with $\frac{dA(\eta)}{d\eta} > 0$ (non-decreasing marginal investment distortion)
- (iii) $A(0) = A$, with A being the initial investment possibility observed by S.

A possible interpretation of the investment cost distortion is that M assigns a costly third-party to verify whether investment was undertaken and its true costs. Another interpretations of the investment distortion relate to standard moral hazard in investment with lower incentives for the investor to screen the investment opportunities, using more expensive external staff to perform work to obtain verifiable information, selection of equipment with higher quality (non-monetary benefits) or kick-backs from the provider to staff (monetary "leaks"), or simply the cost of the coordination of the investment decision.

2.2 Order of Play

1. Nature chooses the initial investment opportunity A from $[A_{low}, A_{high}]$. S observes A .
2. M proposes a mechanism $M_1(Q_1, v_1)$ to S. M may signal investment sharing.
3. S accepts or rejects $M_1(Q_1, v_1)$. If S rejects, go to 8.
4. S decides on disclosure of A . If S discloses, S and M settle on η and M transfers S $\eta A(\eta)$ for $A(\eta) \leq \tilde{A}^{**}$. S invests if possible. S produces Q_1 , demand D_1 is revealed and payouts to all for period 1.

Payoffs	$U_{Mg}(N)$	$U_{Sg}(N)$
$A > \tilde{A}^*$	$\Pi_N > 0$	0
$A \leq \tilde{A}^*$	$\Pi_N > 0$	$\Gamma \geq 0$

Table 1: Non-Cooperation Payoffs

5. M proposes a mechanism $M_2(Q_2, v_2)$ to S. S accepts or rejects $M_2(Q_2, v_2)$. If S rejects go to step 8.
6. S produces Q_2 .
7. M decides on reimbursement of investment (or not). Demand is revealed and payouts to all for period 2.
8. Steps 1 to 7 are repeated for each product generation.

2.3 Actions

Four actions (non-cooperation, joint investment, integrated investment and hold-up) are introduced below for the single-generation subgame and M's and S's payoffs for each action are derived. We assume that M pays a unit wholesale price equal to S's marginal costs of a quantity: $v_1 = v_2 = c$. In case that S discloses information about investment $v_2 = (c - c')$.

2.3.1 Non-cooperation, [N]

In the case of non-cooperation [N], S's action is not to disclose information about investment costs and to invest secretly for $A \leq \tilde{A}^*$.

M cannot observe investment and orders $Q_1 = Q_2 = Q^*$, pay-off equals $U_{Mg}(\cdot) = \Pi_N$ with $\Pi_N = 2[(p - c)Q^*] > 0$.

S's pay-off amounts to $U_{Sg}(\cdot) = cQ^* - (cQ^* + \delta A) + cQ^* - (c - \delta c')Q^*$ which simplifies to $\Gamma = \delta(c'Q^* - A)$. For $A \leq \tilde{A}^*$ ($\delta = 1$) this information rent is non-negative, $\Gamma \geq 0$. For $A > \tilde{A}^*$ ($\delta = 0$) S's payoff is zero since no investment takes place. The payoffs are resumed in Table 1

2.3.2 Joint investment, [J_η]

In the case of joint investment, S discloses information about investment in return for a non-enforcable agreement about joint investment using the sharing parameter η . As described earlier the sharing mechanism distorts the initial investment cost, such that $A(\eta) \geq A$ is the cost occurred.

Payoffs	$U_{Mg}(J_\eta)$	$U_{Sg}(J_\eta)$
$A(\eta) > \tilde{A}^{**}$	$\Pi_N > 0$	0
$A(\eta) \leq \tilde{A}^{**} \wedge A > \tilde{A}^*$	$\Pi_N + \Pi_C + c'Q^{**} - A(\eta) > 0$	0
$A(\eta) \leq \tilde{A}^{**} \wedge A \leq \tilde{A}^*$	$\Pi_N + \Pi_C + c'Q^{**} - A(\eta) - \Gamma > 0$	$\Gamma \geq 0$

Table 2: Joint Investment Payoffs

For $A(\eta) \leq \tilde{A}^{**}$ M orders $Q_1 = Q^*$ in the first and $Q_2 = Q^{**}$ in the second period.

It is immediately noticed that $[J_\eta]$ can be a non-dominated strategy for S only if he is compensated for his information rent from secret investment under non-cooperation, Γ (there must be reward for exposure to hold-up).

Thus, for $A(\eta) \leq \tilde{A}^{**}$ and $A \leq \tilde{A}^*$ M pays $A(\eta)$ for the investment and Γ for investment disclosure. M earns $(p - c)Q^* + (p - (c - c'))Q^{**}$ from production. This can be transformed to $\Pi_N + \Pi_C + c'Q^{**}$ with $\Pi_C = (p - c)(Q^{**} - Q^*) > 0$ and $c'Q^{**} > 0$. Hence M's pay-off is $U_{Mg}(J_\eta) = \Pi_N + \Pi_C + c'Q^{**} - A(\eta) - \Gamma > 0$ and S's $U_{Sg}(J_\eta) = \Gamma \geq 0$.

In the case that $A(\eta) \leq \tilde{A}^{**}$ and $A > \tilde{A}^*$ S's pay-off becomes zero and $U_{Mg}(J_\eta) = \Pi_N + \Pi_C + c'Q^{**} - A(\eta) > 0$.

For $A(\eta) > \tilde{A}^{**}$ the production quantities are $Q_1 = Q_2 = Q^*$ and both players' payoffs in Table 2 remain the same as under non-cooperation.

We abstract from the "extreme distortion" on investment cost where $c'Q^{**} < A(\eta) + \Gamma$. This could happen if $A < \tilde{A}^*$ but the resulting $A(\eta) = \tilde{A}^{**}$, thus yielding positive information rent $\Gamma = (c'Q^* - A) > 0$ but an unprofitable investment $c'Q^{**} - \tilde{A}^{**} - \Gamma < 0$ since by definition $c'Q^{**} = \tilde{A}^{**}$. This would yield the "perverse" outcome, in that a relatively cheap initial investment A which can be secretly internalized by S alone under the lower production quantity Q^* cannot be internalized by the chain under $Q^{**} > Q^*$.

2.3.3 Integrated investment, $[J_1]$

Integrated investment is a special case of joint investment in that the sharing parameter is $\eta = 1$. As under J_η , M pays Γ for information disclosure and S discloses information about investment cost A . The investment is then internalized by M and S carries no risk at all. Production quantities are $Q_1 = Q_2 = Q^*$ without investment or $Q_1 = Q^*$ and $Q_2 = Q^{**}$ with investment. Also in this case we disregard extreme investment distortion with $c'Q^{**} < A(1) + \Gamma$. Payoffs to both players are summarized in Table 3 below.

Payoffs	$U_{Mg}(J_1)$	$U_{Sg}(J_1)$
$A(1) > \tilde{A}^{**}$	$\Pi_N > 0$	0
$A(1) \leq \tilde{A}^{**} \wedge A > \tilde{A}^*$	$\Pi_N + \Pi_C + c'Q^{**} - A(1) > 0$	0
$A(1) \leq \tilde{A}^{**} \wedge A \leq \tilde{A}^*$	$\Pi_N + \Pi_C + c'Q^{**} - A(1) - \Gamma > 0$	$\Gamma \geq 0$

Table 3: Full Investment Payoffs

Payoffs	$U_{Mg}(H)$	$U_{Sg}(H)$
$A(\eta) > \tilde{A}^{**}$	$\Pi_N > 0$	0
$A(\eta) \leq \tilde{A}^{**} \wedge A > \tilde{A}^*$	$\Pi_N + \Pi_C + c'Q^{**} - A(\eta) + \Pi_H > 0$	$-\Pi_H$
$A(\eta) \leq \tilde{A}^{**} \wedge A \leq \tilde{A}^*$	$\Pi_N + \Pi_C + c'Q^{**} - A(\eta) + \Pi_H - \Gamma > 0$	$\Gamma - \Pi_H$

Table 4: Hold-up Payoffs

2.3.4 Hold-up, $[H]$

Hold-up corresponds to the case where M holds up S. The action is applicable only if S plays $[J_\eta]$ for $\eta < 1$ and entails renegeing the second-period reimbursement $\Pi_H = (1 - \eta)A(\eta) > 0$. The payoffs are given Table 4

As for the joint investment strategy $[J_\eta]$, full investment integration $[J_1]$ requires an attribution of a positive rent Γ for $A < \tilde{A}^*$ to S. Note, that for the chain as a whole, playing $[N]$ is suboptimal since $[J_\eta]$ and $[J_1]$ yield higher sales and may therefore result in higher profits.

3 Equilibrium

Now we derive an equilibrium of an infinitely repeated investment-production game consisting of two-period generations.

Obviously, for both players no production yielding utilities $\underline{U}_M = \underline{U}_S = 0$ is weakly dominated by $[N]$, $[J_1]$ and $[J_\eta]$ yielding payoffs equal to or higher than zero. Under $[H]$ M collects the highest possible one-generation payoff, S's payoff may be negative. Since hold-up occurs after S has carried out second-period production it cannot change S's decision about second-period production. Hit-and-run by S fails on verifiability. Thus attention can now be limited to outcomes with production in both periods.

Proposition 1 *In a one-generation subgame, for M :*

- 1) $[H]$ dominates $[J_\eta]$, $[J_1]$ and $[N]$.
- 2) $[J_\eta]$ dominates $[J_1]$ and $[N]$.
- 3) $[J_1]$ dominates $[N]$.

Proof. From the payoffs follows:

For $A(\eta) > \tilde{A}^{**}$: Since $A(\eta) > \tilde{A}^{**}$ and $\frac{\delta A(\eta)}{\delta \eta} \geq 0$ so $A_1 \geq \tilde{A}^{**}$ and $U_{Mg}(H) = U_{Mg}(J_\eta) = U_{Mg}(J_1) = U_{Mg}(N) = \Pi_N$.

For $A(\eta) \leq \tilde{A}^{**}$:

1) Since $\Pi_H > 0$ so $U_{Mg}(H) - U_{Mg}(J_\eta) = \Pi_H > 0$ and since $A(\eta) \leq A(1)$ so $U_{Mg}(H) - U_{Mg}(J_1) \geq \Pi_H$. $U_{Mg}(H) - U_{Mg}(N) > \Pi_H$.

2) $U_{Mg}(J_\eta) - U_{Mg}(J_1) \geq 0$ since $A(\eta) \leq A(1)$. $U_{Mg}(J_\eta) - U_{Mg}(N) \geq 0$.

3) $U_{Mg}(J_1) - U_{Mg}(N) \geq 0$. ■

Proposition 2 *In a one-generation subgame,*

1) *S is indifferent between [N], [J₁] and [J_η].*

2) *For S [N], [J₁] and [J_η] strictly dominate [H] for $A(\eta) \leq \tilde{A}^{**}$.*

Proof. From the payoffs follows:

1) For $A \leq \tilde{A}^*$: $U_{Sg}(N) = U_{Sg}(J_1) = U_{Sg}(J_\eta) = \Gamma \geq 0$.

For $A > \tilde{A}^*$: $U_{Sg}(N) = U_{Sg}(J_1) = U_{Sg}(J_\eta) = 0$.

2) For $A \leq \tilde{A}^*$: $U_{Sg}(H) = \Gamma - \Pi_H < \Gamma = U_{Sg}(N) = U_{Sg}(J_1) = U_{Sg}(J_\eta)$.

For $\tilde{A}^* \leq A \leq \tilde{A}^{**}$: $U_{Sg}(H) = -\Pi_H < 0 = U_{Sg}(N) = U_{Sg}(J_1) = U_{Sg}(J_\eta)$. ■

So far we have looked at payoffs for one-generation subgames. In the repeated game, actions are taken repeatedly and there is a payoff for each player in every product generation. The payoff of the infinitely repeated game is thus the sum of the payoff in first generation $g = 0$ and the discounted expected payoffs for all subsequent generations $g > 0$. As mentioned before there is asymmetric information for $g = 0$: at contracting time S knows the precise values, M does not. M and S share symmetric information about expected values for $g > 0$. We introduce the sequence notation $[G_0, G]$ where G_0 stands for the action played in the first-generation subgame and G for the action played in all subsequent ones.

Future payoffs are discounted with the factor $(1 + r)^{-t}$ with the constant $r > 0$ being M's weighted average generation capital cost and t the generation index, converging to $\lambda = \frac{1}{1-(1+r)^{-1}}$ for $\sum_{t=0}^{\infty} (1 + r)^{-t}$ and to $\psi = \frac{(1+r)^{-1}}{1-(1+r)^{-1}}$ for $\sum_{t=1}^{\infty} (1 + r)^{-t}$.

Proposition 3 1) *There is no pardon in a non-dominated strategy, i.e. investment sharing [J_η] is not played after a hold-up [H] has been executed once.*

2) *Full investment integration [J₁] is the only outcome of a non-dominated strategy after a hold-up.*

Proof. 1) Suppose S chooses to pardon M and to play $[J_\eta]$ after $[H]$. S's acceptance of $[J_\eta]$ after $[H]$ would mean that there is no punishment for exercising a hold-up. For M $[J_\eta]$ is strictly dominated by $[H]$ if $A(\eta) \leq \tilde{A}^{**}$, the expected payoff for M is identical to the one in the previous period, when $[H]$ was played. Thus, M plays $[H]$ after $[H]$. A deviation for S playing $[N]$ or $[J_\eta]$ dominates pardon, since for $A(\eta) \leq \tilde{A}^{**}$ $[H]$ is strictly dominated for him. Therefore $[J_\eta]$ is a dominated strategy after $[H]$.

2) Because of the non-pardon strategy M cannot play $[J_\eta]$ after $[H]$. Hence, after exercising $[H]$ M's only options are $[J_1]$ and $[N]$. Since $[J_1]$ dominates $[N]$ for her, M plays $[J_1]$. As already shown S is indifferent between $[N]$ and $[J_1]$ and does not deviate so any series alternating $[N]$ and $[J_1]$ after $[H]$ fails to satisfy M's efficiency condition. ■

To implement the no-pardon strategy, S may use a trigger strategy in which the firm initiates cooperates and continue cooperating until one firm reneges, in which case the firm refuse to cooperate forever after (cf. Plambeck et al. 2007). In our model this means that S starts by accepting $[J_\eta]$ and continues playing $[J_\eta]$ until M exercises $[H]$, in which case $[J_\eta]$ is never possible again. Proposition 3 shows that communication pre-play communication concerning the trigger strategy is credible.

Proposition 3 also shows that the best M can do after $[H]$ is playing $[J_1]$ forever, i.e. $[H, J_1]$. There is a trade-off for M in long-term between the immediate gain Π_H and the sum of forgone expected future gains $\psi\{E[U_{Mg}(J_\eta)] - E[U_{Mg}(J_1)]\}$. Therefore the infinitely-repeated game is not path-independent: Reputation is decisive for the equilibrium of this game.

As already shown, in a one-generation subgame for M, investment sharing $[J_\eta]$ dominates full investment integration $[J_1]$ and non-cooperation $[N]$. Repetition does not change the conclusion. Without a proceeding $[H]$ S does not deviate since he is indifferent between $[J_\eta]$, $[J_1]$ and $[N]$. Also any series alternating $[J_\eta]$, $[N]$ and $[J_1]$ in the repeated game without $[H]$ fails to satisfy M's efficiency condition and can be excluded from consideration.

Proposition 4 *In an infinitely repeated investment-production game under asymmetric information on investment, joint investment in all product generations $[J_\eta, J_\eta]$ is a Nash equilibrium under the following mechanism.*

(i) *One-period price-quantity contracts*

$M_1(Q^*, c)$ in the first period of a generation and

$M_2(Q^{**}, c - c')$ under the sharing parameter $\eta^* < 1$ such that $[J_{\eta^*}, J_{\eta^*}] \succeq$

$[H, J_1]$ for $A(\eta) \leq \tilde{A}^{**}$ or

$M_2(Q^*, c)$ for $A(\eta) > \tilde{A}^{**}$ in the first period of a generation,

- (ii) Complete reimbursement of distorted investment cost $A(\eta^*)$ spread over two periods,
- (iii) Incomplete rent extraction by M,
- (iv) Non-negative information rent, $\Gamma = \max(c'Q^* - A, 0)$, for S.

Proof. First, assume that $[J_{\eta^*}, J_{\eta^*}]$ is a Nash equilibrium for S.

(i) M's participation constraint is fulfilled since $U_{Mg}(J_{\eta^*}) > \underline{U}_M$ for $A(\eta) > \tilde{A}^{**}$ and $U_{Mg}(J_{\eta^*}) > \underline{U}_M$ for $A(\eta) \leq \tilde{A}^{**}$.

(ii) M's efficiency condition is fulfilled. M does not deviate ordering $Q_1 \neq Q^*$ or $Q_2 \neq Q^*$ for $A(\eta) > \tilde{A}^{**}$ and $Q_2 \neq Q^{**}$ since Q^* and Q^{**} are optimal quantities for her decision. Analogically, deviating to $v_1 \neq c$ or $v_2 \neq c$ for $A(\eta) > \tilde{A}^{**}$ and $v_2 \neq (c - c')$ for $A(\eta) > \tilde{A}^{**}$ would only either result in overpaying S for production or underpaying him (in which case S would reject participation) without any additional value for M. Neither does M deviate offering $\eta_1 < \eta^*$ since η_1 exposes S to the hold up risk. S would anticipate hold-up and deviate to $[J_1]$, which is dominated, without M being able to harvest Π_H . $\eta_2 > \eta^*$ may only increase investment costs because of the non-negative distortion resulting in $U_{Mg}(J_{\eta_2}) \leq U_{Mg}(J_{\eta^*})$.

Because of (i) and (ii) $[J_{\eta^*}, J_{\eta^*}]$ is a Nash equilibrium for M.

Now, assume that $[J_{\eta^*}, J_{\eta^*}]$ is a Nash equilibrium for M.

(i) S's participation constraint is fulfilled since $U_{Sg}(J_{\eta^*}) = 0 = \underline{U}_S$ for $A > \tilde{A}^*$ and $U_{Sg}(J_{\eta^*}) = \Gamma \geq \underline{U}_S$ for $A \leq \tilde{A}^*$.

(ii) S's efficiency condition is fulfilled. Without $[H]$ being played earlier S is indifferent between $[J_{\eta^*}]$, $[J_1]$ and $[N]$ so he has no incentive to deviate. Hit-and-run is outruled by verifiability.

Because of (i) and (ii) $[J_{\eta^*}, J_{\eta^*}]$ is a weak Nash equilibrium for S. ■

This proposition shows that in a decentralized supply chain joint investment is possible and stable, since it is an equilibrium under $M_1(\cdot)$, $M_2(\cdot)$ and η^* . The proposition also shows that, for $A < \tilde{A}^*$, M is not able to extract all chain rent. This result is conform with Laffont et al. (1993) identifying the trade-off between incentives and rent extraction, i.e. the higher the incentive scheme of a contract, the lower the rent extraction and vice versa.

The modelled investment-production game with investment cost sharing is not restricted to cost-reducing investments. Its results can also be applied to capacity increasing investments because of the common characteristics of cost-reducing and capacity increasing investments: funds have to be sunk, investments increase the (value of) output and investments are risky. Therefore, going back to the objective of this work, this joint investment equilibrium means that the capacity problem can be mitigated through M's direct commitment in S's investment.

4 Benchmark of results

To investigate whether the investment sharing mechanism provides any value to the chain we will compare its outcome to the centralized case, to an infinitely repeated investment-production game without investment sharing and to a mixed-strategy game.

4.1 Centralized case

The centralized benchmark corresponds to a vertically integrated chain with a central coordinator maker maximizing chain surplus under full information. Here investment is the result of the horizon control problem $\max_{Q_i, \delta} U_{SC}(\cdot) = \sum_{g=0}^{\infty} U_{SCg}(\cdot)$ with $U_{SCg}(\cdot) = (p - c)Q_1 + (p - c + \delta c')Q_2 - \delta A_g$. The optimal investment decision is governed by $\max(c'Q^{**} - A_g, 0)$ with $\delta = 1$ if $c'Q^{**} \geq A_g$ and $\delta = 0$ else. Again the optimal quantities are $Q_1 = Q^*$, $Q_2 = Q^{**}$ if $\delta = 1$ and $Q_2 = Q^*$ else.

The ex ante overall expected supply chain surplus amounts to:

$$E[SC] = \lambda \left\{ \begin{array}{l} 2(p - c)Q^* \\ + \int_{A_{low}}^{\tilde{A}^{**}} \{(p - c)(Q^{**} - Q^*) + c'Q^{**} - a\} f(a) da \end{array} \right\} \quad (7)$$

4.2 Infinitely repeated investment-production game with investment sharing

The ex ante expected supply chain surplus from $[J_{\eta^*}, J_{\eta^*}]$ equals:

$$E[SC_{\eta^*}] = \lambda \left\{ \begin{array}{l} 2(p - c)Q^* \\ + \int_{\underline{A}_{\eta}}^{\tilde{A}^{**}} \{(p - c)(Q^{**} - Q^*) + c'Q^{**} - a\} f(a) da \end{array} \right\} \quad (8)$$

with \underline{A}_{η} being the lowest value of the verifiable investment function.

Under the sharing mechanism the supply chain does not reach first-best since some profitable investments $A \leq A^{**}$ are rationed. The coordination loss under the sharing mechanism amounts to:

$$E[SC] - E[SC_{\eta^*}] = \lambda \left\{ \int_{A_{low}}^{\underline{A}_{\eta}} \{(p - c)(Q^{**} - Q^*) + c'Q^{**} - a\} f(a) da \right\} \quad (9)$$

The loss is non-negative since the value of the integral is non-negative for $\underline{A}_{\eta} = A_{low}$ and positive for $\underline{A}_{\eta} > A_{low}$.

S's ex ante expected utility from $[J_{\eta^*}, J_{\eta^*}]$ sums up to:

$$E[U_S(\cdot)] = \lambda \int_{A_{low}}^{\tilde{A}^*} \{c'Q^* - a\} f(a) da \quad (10)$$

M's ex ante expected utility from $[J_{\eta^*}, J_{\eta^*}]$ amounts to:

$$E[U_M(\cdot)] = \lambda \left\{ \begin{array}{l} 2(p-c)Q^* \\ + \int_{\underline{A}_{\eta}}^{\tilde{A}^{**}} (p-c)(Q^{**} - Q^*) f(a) da \\ + \int_{\underline{A}_{\eta}}^{\tilde{A}^{**}} \{c'Q^{**} - a\} f(a) da \\ - \int_{A_{low}}^{\tilde{A}^*} \{c'Q^* - a\} f(a) da \end{array} \right\} \quad (11)$$

4.3 Infinitely repeated investment-production game without investment sharing

Without investment sharing, M has to internalize the full investment cost A either in the first period or in the second if she wants it to be disclosed. There is no investment cost distortion through auditing, which is M's instrument to prevent hit-and-run. As before M cannot observe investment, however S may provide a non-verifiable signal of investment.

Suppose M were to reimburse investment costs to S in the first period in exchange for a non-verifiable signal of investment. Because of the lack of verifiability S has an incentive to inflate as much as possible the signalling value V such that it is the highest acceptable cost for M $V \leq \tilde{A}^{**}$. In the case that

$$V > \psi \left[\int_{A_{low}}^{\tilde{A}^{**}} (V - a) f(a) da - \int_{A_{low}}^{\tilde{A}^*} (c'Q^* - a) f(a) da \right]$$

S will exercise a hit-and-run since the immediate utility he realizes dominates his expected future utility from disclosed investment. Since M's one-generation payoff from hit-and-run is $(p-c)Q^* - V$ and thus lower than from non-cooperation $2(p-c)Q^*$, M would not transfer V in the first period under the mentioned condition.

Suppose S accepts a reimbursement in the second period. M holds him up if

$$V > \psi \left[\int_{A_{low}}^{\tilde{A}^{**}} \{(p-c)(Q^{**} - Q^*) + c'Q^{**} - V\} f(a) da \right],$$

i.e. the value of the signal is higher than her expected future gain from cooperation. S anticipates the hold-up and signals the highest V which prevents hold-up or invests secretly.

The supply chain may therefore implement the first-best solution if there is a V^{**} with $A_{low} \leq V^{**} \leq \tilde{A}^{**}$ such that either M has no incentive to hold-up and/or S has no incentive to hit-and-run. Whether or not the chain can implement investment under this regime depends on the underlying parameters. In particular decreasing margins ($p - (c - c')$) favour the implementation of the investment sharing mechanism since they lower the private benefits from investment.

In such a case S's and M's ex ante rents would be as follows:

$$E[U_S^W(.)] = \lambda \int_{A_{low}}^{\tilde{A}^{**}} \{V^{**} - a\} f(a) da \quad (12)$$

$$E[U_M^W(.)] = \lambda \left\{ \begin{array}{l} 2(p - c)Q^* \\ + \int_{A_{low}}^{\tilde{A}^{**}} (p - c)(Q^{**} - Q^*) f(a) da \\ + \int_{A_{low}}^{\tilde{A}^{**}} \{c'Q^{**} - V^{**}\} f(a) da \end{array} \right\} \quad (13)$$

However, there is again a trade-off between chain efficiency and rent extraction. In an investment game without the sharing device M would potentially overpay investment. Hence it may be rational for M to tradeoff the overall efficiency against rent appropriation for herself.

In the case that V^{**} does not exist non-cooperation in all generations is the only equilibrium of the game without a sharing device. There, the use of the sharing mechanism generates a higher surplus for the chain as well as for M.

4.4 Infinitely repeated investment-production game in mixed strategies

The common knowledge on the distribution of the investment cost A creates the background for the game in mixed strategies.

Imagine the following: there is no possibility or willingness of vertical integration, M cannot or does not want to commit to a sharing device and there is no V^{**} such that a first-best solution in pure strategies may be implemented. M can stick to a pure strategy ordering Q^* in every second period of a generation, realizing the payoff of non-cooperation. However, M could also try to extract some more rent by "mixing" her order quantities, Q^{**} for the price $v_2 = (c - c')$ with a positive probability Φ in the second period and Q^* , $v_2 = c$ with $(1 - \Phi)$. In case that S invested in the previous period S would be indifferent between producing or not producing in the second period since investment is sunk at that time. Thus M would be able

Parameters					
p	500	Q^*	450	A_{high}	60,000
c	480	Q^{**}	570	A_{low}	20,000
c'	60	r	12%	A	30,000
$A(\eta) = [\sqrt{(1 + \eta)}]A$					

Table 5: Parameters for Illustration

to extract some additional rent. In the other case S would simply reject the second period contract, refusing production. Hence M's payoff would only reach half of the non-cooperation payoff. In equilibrium M chooses Φ such as being indifferent between the two pure strategies - playing $M_2(Q^{**}, c - c')$ and $M_2(Q^*, c)$ in the second period. Therefore M's horizon payoff reaches the level of non-cooperation $[N]$.

5 Numerical illustration

In this section joint investment is illustrated numerically for chosen parameters in Table 5.

The (third-party) verifiable investment cost function $A(\eta) = [\sqrt{(1 + \eta)}]A$ fulfills the three required characteristics with a maximal distortion $A(1) = 1.41A$.

For calculations we distinguish between the current or contracting generation - where A takes the value of 30,000 - and future generations for which expected values have been used. This distinction is necessary to investigate the utility resulting from a hold-up since hold-up can only occur once and on a current realization of A .

For this setting the numeric values for horizon utilities, $U[SC]$, $U_M(N)$, $U_S(\cdot)$ and $U_M(J_{\eta^*})$, limits for investment decision depending on quantities produced, \tilde{A}^* and \tilde{A}^{**} , the multipliers of future values, λ and ψ , and the minimum sharing parameter favouring joint investment η^* are summarized in table 6.

These results show that there is a 8.2% supply chain efficiency loss through the sharing mechanism since $202,704 = U[SC] > U_M(J_{\eta^*}) + U_S(\cdot) = 186,011$.

We note that S is guaranteed an information rent of $U_S(\cdot) = 5,104$. The investment rationing for "selfish" investments internalized by S is important, 50.7%.

Results					
\tilde{A}^{**}	34200	ψ	8.3	$U[SC]$	202,704
\tilde{A}^*	27000	η^*	0.3	$U_M(N)$	168,000
$U_S(\cdot)$	5,104	$U_M(J_{\eta^*})$	180,907	$U_M(J_1)$	172,670

Table 6: Resulting values

The supply chain profit of the centralized solution is independent of η and constant, as is the full investment integration $U_M(J_1)$.

The existence of an internal solution for the sharing parameter, η^* , is demonstrated in Figure 1. The function $U_{prodHold}(\eta, A)$ illustrates M's payoff from playing $[H, J_1]$ and $U_{prodJoint}(\eta, A)$ from playing $[J_{\eta^*}, J_{\eta^*}]$. $U_{prodJoint}(\eta, A)$ is a decreasing function of η since an increasing η rises investment costs and reduces the probability of investment being undertaken jointly. For $0 \leq \eta < 0.3$, M has a strong incentive to play $[H, J_1]$ since $U_{prodHold}(\eta, A) > U_{prodJoint}(\eta, A)$. For $0.3 < \eta$, $U_{prodJoint}(\eta, A)$ dominates.

For $\eta < 0.3$, S would anticipate $[H, J_1]$ by deviating to $[J_1, J_1]$. Since M's utility from $[J_{\eta^*}, J_{\eta^*}]$ is higher than from $[J_1, J_1]$ and S no reason to reject $[J_{\eta^*}, J_{\eta^*}]$, this particular game has a Nash equilibrium at $\eta^* = 0.3$.

For $0 \leq \eta \leq 0.2$ $U_{prodHold}(\eta, A)$ is higher than $U[SC]$, represented by the graph $U_{integrated}(A)$, since M is "living at S's expenses": M extracts more rent from the chain than the chain creates, leaving S below reservation utility.

The discontinuity in figure 1 stems from loss of a first-period result above non-cooperation payoff beyond this threshold.

6 Conclusions

Decentralized supply chains operating in a volatile business climate under the conditions of short product life cycles, conflicting objectives and asymmetric information often suffer from insufficient production capacity provision. The relevance of the capacity problem has especially been reported for the telecommunications industry (Agrell et al., 2004) and for Ericsson's supply chain (The Economist, 2004). Professional experience in both strategic and operational procurement in the sector of plant engineering and construction from one of the authors confirms the importance of appropriate capacity provision.

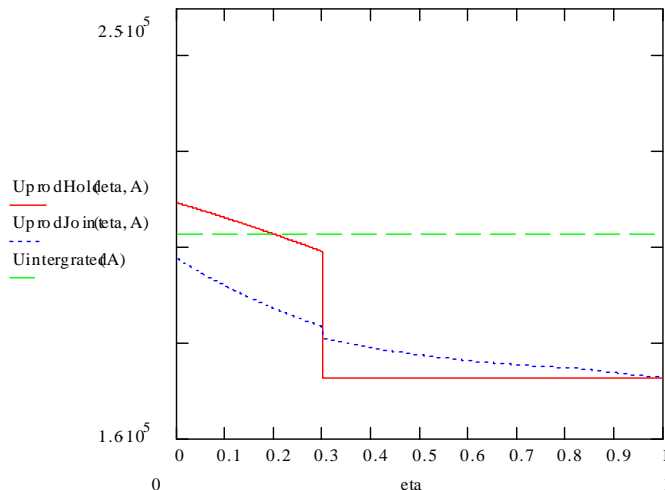


Figure 1: Internal solution for investment sharing parameter η .

Therefore, the findings of this work are primarily relevant to the ex ante capacity incentive problem. We provide some evidence that information disclosure and joint investment form a stable equilibrium of the infinitely repeated game in decentralized supply chains under the previously mentioned conditions. This means that direct investment commitments can mitigate the problem of insufficient capacity. The equilibrium supply chain surplus and the utilities of downstream and upstream participants directly involved in investment are presented.

One of the revealed prerequisites to the implementation of the investment equilibrium lies in the protection of both participants from mutual moral hazard – hit-and-run and hold up – which has its roots in asymmetric information about investment costs and activity. These agency costs render the investment more expensive. The other key to promote investment is to reward cooperation and information sharing by matching the profit levels potentially obtained upstream through secret undisclosed internalized investments. The incentive payment necessary to coordinate the chain corresponds to a pure rent transfer, having no impact on the overall chain performance. Another interesting finding is the existence of internal solutions for the investment sharing η , providing some intuition for the previously quoted MCC smart investment promotion scheme.

Nevertheless, investment sharing in our setting is still a second-best solution due to the limitations in contracting length and the cost of verifiability.

Indeed, contrary more stylized situations, repetition alone may not prevent moral hazard by chain members, either manufacturer's hold-up or supplier's hit and run and that decreasing margins or rent extraction favour the sharing mechanism.

However, the equilibrium may be sensitive to parameter changes. These changes may be favorable, in which case joint investment is not put at risk and an adjustment of the contract variables, e.g. of the sharing parameter, increase the performance of the chain and the coordinator's utility. The opposite direction, disadvantageous parameter changes may require an adjustment of the contract variables in order to safe joint investment lowering the overall performance or may render it impossible. In particular, the shape and parameters for the cost function for verifiable investment cost $A(\eta)$ influence the solutions obtained.

The validity of the dynamic model with repeated interactions is constrained by its assumptions. Only the downstream participant is assumed to shoulder the coordinator-configurator role in the chain. However, a shift of the coordination role to the supplier could provide interesting insights about the advantage or disadvantage of such a configuration and may even change the equilibrium.

The outcome of the two-period investment-production game in the Agrell, Lindroth, Norrman (2004) model is that investment is not an equilibrium in the absence of complete contracts. Known results for repeated interactions are more optimistic, showing that supply chain cooperation in uncertain markets is possible. In contrast, our work shows that even in repeated relationships, poorly designed contracts and information structures may lower the overall surplus, but sharing the burden, even partially may bring feasible solutions in settings where business and technological risks exclude long-term contracting.

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