Risks and Coordination Mechanisms in Telecom Supply Chains

Per J. Agrell, Robert Lindroth, and Andreas Norrman

Abstract. Supply chain management involves the selection, coordination and motivation of independently operated suppliers. The central planner's perspective in operations management translates poorly to vertically separated chains, where suppliers recurrently seem to object to benevolent information sharing and centralized decision rights. Seen from the supplier's perspective, such resistance may very well be rational. A downstream assembly line disclosing reliable information on actual and forecasted sales puts itself at a disadvantage when bargaining on share of chain profits. In this paper, we use a minimal agency model to contrast known optimal mechanisms with the actual practice in the telecommunications industry. A three-stage supply chain under stochastic demand and varying coordination and information asymmetry is modeled. A two-period investment-production game addresses the information sharing and specific investment problem in the telecom industry. The observed price-quantity contracts under limited commitment are shown to be inadequte under realistic asymmetric information assumptions. More a result of gradually evolving changes in bargaining power than coordination efforts, the upstream urge to coordinate may further deteriorate performance in terms of our model.

1. Introduction

Supply Chain Management (SCM) has been increasingly discussed in academia since the mid-1980s (e.g. Houlihan 1985; Jones & Riley 1985). There have been numerous definitions of SCM (see e.g. Mentzer et al, 2001) but most include the selection, coordination and motivation of independently operating suppliers in at least a three-tier chain. Although one core concept of SCM is close relationships, industrial experience has showed that it is difficult to work across inter-organizational borders. A key component for making this happen is to share both risks and rewards among the members of the supply chain. Especially in industries moving towards longer supply chains (e.g. due to outsourcing) and facing increasingly uncertain demand as well as supply, the issue of supply chain risk handling and risk sharing along the supply chain is a topic of growing importance.

In the field of business logistics, these important risk-sharing issues are often mentioned but not further elaborated on (e.g. Cooper & Ellram 1993; Cooper, Lambert & Pagh 1997; Motwani et al. 1998; Skjoett-Larsen 1999; Mentzer et al 2001). Far more efforts have been spent on risks and different types of supply chain

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contracts in the quantitative and modeling oriented research stream of SCM. Although many interesting risk sharing instruments (especially contracts) have been analyzed, the context has often been rather stylized, often involving two-stage supply chains with a single product, single buyer and single supplier. Reviewing recent advances in the field, Tsay et al. (1998) conclude that the design of contracts and analysis of supply chain behavior and performance is still an important and challenging field of research. They also argue that the scope of issues that the literature has addressed so far has been limited, neglecting dynamics, strategic interaction and production economics.

One complication for supply chain risk sharing is that the companies involved often have different business logic, e.g. in terms of how their revenues and costs are generated, and the size, specificity and life span of investments. The firms have individual relations between revenue and product life cycles, "clockspeed" (Fine, 2000), and the design of products and processes. The differences in business logic and clockspeed might reduce truthful information sharing and introduce production inefficiency as well as risks of technological inefficiency. In other words, although the need for joint coordination and risk sharing might be larger, the increased asymmetry of information and business logic would probably result in the separate companies of a supply chain trying to myopically reduce their own risk. A lack of effective incentive structure to induce global supply chain optimization may promote the opportunistic and myopic behavior of the chain firms. This behavior is Pareto-dominated, i.e. it implies a suboptimal overall chain profit and it may even threaten the long-term viability of the chain. Telecommunications is one example of a heterogeneous industry where the clockspeed has increased considerably and where the business logic has changed during the past decade. Among the factors that contribute to an increased need for improved coordination mechanisms in the telecom industry are an increased use of outsourcing of manufacturing and R&D to suppliers, shorter product life cycles and compressed time-to-market (i.e. increased clockspeed). Furthermore, capacity limitation of key components, heavy ramp-up of demand early in product life cycles and an increased demand for on-time deliveries in shorter time frames, and generally shorter lead times all increase the risks in the supply chain.

The purpose of this paper is to critically analyze two key coordination challenges in the telecom industry, in order to find theoretical as well as practical arguments for the development of new coordination mechanisms. The methodology will draw on common approaches of industrial organization and agency theory, using a dynamic three-stage supply chain model under stochastic demand.

The paper is structured as follows: In the next section we review previous work on supply chain risk sharing. Thereafter the telecom industry and some key features are discussed. In the fourth section the model is defined and some initial properties are derived. A numerical illustration is provided in section five. The paper closes with some conclusions and policy implications.

2. Previous work

When reviewing the literature on supply chain risk management, it is apparent that two major research streams are present. One contains conceptual exploratory research, and the other is mathematical modeling. In the first stream researchers try to grasp and structure managerial issues related to supply chain risks, while the other stream is focused on modeling to explore or devise decision rules for clearly defined risk-sharing instruments, e.g. contractual mechanisms.

2.1. Conceptual Exploratory Research. Examples of conceptual exploratory research are Zsidisin and Ellram (1999), Zsidisin et al. (2000) and Hall (1999).

Zsidisin et al. (2000) look at the purchasing organizations' involvement in risk assessment and risk management. They list a number of key supply risks: business risk (e.g. supplier's financial stability); supplier capacity constraints (e.g. lack of equipment, people or input to handle demand fluctuations); quality; production technology changes (e.g. current technology becomes obsolete), product design changes (e.g. because of dynamic customer demands); and disasters. The conclusion from this study is that although many companies were aware of risks associated with supply, many did not take the requisite actions to mitigate them. Although using a dyadic focus, the study gives voice to more general supply chain problems. A normative guide for handling purchasing risks is given in Zsidisin and Ellram (1999).

2.2. Mathematical Modeling. Tsay et al. (1998) classify the supply chain modeling literature into eight streams based on contract clauses: specification of decision rights; pricing, minimum purchase commitments; quantity flexibility; buy-back or returns policies; allocation rules; lead times; and quality.

In the pricing stream, Jeuland and Shugan (1983) show how quantity discounts can influence and improve channel (dyad) coordination, but also point out implementation barriers. Moorthy (1987) argues that a two-part tariff (a fixed franchise fee + quantity dependent cost) is superior to quantity discount: it is simpler and it separates the problems of coordination from the problem of profit sharing. The mechanism design results are confirmed in the general coordination framework by Laffont and Tirole (1993). Li and Kourvelis (1999) model risk-sharing supply contracts by incorporating explicit risk premiums. They focus on the buyer in a context of deterministic demand and uncertain price. Within the price window the buyer pays the agreed price, but outside of this the firms share (in a way agreed upon) additional costs or benefits.

Eppen and Iyer (1997) study inventory commitment and buy-back agreements in the fashion industry. The buyer commits to a volume and contracts on a predetermined capacity before the sales period, with deliveries in two periods. Penalties are applied in case the buyer does not fully exercise the delivery option.

Quantity flexibility issues are important tools for handling and sharing supply chain risks. Such contracts can define flexibility regarding quantity, time or capacity.

Riordan (1984) considers a two-level system with asymmetric information on demand at the retailer and private information on manufacturing costs at the supplier. The decentralization mechanism proposed is a payment schedule that uses information revealed by the managers to achieve optimal coordination. Porteus and Whang (1991) address the intra-firm agency problem between effort-averse marketing managers and a manufacturing process allocating the realization of a stochastic capacity. Their optimal incentive scheme translates into a franchising model with a fixed fee per unit ex post capacity delivered in return for an ex ante fixed franchise fee paid to the owner. A second contract makes the marketing function the residual claimant for realized capacity by delegating allocation decisions to a secondary market. Porteus and Whang (1991) show that the latter incentive plan is costly for the owner, although it achieves an optimal allocation of capacity and managerial effort.

van Mieghem (1999) investigates the effectiveness of three contract types, fixed price, bargaining and state-dependent contracts, for a single-period two-level coordination and capacity investment problem. Although production coordination can be achieved, only the state-dependent bargaining contract achieves full coordination, but, unknown ex ante, the distribution of the surplus relies on verifiable investments by the parties.

The coordination problem of production and inventory holding in a multi-echelon system is studied by Lee and Whang (1999), who present an optimal implementable mechanism assuming stationary parameters and perfect information. The mechanism implements an order-up-to system, using a state-dependent contract of consignment and non-linear backlog and shortage penalties. Cachon and Zipkin (1999) give a set of linear contracts for a similar production-inventory multi-echelon system. Their mechanism is based on ex post echelon and stage inventory and backorder levels.

Cachon and Lariviere (1999) look at the so-called turn-and-earn allocation rule among multiple suppliers. The allocation rule is investigated in a non-cooperative setting, showing rent distortions for most capacity-constrained cases towards the supplier. The retailers are competing for capacity even when capacity utilization is low, which distorts sales to assure future availability.

Our model extends the existing research by explicitly addressing a three-stage model under asymmetric information and limited commitment. By offering more realistic assumptions for the telecom industry, where full integration is infeasible or unattractive, we can offer more detailed policy advice to the industry. We also address the implications for supply chain policy of evolving partnership/coordination roles in the chain. Further, by modeling the ex ante investment decision and ex post information revelation problem jointly, we focus at aggregate effects on supply chain performance.

3. The Telecommunications Industry

The telecom supply chain has undergone major shifts during the past decade, and is still turbulent. Because of demand uncertainty in both level and timing, the roles and responsibilities in the supply chain are changing, often accelerated by outsourcing, leading to initially unclear interfaces. There is also strong growth and consolidation among suppliers, leading to shifts in the power balance, and different business logic and clockspeed among the players. Our focus is on an OEM (Original Equipment Manufacturer) delivering infrastructure such as networks and radio base stations and his two closest tiers of suppliers.

Telecom supply chains in general involve many different types of players and deliver different outputs such as physical products, immaterial capacity, and installations as well as personal services (Figure 1). A major EMS (Electronics Manufacturing Services Provider, e.g. Flextronics or Solectron), may support many of the OEMs (e.g. Nokia, Ericsson or Lucent) (Weinberg 2001). Global operators (e.g. Vodafone or Telefonica) usually choose different OEMs to supply different countries, and quite frequently they use more than one supplier within a country. Furthermore, some 2nd and 3rd tier suppliers are supplying not only the next step

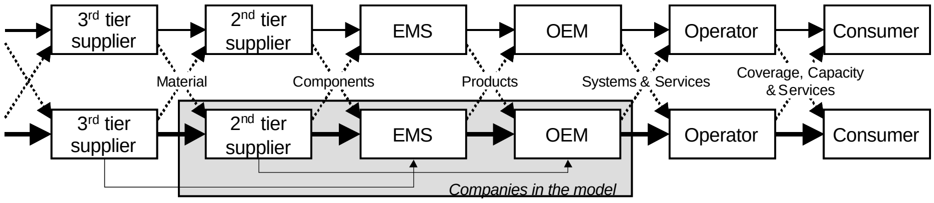

FIGURE 1. Simplified telecom supply chain with model scope in center grey zone.

in the supply chain, but also companies further downstream. However, in this paper we focus primarily on three of the players: 2nd tier supplier, EMS and OEM.

3.1. Uncertain Demand. A key feature of the telecom industry is the uncertain demand. The uncertainty on the telecom market, and the short product life cycles, make it very difficult to produce reliable forecasts of required supply chain capacity. There are many reasons for the uncertainty in the underlying demand: new operators emerge, and the introduction of the new 3G telecom systems is subject to governmental regulations regarding timing and coverage, causing a very fast ramp-up of volumes. Large orders must be delivered simultaneously to remote areas in different countries.

New consumers are continuously added, both geographically (new countries) and in markets (e.g. transmission of data), in consumer segments (e.g. teenagers, children and senior citizens) and in technology (shift from 2nd generation, e.g. GSM or TDMA, to 3rd generation technology, such as WCDMA). On the whole, the underlying demand for coverage, capacity and services has been growing profoundly, and was expected to explode, making it extremely difficult to forecast demand accurately. However, in the past year another side of this dynamic industry has been revealed that further underscores the risks faced by the supply chain. Despite a promising future, major telecom players have postponed many 3G plans. Profit warnings and adjusted market forecasts have triggered massive restructuring programs, lay-offs and of course reduced demand for equipment. Suppliers planning for a seemingly prosperous future may have been building capacity that will not be needed for years.

OEMs have increased the service and software part of their offering. There is also an observed tendency in the leading edge of the industry to redefine core services — away from hardware (switches and antennas) into pure technology development (see, e.g., Feder, 2001).

3.2. Outsourcing and Unclear Interfaces. Another distinguishing feature of the industry is its extensive use of outsourcing. Apart from traditional logistics and internal support activities, even manufacturing activities have been outsourced. In recent years the EMSs have increased their share of manufacturing and assembly. In many cases this has been done by acquiring plants from the OEMs. An immense growth of contract manufacturing can be seen: Flextronics increased their net sales eight times from 1997-2001 (Flextronics 2001). Part of this growth can be explained by consolidation. EMSs also add new services (e.g. logistics) to their services

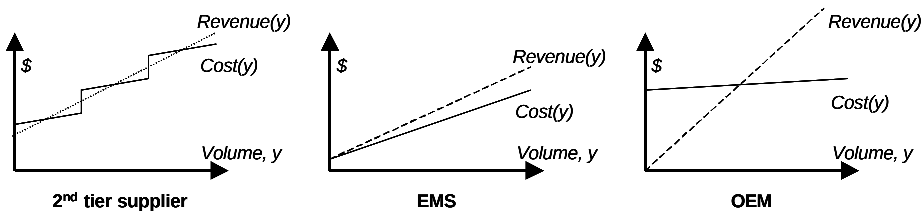

FIGURE 2. Schematic cost and revenue functions in an empirical telecom supply chain.

offered, often by buying companies that possess the desired capabilities. These changes have gradually changed the bargaining position of the EMSs relative to the OEMs.

Thus it often happens that 2nd tier suppliers deliver and contract standard products. However, for strategic or customized components, the interrelation with the OEM could be quite strong both during the development phase and also during the production phase. While forecasts and planning information are normally sent from the OEM to the EMS, and from the EMS to the 2nd tier supplier, there are situations where the OEM and the 2nd tier supplier shortcut this loop with medium-term and long-term forecasts to counteract adverse supply chain effects, e.g. bullwhip effect. For the most strategic components the OEM might do this to secure the supply, sometimes also by financially helping the 2nd tier supplier with specific assets, investments and raw material purchase. Being able to trust the information supplied and the commitment given to coordination is important for the smooth operation of a dynamic supply chain.

3.3. Heterogeneous Business Logic. As the telecom supply chain evolves, the business logic of the companies within the supply chain differs and changes over time. Looking at the three tiers in our model, the cost and revenue functions are different, as is illustrated in Figure 2.

The 2nd tier supplier invests in manufacturing capacity that involves building new production lines or plants (Figure 2). Production is capital intensive and relies heavily on fixed assets and less on more flexible resources such as manpower. Investment decisions have to be made years before the final products reach the market. Once the investment is made, the production yield is maximized. New investments to increase capacity can make them temporarily unprofitable until a new break-even volume is reached. One major risk for a 2nd tier supplier is low utilization of production capacity; another is that technology or market changes downstream will make its products and processes obsolete.

In many cases the EMS is not taking much risk regarding volume or specific investments (Figure 2). The major activity is labor-intensive product assembly. Typically, the OEM reimburses the EMS by a cost-plus contract: cost reimbursement and an additional markup for profit. If the EMS has acquired specific facilities from the OEM, the OEM usually guarantees a certain demand level for the first years - the OEM carries the demand risk despite the outsourcing arrangement. A key performance indicator for many EMSs is inventory turnover rate, thus they are reluctant to carry inventory of supplies, regardless of who assumes the actual holding cost.

The OEM, finally, has huge investments in technology and product development. In order to reach profitable volumes it is critical to hit the market window with accurate timing. The market window tends to be rather tight, so payback time on the investments must be short. The costs of the OEM tend to be rather volume-independent: once the product development is done, the variable costs are quite insignificant. The OEM faces the risk of inadequate production capacity at the supplier level. In early 2000, this was the case for many electronic components in the industry, leading to allocations. Since late 2001 the situation is the opposite: overcapacity plagues the business. The business logic implies that the OEM desires to satisfy any realized demand in the narrow market window. He must be able to deliver as much as possible when the demand hits his most positive forecast to get payback on early investments. The upstream tiers facing limited capacity and variable costs will not have the same leverage on volume. From the upstream (myopic) perspective, a conservative capacity assessment lowers the risk and increases profit in case of low demand.

From a decision-making perspective, we may distinguish three stages in the development of the supply chain: the centralized stage, the transition stage, and the decentralized stage.

Before the entrance of the EMS, the OEM produced and assembled in-house. He enjoyed considerable bargaining power toward the upstream supplier, by virtue of size and privileged information.

As the OEM outsources the assembly process to the EMS, the roles change gradually. Initially, the OEM gains an exceptional advantage by retaining full cost information on the EMS, yielding bargaining power but rejecting the actual production responsibility.

In the third stage, the OEM's cost information on the upstream tiers is weakened. This naturally affects its authority to coordinate and allocate supply chain rents. Depending on the upstream economies of scale and product differentiation, the relative power positions between the OEM and the EMS may alter. Decision making in this stage is conducted in a decentralized manner, where each member of the supply chain independently reviews coordination initiatives.

The organizational and informational evolution in the industry has not been accompanied by a corresponding development of the contractual coordination mechanisms. Our research attempts to highlight the implications for supply chain performance of such approaches.

4. Model

The model structure has three participants, an OEM (or retailer) R serving the final market, an EMS factory F (or first tier supplier) assembling the product on order from the OEM, and a (second tier) supplier S providing components on fixed orders from the factory. Production and sales take place during two periods $t = 1, 2$. The modeled chain reflects the current institutional structure in the vertically separated chains in the telecommunications industry, where manufacturing operations are frequently outsourced and the organizational distance to the first-tier suppliers is often long. Only a single product and a single firm in each echelon are considered; thus there is no possibility to implement tournaments or yardstick regimes. The OEM is a price taker with a price p on a competitive market with stochastic demand D. The EMS unit price $w_t = (1 + \alpha)\, v_t$ in period t is based on

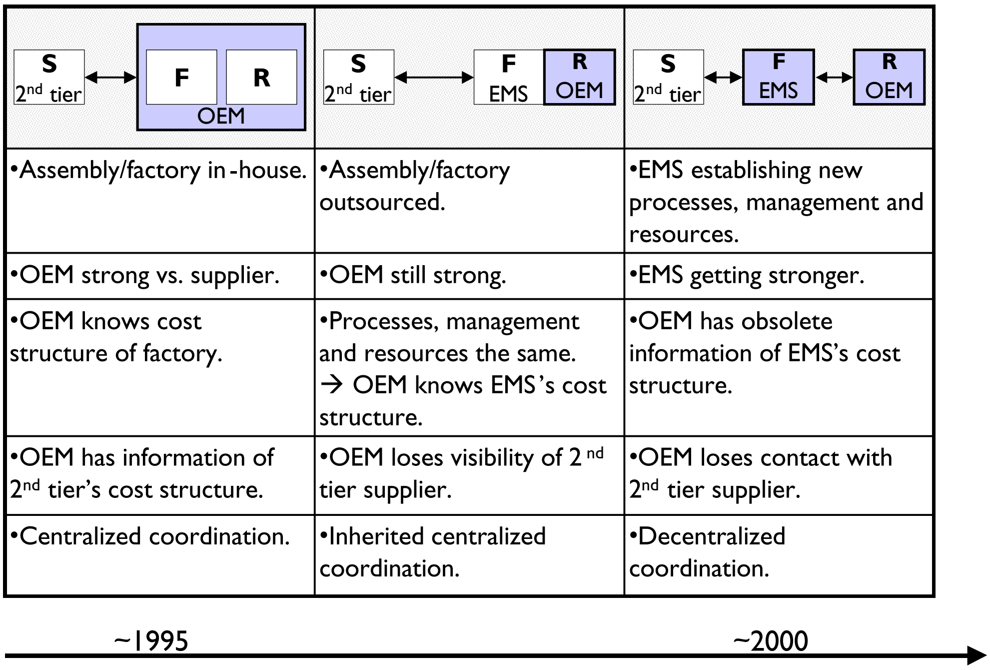

FIGURE 3. Summary of organizational and information evolutions in the telecom industry between 1995 and 2000.

a verifiable and observable input cost v_t and a negotiated markup α. The supplier produces at cost function $C(Q)$ and charges the factory a unit price v_t for the common order size Q at period t.

Below, we will elaborate on the informational assumptions regarding the three firms.

The continuously differentiable, invertible and monotonous probability distribution function $F(.)$ of the demand, with distribution function $f(.)$ and the price p are common knowledge.

The OEM may transmit a forecast s to signal the expected demand for the upcoming period. Under any informational assumptions, the OEM sequentially decides upon the order quantities for the two periods, Q_1 and Q_2. The forecast is observable but not verifiable in court. The OEM maximizes the two-period echelon profit U_R,

$$U_R(.) = (p - w_1) Q_1 + (p - w_2) Q_2 - p \left(\int_0^{Q_1} F(x_1)\, dx_1 + \int_0^{Q_2} F(x_2)\, dx_2 \right)$$

For notational convenience, denote by $G(Q) = \int_0^Q F(x)\, dx$ the expected number of units not sold at production level Q. The EMS factory maximizes the horizon objective function $U_F(.) = \sum_{t=1}^{2} \alpha v_t Q_t$. We assume that the fixed costs for F are normalized to zero. Later, we will introduce an additional informational assumption on behalf of the factory that will render its role more interesting.

The supplier S has private information about its cost function $C(Q)$ and investment opportunities. At the beginning of the first period, the supplier learns the

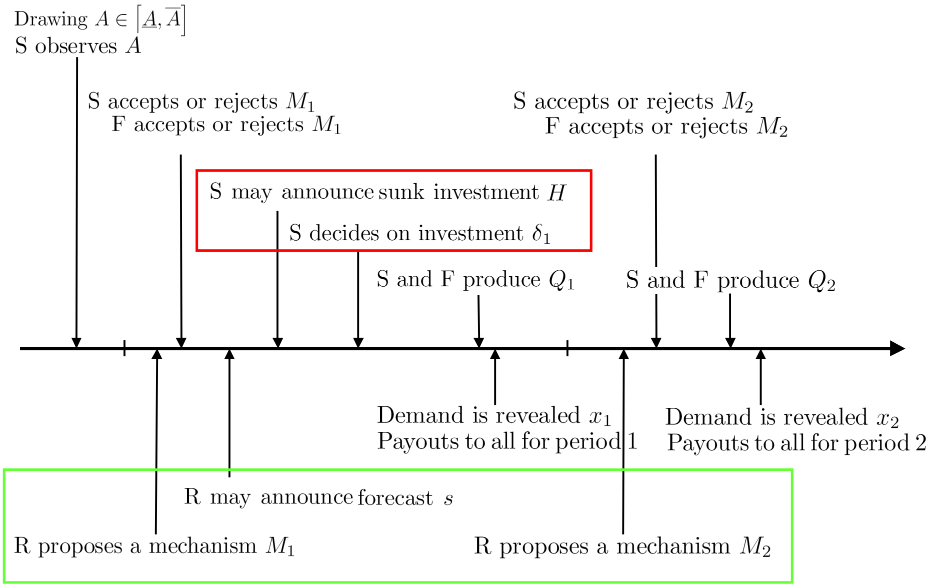

FIGURE 4. Timeline for the investment-production game with OEM coordination and asymmetric information.

amount A it would take in order to achieve a decrease of marginal cost $c'Q$ in the next period. The initial investment amount is a draw from a uniform distribution with support on $[\underline{A}, \overline{A}]$. The supplier has the first period cost function

$$C_1(Q_1, \delta_1) = \frac{1}{2}cQ_1^2 + \delta_1 A$$

where Q_1 is the actual production ordered in the first period, and $\delta_1 = 1$ if an investment of size A is undertaken in period 1 and $\delta_1 = 0$ otherwise. The second period cost function $C_2(Q_2, \delta_1)$ is

$$C_2(Q_2, \delta_1) = \frac{1}{2}(c - \delta_1 c')\, Q_2^2$$

where δ_1 is the indicator of previous period investments and Q_2 is the second period's realized production. The supplier maximizes the horizon echelon profit U_S,

$$U_S(.) = v_1 Q_1 + v_2 Q_2 - C_1(Q_1, \delta_1) - C_2(Q_2, \delta_1)$$

Fixed costs at any stage are ignored, as the focus is on the profit contribution of a particular decision.

4.1. Production Game. The decisions, production and information exchange are modeled as a two-period game, which is structured below. We ignore discounting effects, assuming that the values are given in real terms or that the interval is limited. However, this implies no loss of generality. The decisions in the model, illustrated in Figure 4 are made in the following order, which has importance with respect to the contracts derived.

(1) S draws and observes initial investment A from $[\underline{A}, \overline{A}]$.
(2) R proposes a mechanism $M_1(w_1, v_1, Q_1, X_1)$ to S and F.

(3) S accepts or rejects M_1
(4) F accepts or rejects M_1
(5) (If M_1 accepted) R may announce (non-verifiably) a demand forecast s for period 2.
(6) (If M_1 accepted) S may announce (non-verifiably) a sunk investment of H
(7) (If M_1 accepted) S decides on investment $\delta_1 \in \{0, 1\}$
(8) (If M_1 accepted) S and F produce Q_1
(9) (If M_1 accepted) Demand is revealed x_1
(10) (If M_1 accepted) Payouts to all for period 1 according to $M_1(w_1, v_1, Q_1, x_1)$
(11) R proposes a mechanism $M_2(w_2, v_2, Q_2, X_2)$ to S and F.
(12) S accepts or rejects M_2
(13) F accepts or rejects M_2
(14) (If M_2 accepted) S and F produce Q_2
(15) (If M_2 accepted) Demand is revealed x_2
(16) (If M_2 accepted) Payouts to all for period 2 according to $M_2(w_2, v_2, Q_2, x_2)$

Next, we will model the decentralized scenario as a function of (i) bargaining power (or coordination role) and (ii) information access/asymmetry. In the first case, the single-period price-quantity contract under full and OEM coordination will be studied as a benchmark. The second case adds asymmetric information on the supplier cost/capacity decision, still under OEM coordination. The third case shifts the coordination role to the EMS, while maintaining the private information on the supplier side and the single-period price-only contracts. The problems are so chosen as to illustrate the outline of organizational development in the telecom industry, where the roles and information access have been gradually evolving.

4.2. Centralized model. In the centralized solution, the three firms coordinate to achieve chain profit maximization. Note that the parameter $\alpha = 0$ in the integrated scenario is set to avoid double marginalization. Instead, the joint profit contribution is distributed *ex post* in some arbitrary way that we represent with a triple (π_R, π_F, π_S) later in the propositions. The joint investment is the result of the horizon control problem

$$\max_{Q_1, Q_2, \delta_1} E\left[\Pi\left(Q, \delta_1\right)\right] = \sum_{t=1}^{2} \left[p\left(Q_t - G\left(Q_t\right)\right) - C_t\left(Q_t, \delta_1\right)\right]$$

which for the investment case simplifies to a two-period newsboy problem

$$\begin{aligned} E\left[\Pi\left(., \delta\right)\right] &= p\left(Q_1 - G\left(Q_1\right)\right) - \frac{1}{2} c Q_1^2 - A\delta_1 \\ &\quad + p\left(Q_1 - G\left(Q_2\right)\right) - \frac{1}{2}\left(c - \delta_1 c'\right) Q_2^2 \\ &= p\left(E\left[X_1 | Q_1\right] + E\left[X_2 | Q_2\right]\right) \\ &\quad - \frac{1}{2} c \left(Q_1^2 + Q_2^2\right) + \left(\frac{1}{2} c' Q_2^2 - A\right) \delta_1 \end{aligned}$$

with the first order conditions

$$\begin{aligned}
\Pi_{Q_1}(.) &= p - pF(Q_1) - cQ_1 = 0 \\
\Pi_{Q_2}(., \delta_1) &= p(1 - F(Q_2)) - (c - \delta_1 c') Q_2 = 0 \\
\Pi_{\delta_1}(.) &= \frac{1}{2} c' Q_2^2 - A
\end{aligned}$$

and second order conditions

$$\begin{aligned}
-pf(Q_1) - c &< 0 \\
-pf(Q_2) - (c - \delta_1 c') &< 0
\end{aligned}$$

which indicate a concave function in Q.

Thus, the optimal policy devolves from $C(Q_t^{**}, \delta_1^{**})$ with the implicitly given order quantities

$$\begin{aligned}
\frac{\overline{F}(Q_1^{**})}{Q_1^{**}} &= \frac{c}{p} \\
\frac{\overline{F}(Q_1^{**}(\delta_1^{**}))}{Q_1^{**}(\delta_1^{**})} &= \frac{c - \delta_1^{**} c'}{p}
\end{aligned}$$

where $\overline{F}(x) = 1 - F(x)$. Obviously, $Q_2^{**}(0) = Q_1^{**}$, thus the argument can be suppressed from $Q_2^{**} = Q_2^{**}(1)$. To avoid trivial or atypical solutions in the game, we introduce the assumption of a non-trivial investment policy: $\frac{1}{2}c'(Q_2^{**})^2 < \overline{A}$. Let $\widetilde{A}^{**} = \frac{1}{2}c'(Q_2^{**})^2$ denote the highest acceptable investment cost under order quantity Q_2^{**}. The investment decision $\delta_1^{**} = 1$ is now governed by the decision rule $A \leq \widetilde{A}^{**}$, else investment is not undertaken, $\delta_1^{**} = 0$. The overall integrated channel profit contribution SC^{**} is calculated as

$$\begin{aligned}
SC^{**} &= p(Q_1^{**} - G(Q_1^{**})) - \frac{1}{2} c Q_1^{**2} \\
&\quad + \int_{\underline{A}}^{\widetilde{A}^{**}} \left\{ p(Q_2^{**}(1) - G(Q_2^{**}(1))) - \frac{1}{2}(c - c') Q_2^{**2}(1) - a \right\} f(a)\, da \\
&\quad + \int_{\widetilde{A}^{**}}^{\overline{A}} \left\{ p(Q_2^{**}(0) - G(Q_2^{**}(0))) - \frac{1}{2} c Q_2^{**2}(0) \right\} f(a)\, da \\
&= \left[p(Q_1^{**} - G(Q_1^{**})) - \frac{1}{2} c Q_1^{**2} \right] \left(\frac{2\overline{A} - \widetilde{A}^{**} - \underline{A}}{\overline{A} - \underline{A}} \right) \\
&\quad + \left[p(Q_2^{**} - G(Q_2^{**})) - \frac{1}{2}(c - c') Q_2^{**2} - \frac{1}{2}\left(\widetilde{A}^{**} + \underline{A}\right) \right] \left(\frac{\widetilde{A}^{**} - \underline{A}}{\overline{A} - \underline{A}} \right)
\end{aligned}$$

In the centralized model, the forecast s and the investment information H are truthfully disseminated to all players and the potential expected profit of higher accuracy would be added to the expected payoff.

4.3. OEM Coordination with Full Information. We now turn our attention to the decentralized case where the decision makers behave strategically with respect to their information and decision opportunities. A key element in the modeling is which player, if any, has the leading role. In the particular case of telecommunications, we can empirically observe that the OEM has the direct link to the market, the product definition and a prehistory as a vertically integrated firm. Thus, it is natural to allocate the decision initiative to the OEM. Initially, we pass through the results assuming perfect information. For this model, all signaling options are ignored.

Although the OEM observes *ex post* the investment decision δ, the performance of the supply chain will heavily depend on its ability to contract *ex ante* on the revealed information. We first state the most favorable case, where the OEM makes the first-period contract contingent on the *ex post* investment observation. The leverage for the supplier is now limited to rejection of single-period contracts, which forces the OEM to fully internalize the investment. In effect, this extreme coordination achieves integration with some limits to the profit sharing mechanism.

PROPOSITION 1. *Under perfect information and reservation utilities normalized at zero for S and EMS, the OEM may implement the first-best solution Q_t^{**} by offering the price-quantity single period contracts contingent on δ*

(i) The investment is imposed $\Gamma^* = 1$ iff $\frac{1}{2}c'\left(Q_2^{**}(1)\right)^2 \geq A$ else $\Gamma^* = 0$

(ii) The first-best production $Q_1^{**} = F^{-1}\left(\frac{p-c}{p}\right)$, $Q_2^{**}(\Gamma^*) = F^{-1}\left(\frac{p-c+c'\Gamma^*}{p}\right)$

(iii) No EMS rent $\alpha^* = 0$,

(iv) Full reimbursement of investment

$$v_t^*(\Gamma, \delta) = \left\{ \begin{array}{cc} \frac{1}{Q_1^*} C_1\left(Q_1^{**}, \Gamma\right) & \textit{for } t = 1,\ \delta = \Gamma \\ \frac{1}{Q_2^*(\Gamma)} C_2\left(Q_2^{**}(\Gamma), \Gamma\right) & \textit{for } t = 2,\ \delta = \Gamma \\ \frac{1}{Q_1^*} C_1\left(Q_1^{**}, 0\right) & \textit{otherwise} \end{array} \right\}$$

(v) Supply chain surplus SC^{**} is extracted by the OEM without distortion, $(SC^{**}, 0, 0)$.

PROOF. The control variables of the OEM are $v_t(\delta), \alpha, Q_t$. The reaction function for the supplier depends on the net transfer offered, $v_t(\delta) Q_t$ in each period t,

$$\max_{\delta} \left\{\max\left\{v_1(\delta) Q_1 - C_1(Q_1, \delta), 0\right\} + \max\left\{v_2(\delta) Q_2 - C_2(Q_2, \delta), 0\right\}\right\}$$

A hold-up strategy by the OEM would not be an equilibrium, since the outcome is a rejected investment in the first period and a rejected contract in the second. Thus, a strategy that postpones the reward to the second period is not implementable due to lack of commitment power. A hit-and-run deviation from the supplier, to collect the investment premium without undertaking the investment and then rejecting the second period contract, falls on the observability. The EMS has no decision and subsequently no rent in this problem. Hence, the policy where the OEM orders first-best, sinks an optimal investment in the first period, and the two other tiers comply with the optimal policy, is a (weak) NE. □

Removing the contractability of the investment observation decreases the outcome space in the problem. The OEM is now constrained to a single-period contract, although the possible investment is observable for the second-period contract.

PROPOSITION 2. *Under perfect information and reservation utilities normalized at zero for S and EMS, the OEM may implement the third-best solution* Q_t^* *by offering the price-quantity single period contracts*
(i) No investment is undertaken $\delta_1 = 0$
(ii) Production $Q^* = Q_1^* = Q_2^* = F^{-1}\left(\frac{p-c}{p}\right)$
(iii) No EMS rent $\alpha^* = 0$,
(iv) Full reimbursement of investment

$$v_t^*(\delta) = \begin{Bmatrix} \frac{1}{Q_1^*} C_1(Q_1^*, 0) & \text{for } t = 1, 2\ \delta = 0 \\ \frac{1}{Q_2^*(1)} C_2(Q_2^{**}(1), 1) & \text{for } t = 2,\ \delta = 1 \end{Bmatrix}$$

(v) Supply chain surplus $SC^1 = 2\left(p(Q^* - G(Q^*)) - \frac{1}{2}cQ^{*2}\right)$ *that is extracted by the OEM,* $\left(SC^1, 0, 0\right)$.

PROOF. The control variables of the OEM are v_t, α, Q_t. The reaction function stays as above, but the first-period revenue is no longer contingent on the investment,

$$\max_{\delta} \{\max\{v_1 Q_1 - C_1(Q_1, \delta), 0\} + \max\{v_2(\delta) Q_2 - C_2(Q_2, \delta), 0\}\}$$

The first-best solution is generally not implementable, since the supplier would hit-and-run in the case of $\Gamma = 1$. The OEM could not credibly provide incentives for the supplier to sink the investment A, since the hold-up strategy dominates strictly in the second period, where the investment is observed. Thus, the only NE is where no investment is undertaken, irrespective of cost and the quantities $Q^* = Q_1^* = Q_2^* = F^{-1}\left(\frac{p-c}{p}\right)$. The OEM has no incentive to deviate in the absence of investment. The supplier has no incentive to internalize an investment, nor any reason to reject the contract.

The OEM collects a constant profit contribution of

$$SC^1 = \Pi_R^1 = 2\left(p(Q^* - G(Q^*)) - \frac{1}{2}cQ^{*2}\right)$$

□

The results in Proposition 2 are hardly surprising, as perfect information enables OEM to observe, but not necessarily promote, chain coordination. However, this effect is a general artifact of limited commitment, which, under dominant strategy[1], could be addressed by repeated contracting or reputation. In the context of this presentation, the result merely gives a reference point for the cases under asymmetric information.

4.4. OEM Coordination with Asymmetric Information. We now introduce asymmetric information on the supplier capacity investment, such that OEM cannot observe either the outcome of the cost A, or whether the investment has been undertaken, i.e. δ_1. In this scenario, the OEM needs either to commit to future payments, or to accept that the supplier enjoys an information rent on its private knowledge about the information.

[1]In this context, we are not considering mixed strategies for the bargaining game.

PROPOSITION 3. *Under asymmetric information on the investment, single period contracts and reservation utilities normalized at zero for S and EMS, the OEM may implement the second-best solution Q_t^* by offering a price only-contract*

(i) Production $Q_1^* = F^{-1}\left(\frac{p-c}{p}\right)$ and

$$Q_2^*(H) = \left\{ \begin{array}{cc} F^{-1}\left(\frac{p-c}{p}\right) & \text{for } H = 0 \\ F^{-1}\left(\frac{p-c+c'}{p}\right) & \text{for } H > 0 \end{array} \right\}$$

(iii) No EMS rent $\alpha^* = 0$,

(iii) No reimbursement of investment $v_1^* = \frac{1}{Q_1^*} C_1(Q_1^*, 0)$, and

$$v_t^*(H) = \left\{ \begin{array}{cc} v_1^* & \text{for } H = 0 \\ \frac{1}{Q_2^*(1)} C_2(Q_2^*(1), 1) & \text{for } H > 0 \end{array} \right\}$$

(iv) Secret investment $H^*(.) = 0$

(v) Distorted investment is undertaken

$$\delta_1^*(A) = \left\{ \begin{array}{cc} 1 & \text{iff } A \leq \frac{1}{2} c' (Q^*)^2 = \widetilde{A}^* < \widetilde{A}^{**} \\ 0 & \text{else} \end{array} \right\}$$

(vi) Supply chain profit sharing $\left(\Pi_R^2 = SC^1, 0, \Pi_S^2\right)$ under incomplete rent extraction,

$$\begin{aligned} SC^2 &= SC^1 + \frac{1}{2}\left[c' Q^{*2} - \widetilde{A}^* - \underline{A}\right]\left(\frac{\widetilde{A}^* - \underline{A}}{\overline{A} - \underline{A}}\right) \\ &= \Pi_R^2 + \Pi_S^2 \end{aligned}$$

PROOF. The EMS is still without leverage and cannot demand rents, $\alpha^* = 0$. The reaction function of the supplier now reflects the two decision variables δ, H, where only the second period contract possibly contingent on H, and the private information leverage

$$\max_{\delta, H} \{v_1 Q_1 + v_2(H) Q_2(H) - C_1(Q_1, \delta) - C_2(Q_2(H), \delta), 0\}$$

The first-best solution $Q_1^{**}, Q_2^{**}(\delta)$ is not an equilibrium under truthful signaling, since the supplier's hit-and-run strategy strictly dominates investment. Since the signal H precedes the second period contract, the supplier has limited use if it. On the other hand, the OEM may safely conclude *ex post* that $H > 0$ implies a sunk investment to be exploited. This recursively reduces the value of the signal to nil. The equilibrium outcome is $Q^* = Q_1^* = Q_2^*$ but with higher integrated rent, since the supplier safely invests under the distorted criterion

$$A \leq \frac{1}{2} c' (Q_1^*)^2 = \widetilde{A}^*$$

and signal $H = 0$ in the first period. Signalling $H > 0$ would in the case $\delta = 1$ yield a second period contract $Q_2^{**}(1)$ with no profit contribution and in the case $\delta = 0$ a rejected contracts and stalled production, $Q_2 = 0$.

The OEM has no incentive to deviate by offering higher compensation in the first period, since it only transfers rent without warranting future capacity. Deviation by offering lower contracts in the second period would risk rejection. The analysis is analogous for the OEM order quantities. The OEM surplus stays at level $\Pi_R^1 = SC^1$

The expected supplier surplus follows from the distribution of A

$$\begin{aligned}\Pi_S^2 &= \int_{\underline{A}}^{\widetilde{A}^*} \left(\frac{1}{2}c'(Q^*)^2 - a\right) f(a)\, da \\ &= \frac{\left(\widetilde{A}^* - \underline{A}\right) c'(Q^*)^2 - \left(\widetilde{A}^2 - \underline{A}^2\right)}{2\left(\overline{A} - \underline{A}\right)}\end{aligned}$$

□

We notice here that the OEM with bargaining power limited to the EMS stage cannot extract all rents from the chain. However, as opposed to the situation with incomplete contracts under full information, the private information actually allows the supplier to internalize the investment. Hence, the supply chain performance actually increases when the OEM accepts the limitations of the contract-horizon setup and abstains from investment verification. This interpretation follows the intuition that an overly leveraged party may gain from refraining *ex ante* of certain instruments or *ex post* renegotiation. A regulatory body may increase social welfare under risks of political capture by using incomplete instruments that limit the possibility of post contractual opportunism.

A small remark can be made on the timing of the investment signal. If the supplier could present non-verifiable information on the investment cost before the first-period contract is signed and the investment is made, how would it change the results? First, the OEM would now face the additional option of using a first-period transfer $v_1^{**}Q_1^{**} + H$, followed by a second-period contract $v_2^{**}Q_2^{**}(1)$, which is first-best if $H = A \leq \widetilde{A}^{**}$. However, the supplier would deviate by reporting $H = 0$ or $\overline{A}$ for all $A \in \left[\underline{A}, \widetilde{A}^*\right]$ and $H = \widetilde{A}^{**}$ for $A \in \left[\widetilde{A}^*, \overline{A}\right]$. For the first interval, the supplier makes a secret investment and internalizes the profit. If a private investment is not profitable, the supplier signals the maximum public investment and makes a hit-and-run, rejecting the second-period contract. Thus, changing the information timing does not bring higher value to the chain, it merely changes the nature of the distortion. In any case, the signal does not convey any meaningful information.

4.5. EMS Coordination with Asymmetric Information. To reflect the ongoing changes in the leverage between actors in the telecommunications supply chain, we study the case with asymmetric information under which the OEM orders, S invests and EMS holds the bargaining power to suggest and coordinate contracts. One may perceive this solution as the result of a far-reaching decentralization, from which the EMS factory has gained more stable or important revenue streams than the OEM.

We state the properties in a proposition.

PROPOSITION 4. *Under asymmetric information on the investment, single period contracts and reservation utilities normalized at zero for S and OEM, the EMS may implement the third-best solution* Q_t^E *by offering a price only-contract*

(i) Production $Q^E(w^*) = F^{-1}\left(\frac{p-w^*}{p}\right)$

(ii) No reimbursement of investment

$$v_t^E(H) = \left\{ \begin{array}{ll} \frac{1}{Q^E(w^*)} C_1\left(Q^E(w^*), 0\right) & \textit{for } H = 0 \\ \frac{1}{Q^E(w^*)} C_2\left(Q^E(w^*), 1\right) & \textit{for } H > 0 \end{array} \right\}$$

(iii) Secret investment $H^E = 0$

(iv) Distorted investment is undertaken

$$\delta_1^E(A) = \left\{ \begin{array}{ll} 1 & \textit{iff } A \leq \frac{1}{2}c'\left(Q^E\right)^2 = \widetilde{A}^E < \widetilde{A}^* \\ 0 & \textit{else} \end{array} \right\}$$

(v) Double marginalization $\alpha_t^E(w^*) = \frac{w^*}{v_t^E(w^*)} - 1 > 0$

(vi) Supply chain surplus division $\left(\Pi_R^3, \Pi_F^3, \Pi_S^3\right)$ *under incomplete rent extraction,*

$$SC^3 = 2p\left(Q^E\left(w^E\right) - G\left(Q^E\left(w^E\right)\right) - \frac{1}{2}cQ^{E2}\right) + \frac{1}{2}\left(c'Q^{E2} - \widetilde{A}^E - \underline{A}\right)\left(\frac{\widetilde{A}^E - \underline{A}}{\overline{A} - \underline{A}}\right)$$

Proof. The EMS decision variables are $\alpha, w_t(.)$ and $v_t(.)$. The OEM acts a double pricetaker towards the market and the supply, optimizing the order quantities Q_t over the two periods

$$\max_{Q_t} E\left[U_R(Q)\right] = \sum_{t=1}^{2}\left(\left(p - w_t(.)\right)Q_t - p\int_0^{Q_1} F(x)\,dx\right)$$

which yields a convex problem with the solutions

$$Q_t^E(w_t) = F^{-1}\left(\frac{p - w_t}{p}\right)$$

The supplier follows the reaction function under asymmetric information, using the signal H, the investment δ and the veto right,

$$\max_{\delta, H}\left\{v_1 Q_1^E(w_1) + v_2(H)\, Q_2^E(w_2(H)) - C_1\left(Q_1^E(w_1), \delta\right) - C_2\left(Q_2^E(w_2(H)), \delta\right), 0\right\}$$

The EMS now faces the control problem in $w_t(H)$, since $v_t(w_t, H)$ is implicitly given from the participation constraint as $v_1(w_1) = \frac{1}{2}cQ_1(w_1)$ and $v_2(w_2, H) = \frac{1}{2}(c - c')\,Q_2(w_2(H))$. However, as in the OEM coordination case with private information, the equilibrium does not involve any signaling. Instead, the supplier undertakes the investment with the distorted decision rule $\delta_1^E = 1$ iff $A \leq \frac{1}{2}c'\left(Q^E\right)^2 = \widetilde{A}^E$. Ignoring the signal H and suppressing it as an argument for clarity, we concentrate on the case where the EMS applies a uniform policy and lets the supplier internalize the investment. Simplifying the price signal $w = (1 + \alpha)\,v$ to the OEM enables the markup factor α to fall out of the participation constraint for the supplier,

$$\alpha^E(w) = \frac{w}{v_1(w)} - 1$$

The EMS solves the following program in w for the non-imperative investment case

$$\max_w U_F(w) = 2\left[wQ^E(w) - C_1\left(Q^E(w), 0\right)\right] \tag{4.1}$$

with the first order conditions (suppressing the superscript E in the implicit response function $Q^E(w)$)

$$Q\left(w^E\right) + \left(w^E - cQ\left(w^E\right)\right)Q'\left(w^E\right) = 0$$

and second order condition

$$2Q'\left(w^E\right) + Q''\left(w^E\right)\left(w^E - cQ\left(w^E\right)\right) - c\left(Q'\left(w^E\right)\right)^2 < 0$$

Due to monotonicity of F there exists a unique solution w^*. The OEM retains the expected surplus

$$\Pi_R^3 = 2p\left(Q^E\left(w^E\right) - G\left(Q^E\left(w^E\right)\right)\right) - 2\left(1 + \alpha^E\left(w^E\right)\right) v\left(w^E\right) Q^E\left(w^E\right)$$

where the EMS supplies the OEM with the optimal marginal cost and keeps the surplus between the average cost v^E and the marginal cost w^E . The supplier surplus follows from its internalized investment

$$\begin{aligned}\Pi_S^3 &= \int_{\underline{A}}^{\widetilde{A}^E} \left(\frac{1}{2}c'\left(Q_2^E\left(w^E\right)\right)^2 - a\right) f\left(a\right) da \\ &= \frac{\left(\widetilde{A}^E - \underline{A}\right) c'\left(Q_2^E\left(w^E\right)\right)^2 - \left(\widetilde{A}^{E2} - \underline{A}^2\right)}{2\left(\overline{A} - \underline{A}\right)}\end{aligned}$$

The EMS retains the profit contribution

$$\Pi_F^3 = 2\alpha^E\left(w^E\right) C_1\left(Q^E\left(w^*\right), 0\right)$$

□

The EMS coordination implies a further lowering of supply chain performance due to the superposing of asymmetric information at the supplier stage and double marginalization at the OEM stage. Limited by the contractual structure, the EMS is forced to extract the differential between the average and the marginal supplier cost by a mark-up. However, this impediment serves to discipline the EMS in its relation with the OEM. The downstreams agent OEM implicitly allocates part of the supply risk to be anticipated by the EMS, compensated by a lion's share of the chain profits.

5. Illustration

To numerically illustrate the model and the findings, the three stages are parameterized as in Table 1. The results are summarized in Table 2, where the production quantities, the profit contribution shares, the total chain profit and the investment cut-off limit are given for the base case and the three other cases. Note that the EMS coordination performs worse than the no-investment case 1. The differences are, however, fairly low with the given parameters: -3.4%, -1.5%, -3.5% coordination loss relative to optimal coordination, respectively. This should not be interpreted with respect to the actual telecom scenario, as the relative share of variable to capacity cost parameters for the simplified scenario has not yet been validated. Finally, with respect to the investment, one may notice that contracting problems preclude 50% and 54% of the optimal investments in cases 2 and 3, respectively. This finding has some anecdotal evidence in the industry, where suppliers have recently demanded more active participation to undertake specific invesments under uncertainty.

Parameter			
p	500	D	$N(1000, 200)$
c	1.00	$\overline{A}$	55000
c'	0.25	$\underline{A}$	10000

TABLE 1. Parameters for the numerical illustration.

Centralized case		Case 1		Case 2		Case 3	
Q_1^{**}	497.02	Q^*	497.02	Q^*	497.02	Q^E	481.15
Q_2^{**}	642.14	$Q_2^*\,(H>0)$	642.14	$Q_2^*\,(H>0)$	642.14	$Q_2^E\,(H>0)$	575.24
		Π_R^1	249,608	Π_R^2	249,608	Π_R^3	1,982
		Π_F^1	0	Π_F^2	0	Π_F^3	247,364
		Π_S^1	0	Π_S^2	4,844	Π_S^3	3,985
SC^{**}	258,285	SC^1	249,608	SC^2	254,452	SC^3	249,347
$\widetilde{A}^{**}$	51,544	$\widetilde{A}$	0	$\widetilde{A}^*$	30,879	$\widetilde{A}^E$	28,938

TABLE 2. Numerical results for the centralized case and the cases 1, 2, 3.

6. Conclusion

We have proposed a three-level, two-period supply chain model as a vehicle to model incentive conflicts and coordinating contracts in the telecom supply chain. Basing our structure on the telecom sector, some early results from the model suggest that the shifting positions of bargaining strength may undermine chain performance when the contractual structure is misaligned. Especially in the case of previously integrated firms that hold bargaining power, but suffer from asymmetric information and limited contractual commitment, the findings would suggest reallocation of bargaining power and chain risks upstream. From an applied perspective, the current analysis points out the shortcomings of price-quantity-only coordination in the absence of long contracts. However, the bounds on rent extraction that result from a reallocation of bargaining power to the EMS factory give rise to some interesting speculations. Our conclusions for the scenarios are summarized in Table 3. Although full coordination can theoretically be obtained with simple price-quantity contracts, asymmetric information, even in limited three-tier setting, will constrain the potential performance. A shift of bargaining power from the OEM to the EMS is, in our model, not an improvement of coordination.

The recent changes in scope and profitability in the industry may be not only the result of market outcomes on the retail or OEM level, but also an affect of the existing imperfect contractual instruments. Although not covered in the formal analysis, some other benefits in terms of forecast accuracy and investment efficiency may also spring from this seemingly inadequate structure. Advanced contractual instruments that contract on forecasts and outcomes may, in the perspective of asymmetric information, force the OEM to internalize investment costs based on incomplete information. This may imply a downward distraction of forecasts that may affect supply chain performance. Simple contracts that allocate inventory risks upstream are not subject to the same biases.

Information	*Coordinator*	*Contractual relations*	*Findings*
Perfect information	OEM	Single-period, v, w, Q contracts Investment observable	No investment Even production Losses of renegotiation
Asymmetric information	OEM	Single-period, v, w, Q contracts S decides privately on δ	Second-best chain profit S internalizes investment Secret investment Losses due to renegotiation
Asymmetric information	EMS	Single-period, v, w contracts S decides privately on δ OEM decides on Q OEM decides on quantity	Third-best chain profit S internalizes investment Losses due to renegotiation Double marginalization

TABLE 3. Model structure, relations and some findings.

Whether this structure could be improved by more advanced contractual instruments, such as two-part tariffs and minimum quantity contracts, is the subject of the next analysis stage. In any case, the dynamics and complexity of the underlying business logic in the industry may very well be reflected in the optimal contractual structure. Thus, to pursue the pervasive target of optimal mechanisms under the true contractual conditions might be largely a futile exercise, whereas a thorough analysis of stable and implementable mechanisms always conveys value to industry and academia as well. In all modesty, perhaps this provides a new angle on integrated supply chain management research.

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(Per Agrell) IAG School of Management, Catholic University of Louvain, 1 Place des Doyens, B-1348 Louvain-la-neuve, BELGIUM
E-mail address, Per Agrell: agrell@poms.ucl.ac.be
URL: http://www.poms.ucl.ac.be.

(Robert Lindroth and Andreas Norrman) Engineering Logistics, Department of Industrial Management and Logistics, Lund University, P.O.B. 118, S-221 00 Lund, SWEDEN
E-mail address, Robert Lindroth: robert.lindroth@tlog.lth.se

E-mail address, Andreas Norrman: andreas.norrman@tlog.lth.se
URL: http://www.tlog.lth.se