Risk Ownership in Contract Manufacturing

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We consider a supply chain where a contract manufacturer (CM) serves a number of original equipment manufacturers (OEMs). Investment into productive resources is made before demand realization, hence the supply chain faces the risk of under- or overinvestment. The CM and OEMs differ in their forecast accuracy and in their resource pooling capabilities, leading to a disparity in their ability to minimize costs due to demand uncertainty. We consider two scenarios in which this risk is borne by the OEM and CM, respectively. We determine which party should bear the risk so that maximum supply chain profits are achieved. We investigate the effectiveness of premium-based schemes in inducing the best party to bear the risk, and conclude that they function well despite information asymmetry when double marginalization is not very high.

Key words: information asymmetry; risk ownership; contract manufacturing; resource pooling

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1. Introduction

In the last few years, outsourcing has become a staple of the electronics industry. Following the lead of companies such as Cisco that have few production assets, traditional original equipment manufacturers (OEMs) decided to exit production-related activities that they did not consider to be their core competency anymore. They decided to be involved primarily in new product introduction and marketing activities, rather than manufacturing the product itself. This trend led to the creation of the electronics manufacturing services (EMS) industry, with estimated global revenues of US$116.5 billion in 2004 (E-Asia Online 2005).

A downturn in the electronics sector highlighted the lack of clarity about who should bear the risk arising from supply-demand mismatches. A March 2001 article (BusinessWeek, March 19, 2001) states: “Manufacturers have given contractors and distributors more control over procuring parts. Now, it’s unclear who owns excess inventory.” Indeed, during the Supply Chain Forum on Contract Manufacturing held at INSEAD in June 2001, we observed two conflicting points of view regarding the best location for risk ownership in a supply chain. The contract manufacturers (CMs) argued that the OEMs should be responsible for managing the risks because of demand uncertainty because they have better information about the market. This was countered by the OEM point of view that the CM should be responsible for managing these risks because they can hedge their risks by using their resources for many different customers.

The goal of this paper is to investigate these claims and to identify conditions under which they are valid. To this end, we consider a supply chain where several OEMs have outsourced their production operations to a single CM. The OEMs and CM differ in their ability to minimize costs because of demand uncertainty and in their information about demand: Since she serves multiple clients operating in different markets, the CM has the ability to minimize the impact of demand uncertainty by pooling resources. On the other hand, since they are closer to the end customers, the OEMs have more reliable information about future demand. Obviously, the highest profits for the supply chain would be achieved when the OEM credibly shares information with the CM and the CM bears the risks. However, in practice, this may not be possible because of incentives to misrepresent information (Cohen et al. 2003). In this paper, we
study risk ownership in a setting that prevents the OEM and CM from having access to the same information.

In this paper, we consider operational risk rather than financial risk, commonly represented in the finance literature as the variance in returns. We define risk as the cost of supply-demand mismatches (cost of overage and underage) because of demand uncertainty. We first consider two scenarios where only one of the parties makes a risky decision, a quantity decision in the face of uncertain demand. In these two scenarios, the decision maker incurs the entire cost of uncertainty. We refer to making the quantity decision as taking responsibility because it is bundled with bearing the risk. This structure allows us to investigate the validity of the above claims. In particular, we address the following questions: First, to maximize total supply chain profits, which party in the supply chain should take the responsibility for the deployment of productive resources? In other words, at what stage of a supply chain should risk be managed? Second, do the individual firms benefit from assuming this responsibility? Finally, if taking the responsibility is undesirable, how can supply chain optimal behavior be induced?

To answer these questions, we consider two scenarios where either the OEM or CM is the responsible party and makes a committed quantity decision so as to maximize its own profit. We compare the supply chain profits under these two scenarios and show that depending on the relative accuracy of information, the number of OEMs in the CM’s portfolio, and the cost structure, the OEM or CM may carry risks more effectively from a supply chain point of view. The allocation of responsibility is especially important when uncertainty and production cost are high, and there is double marginalization. However, it is also observed that each party would prefer to avoid taking responsibility. Next, the payment of premiums to the risk-bearing party is investigated as a mechanism to achieve supply chain optimal behavior. It is seen that there always exists a range of premiums that induces one of the parties to voluntarily bear the risk, however, this party is not always the right one from a supply chain perspective. When double marginalization is present, the loss because of misallocation of responsibility can be significant, even in the presence of premiums for risk bearing. In other cases, premiums are quite effective. Finally, we consider a third scenario where both parties take some risk—the OEM by making a committed quantity decision, and the CM by independently making a quantity decision that may differ from the OEM’s commitment. We identify conditions under which the CM benefits from taking on this risk and deviating from the OEM commitments.

The remainder of this paper is organized as follows: In §2, we review the relevant literature and highlight our contribution. Our modeling framework is presented in §3. Section 4 examines the cases under which OEM and CM responsibility lead to higher profits for the supply chain. In §5, we consider firm-level profits for the first two scenarios under consideration. In §6, we find ranges of premiums that induce supply chain optimal behavior. Section 7 analyzes the third scenario where both parties bear some risk. Section 8 discusses the implications of relaxing some of the assumptions. We conclude in §9 with a discussion of our results.

2. Literature Review

In this paper, we examine the impact of the decision making and risk ownership structure on supply chain profits. The main elements of our model are risk pooling because of the multiplicity of customers at the CM and asymmetric demand information at different stages of the supply chain.

The decision to vertically integrate or outsource, which has been studied extensively in the economics and strategy literatures, has recently attracted attention in the operations management literature as well. Van Mieghem (1999) evaluates the option value of subcontracting in a two-firm setting where an OEM faces the choices of manufacturing in house, or fully or partly outsourcing, and examines the ability of price-only contracts, state-dependent contracts, and incomplete contracts to coordinate the channel. Plambeck and Taylor (2005) consider the trade-off between pooling effects and the incentive to innovate when manufacturing and innovation occur in different organizations, at the CM and OEM, respectively. They conclude that outsourcing production to CMs improves profits only when the OEM has higher bargaining power because incentives to innovate are distorted otherwise.
In our paper, the outsourcing decision has already been taken, and we consider the question of the allocation of risk between the parties involved.

Several papers examine the allocation of inventory responsibility in the supply chain. Cachon (2004) considers the allocation of inventory risk in a two-party supply chain. The contracts are solely based on wholesale prices and risk is allocated by changing the location of decisions. It is shown that supply chain profits can be improved simply by shifting the location of decisions, since the inefficiency because of double marginalization depends on the party that determines the quantity. In our paper, the location of decision making impacts profits not only because of double marginalization but also because of the information and pooling differentials. Netessine and Rudi (2004) compare individual stocking by retailers and direct delivery to end customers by the wholesaler (drop shipping). It is shown that there exist instances where both parties prefer the drop-shipping mode in which the risk is borne by the distributor. This paper does not consider information asymmetry.

In our paper, risk allocation is based on decision responsibility in the face of uncertainty (Pasternack 1985). Buyback contracts have been studied as another mechanism to shift risks between the parties. Kandel (1996) shows that both the manufacturer and retailer prefer to take the responsibility for inventory risk when contract parameters are set by the responsible party. Glenn (2004) examines a supply chain where the retailer is pessimistic about the market potential. Depending on the buyer’s belief about the quality of manufacturer forecasts, buyback contracts may be used in two ways: (1) they may either serve as a signal of market potential or (2) they may increase the order quantity by reducing the retailer’s risk. Webster and Weng (2000) examine percentage and quantity-based returns policies. They show that it is always possible to make Pareto improvements over wholesale price contracts with returns based on quantities, but not with those based on percentages. Granot and Yin (2005) show that when price is a decision variable, buybacks are not always introduced in equilibrium, and when they are introduced, the improvement in efficiency is insignificant. They argue that buyback contracts may be used mainly for shifting profits from the retailer to the manufacturer.

We assume that the OEM and CM are risk neutral, and are concerned only with the expected cost of uncertainty that results from over- or underinvestment. A stream of recent papers consider supply chain coordination with risk-averse agents. Agrawal and Seshadri (2000) show that a risk-neutral distributor can induce risk-averse newsellers to select the optimal order quantity by offering a menu of risk-reducing contracts. Gan et al. (2004) modify the definition for coordination to address different forms of risk aversion (“Pareto-optimal solution acceptable to each agent”). In a followup paper, Gan et al. (2005) show that when the buyer has downside risk aversion, standard buyback, and revenue-sharing contracts do not coordinate the supply chain, however, coordination can be achieved by using a limited refund contract. Finally, Deng and Yano (2005) examine a supply chain where both the buyer and seller face downside risk constraints. It is shown that buyback and revenue-sharing contracts fail to coordinate the channel, and the best possible contract is one that satisfies least risk sharing, one that minimizes the probability that both parties have a profit lower than their thresholds.

Pooling has been analyzed in a variety of contexts. Firms can pool risks over multiple demand sources with flexible production technologies (Van Mieghem 1998), common components (Tang and Lee 1997), and by centralizing inventory physically (Eppen 1979, Schwarz 1989) or virtually (Krishnan and Rao 1965). In this paper, we allow for resource pooling by the CM serving several OEMs.

In a decentralized system, one of the parties can be better informed, for instance, about cost (Corbett 2001, Corbett and de Groot 2000, Corbett et al. 2004) or future demand (Cachon and Lariviere 2001, Lariviere 2002, Özer and Wei 2003, Glenn 2004). Even though the system can benefit from information sharing, this may not be possible because of the nature of information or individual incentives to misrepresent it (Cohen et al. 2003). In the former case, Anand and Mendelson (1997) show the importance of matching information and decision structures. In the latter case, it may be possible to design special mechanisms for truthful disclosure of private information. The informed party can take the lead and signal its information (type) by incurring a certain cost that another type could not afford. Alternatively, the uninformed party can screen
the types by offering a menu of contracts. In this case, the informed party is expected to choose the contract that maximizes its profits, and thereby disclose her type.

In this paper, we assume that information is not shared credibly. From a theoretical point of view, multidimensionality of firm types means that separation of types, and therefore information sharing is possible only under limited conditions; bunching is a generic property (Salanié 1997). From a practical point of view, menus of contracts are complex and are rarely used in practice (Brown 2003). A prevalent contract type in EMS is the simple cost plus contract (Keranen 2000) that charges a constant premium over costs. After showing that simple cost-plus contracts eliminate double marginalization, we analyze the general case with double marginalization.

3. The Model

We consider a CM that uses the same productive resource to serve M OEMs that face markets with uncertain demand. This section introduces the assumptions about the supply chain structure and describes the scenarios considered.

The demands in the end markets, , are independent. They are distributed as , which is common knowledge for the OEMs and CM. Before making quantity decisions, the OEMs and CM observe noisy signals from the end markets and update their priors. Let and respectively, denote the signals received by the relevant OEM and CM for market , with and representing the normally distributed noise components. In particular, the signal corresponding to a particular future realization of demand in market is drawn from the distribution for the OEM and for the CM.

We assume that the noise and the demand are independently distributed. After observing the signal, the OEM information is summarized by the posterior distribution , where is a weight that depends on signal accuracy. The posterior for the CM is similarly given by , where .

We assume that the OEMs receive more accurate signals because of their location in the supply chain; that is, . While the CM knows that the accuracy of the OEM’s signal is higher (i.e., knows that ), he does not know , nor does he have access to the OEMs signal (and similarly for the CM): the signals and their accuracy are private information. In the case of a new product, the information advantage may result from market research information at the OEM that is not available to the CM (Brown 1999, Cachon 2004, Özer and Wei 2003). In addition, the OEMs are not subject to the bullwhip effect (Lee et al. 1997) as a result of their direct interaction with end customers.

We focus on a setting where there is no effective information exchange between the CM and OEMs. While the supply chain would benefit from information sharing (Lee et al. 1997, Chen 1998, Gavirneni et al. 1999, Cachon and Fisher 2000), Cohen et al. (2003) find empirical evidence against its use in practice: “Fearing order cancelation, the supplier, by and large, ignores the preliminary forecast information” (p. 1654). The contracting literature shows that credible information disclosure does not occur unless the right incentive mechanisms are put in place (Cachon and Lariviere 1999, 2001; Corbett 2001; Lariviere 2002; Özer and Wei 2003). However, such contracts are complex and are not commonly observed in practice. In addition, such contracts typically lead to pooling equilibria: no information is disclosed under the more realistic assumption that the firms have multiple type dimensions.

We refer to the productive resource as capacity throughout this paper. However, the results are applicable to inventory as well, unless otherwise stated. Prior to demand realization, an initial capacity investment is made at a unit cost . We assume that realized demand is fully satisfied by using expedited output (if necessary) at a unit cost of . Because of this assumption, there are no lost sales. The salvage value is assumed to be 0. The implication of relaxing this assumption is discussed in §8.

We consider two scenarios that capture the points of view raised in §1 regarding the location of risk ownership. In Scenario I, the OEMs take the responsibility, i.e., incur the cost of excess or insufficient capacity; the CM is shielded from these risks. The OEM commits to pay a wholesale price for a certain quantity regardless of the actual demand realization, and the CM produces the requested quantity for each

\[ F_{D_i|\epsilon} = N(\mu_i, \sigma_i) = N((1 - \gamma_0)\mu_i + \gamma_0 s_i^2, \sqrt{\gamma_0} \sigma_i^2), \quad \text{where} \quad \gamma_0 = \frac{\sigma_i^2}{\sigma_i^2 + \sigma^2}. \]
OEM. Next, demands are observed, and are filled from the amounts originally produced for each OEM. The excess demand, if any, is expedited at the expense of the OEM at a wholesale price $w'$ per unit. In this scenario, the quantity produced for one OEM is not used for any other client.

In Scenario II, the responsibility is assumed by the CM. The CM determines the regular production capacity based on her own assessment of demand before orders are placed. The OEMs place their orders only after demand is observed. All demand is filled by the CM using regular or expedited production. In this scenario, the CM incurs the costs of expedited production as the same wholesale price $w$ is charged for both modes of production. OEM orders perfectly match demand, because orders are placed only after the market demand is observed. Note that the total cost of the supply-demand mismatch is scenario specific.

In §7, we examine Scenario III, an intermediate case where both the OEM and CM make a capacity choice, and thereby bear a certain level of risk. The OEM commits to pay for capacity $K_i$ regardless of the realization of demand. However, the CM may decide to deviate from the committed capacity and build $K_c \neq \sum K_i$ with the intention of achieving higher profits.

The unit margins for the OEM and CM are positive in both modes, and expedited production is more expensive for both ($w' > w; w > c; w' > c'$). We assume that the retail price charged to the end customers by the OEM, denoted by $r$, is fixed across the two scenarios for comparison purposes, with $w' < r$.

We assume that the parties involved are risk neutral: they maximize expected profit without regard to its variance. They consider the operational risk because of uncertain demand, which is effectively the expected cost of supply-demand mismatches (costs of expediting and excess capacity) resulting from demand uncertainty. We do not consider the financial risk, which can be measured by the variance in the returns. The implications of relaxing this assumption are discussed in §8.

4. Comparison of Supply Chain Profits

In this section, we analyze the supply chain profits. First, we determine the profits for the two scenarios described in §3. Then, we determine conditions under which OEM or CM responsibility is beneficial for the supply chain. Finally, we carry out sensitivity analysis.

4.1. Computing Supply Chain Profits

In this subsection, we analyze the model described in §3. We find the optimal supply chain profits under the two scenarios.

4.1.1. Scenario I: OEMs Bear the Risk. In this scenario, each OEM optimizes his expected profit over his initial quantity commitment, $K_i$, while the CM responds by producing the total requested quantity ($\sum_{i=1}^{M} K_i$).

The OEM profit is

$$\Pi^I_{\alpha}(K_i, D) = -wK_i + r\min(K_i, D_i) + (r - w')\max(D_i - K_i, 0).$$

The first term in the profit expression is the cost of initial committed orders, the second term is the revenue earned with these orders, and the last term is the profit from expedited orders. After observing the signal, the OEM calculates his expected profit from choosing $K_i$ based on the posterior distribution $\mathcal{E}_{D_i | s^I}$ as

$$E_{D_i | s^I}[\Pi^I_{\alpha}(K_i)] = -wK_i + r\mu_{\alpha} - w'L_{D_i | s^I}(K_i).$$

**Lemma 1.** The optimal regular production quantity maximizing each OEM’s own profit based on the signal $s^I_i$ is $K_i^* = \mu_{\alpha} + z_\alpha\sigma_{\alpha}$, where $z_\alpha = \Phi^{-1}(1 - w/w')$. This results in a total regular production quantity of $\sum_{i=1}^{M} (\mu_{\alpha} + z_\alpha\sigma_{\alpha})$ at the CM. The expected supply chain profit in Scenario I (obtained by taking the expectation over all possible signal realizations) is given by

$$E[\Pi^I_{\alpha}] = (r - c)\sum_{i=1}^{M} \mu_i$$

$$- \sum_{i=1}^{M} \sigma_{\alpha} (\phi(z_\alpha)c' + z_\alpha(c' - c'w/w')).$$

The last term in the supply chain profit expression is the opportunity cost because of double marginalization. It is possible to eliminate this cost by using a simple contract that charges the OEM the same percentage margin under the expedited production mode as under the regular production mode: $(w' - c')/c' = (w - c)/c$. 

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Proposition 1. The contracts \((w, w')\) defined such that \(w/c' = w/c\) eliminate double marginalization in Scenario I.

This variant of cost-plus contracts is used very commonly in the EMS industry (Keranen 2000). In these contracts, bilateral negotiations determine the percentage margin charged by the CM above her unit cost. These negotiations are influenced by the prevailing industry standard—in the EMS industry, the percentage margins are fixed around 5% (Investor's Business Daily 2002).

In the remainder of this paper, we examine the general case with double marginalization and comment on this special case where appropriate.

4.1.2. Scenario II: The CM Bears the Risk. In this scenario, the CM sets the regular production quantity, \(K\), after receiving signals for each of the end markets. As the markets are independent from each other, the signal for one market does not disclose any information about the rest. The total market demand is the sum of individual market demands, i.e., \(D = \sum_{i=1}^{M} D_i\).

After observing the signals, the overall demand distribution is \(F_{D|\tilde{s}_1, \ldots, \tilde{s}_M} = N(\mu_c, \sigma_c)\), where
\[
\mu_c = \sum_{i=1}^{M} \mu_{c_i} = \sum_{i=1}^{M} (\gamma_i \mu_i + \gamma_i \tilde{s}_i)
\]
and
\[
\sigma_c^2 = \sum_{i=1}^{M} \sigma_{c_i}^2 = \sum_{i=1}^{M} \sigma_i^2 + \sum_{i=1}^{M} (1 - \gamma_i) \sigma_i^2.
\]

Based on the posterior distribution \(F_{D|\tilde{s}_1, \ldots, \tilde{s}_M}\), the CM calculates her expected profit from choosing \(K\) to be
\[
E_{D|\tilde{s}_1, \ldots, \tilde{s}_M}[\Pi^U_c(K)] = -cK + \sum_{i=1}^{M} \mu_{c_i} - c' L_{D|\tilde{s}_1, \ldots, \tilde{s}_M}(K).
\]

Lemma 2. The regular production quantity maximizing the CM’s expected profit given signals \(\tilde{s}_1, \ldots, \tilde{s}_M\) is \(K^* = \mu_c + z_c \sigma_c\), where \(z_c = \Phi^{-1}(1 - c/c')\). The expected supply chain profit in Scenario II (obtained by taking the expectation over all possible signal realizations) is given by the following expression:
\[
E[\Pi^U_c] = (r - c) \sum_{i=1}^{M} \mu_{c_i} - c' \sigma_c \phi(z_c).
\]

4.2. CM or OEM Responsibility?

Let us assume that demand variances \((\sigma_i = \sigma)\) as well as the signal accuracy for each of the markets \((\sigma_{c_i} = \sigma_{c'}, \sigma_{e_i} = \sigma_{c'})\) are identical and define \(R\), a measure of how accurate the CM signals are relative to OEM signals as follows:
\[
R = \frac{1 - \gamma_c}{1 - \gamma_e} = \frac{\sigma_c^2}{\sigma_{c'}^2} + \frac{\sigma^2}{\sigma_{e'}^2} = \frac{\sigma_c^2}{\sigma_e^2}.
\]

Define \(\Delta \Pi_T\) as the expected profit differential between supply chain profits in Scenarios I and II as follows:
\[
\Delta \Pi_T = E[\Pi^U_{T1}] - E[\Pi^U_{T2}]
\]
\[
= c' \sigma_c M \phi(z_c) \left(\frac{\phi(z_c) + z_c (c/c' - w/w')}{\phi(z_c)} - \frac{\sqrt{R}}{\sqrt{M}}\right).
\]

\(\Delta \Pi_T > 0\) implies that CM responsibility is preferable because of its pooling advantage as well as the avoidance of double marginalization. Similarly, \(\Delta \Pi_T < 0\) implies that OEM responsibility is preferable because of his information advantage, despite the existence of double marginalization and his inability to pool demand. Proposition 2 compares the expected system profits under OEM and CM ownership of risk, and delineates under which conditions each one is preferable from the supply chain perspective.

Proposition 2. For a given set of economic parameters, both the OEM and the CM may be better able to minimize costs because of demand uncertainty, depending on the number of clients served and the accuracy of information at the CM. In particular, when OEMs are symmetric,

(i) Higher accuracy of OEM information \((R > R_1(M))\) favors OEM responsibility.

(ii) A larger base of clients \((R < R_1(M))\) favors CM responsibility.

The function \(R_1(M) = (\sqrt{z_c (c/c' - w/w') + \phi(z_c)})^2 M\) represents the relative forecast inaccuracy that can be tolerated at the CM, given its customer base. When \(R_1(M) < R\), CM inaccuracy dominates the pooling effect. Therefore Scenario I is preferable from the supply chain perspective. The reverse is true when \(R_1(M) > R\).

\(R_1(M)\) increases in \(M\): Larger scale makes higher CM inaccuracy tolerable. Furthermore, the slope of
R_{i}(M)$ depends on the relationship between cost structure and pricing. The largest OEM region is observed under a cost-plus contract with equal percentage margins for both production modes ($(w - c)/c = (w' - c')/c'$), since such a contract eliminates double marginalization observed in Scenario I. As the margins for the two production modes diverge, the OEM region shrinks. Note that the OEM and CM regions are not affected by the level of uncertainty or the magnitudes of costs and prices for fixed cost and price ratios.

To summarize, there is no unique place in the supply chain that is better fit for bearing the demand risks. Depending on operational flexibility, the extent of information deficiency at the CM, cost structure, and pricing, the OEM or CM may be better placed to bear the risk. Therefore it may be possible to improve supply chain profits by changing the location of decision making and risk bearing.

In the general case with nonidentical markets and signal errors, the optimal location of responsibility depends on the priors for each of the markets, as well as the signal errors for the OEMs and the CM. The accuracy differential for each specific market needs to be taken into account rather than one overall value. Therefore it is not possible to separate the OEM and CM responsibility regions with a simple curve based on the relative accuracy $R$ and the number of OEMs, $M$.

### 4.3. Sensitivity Analysis

In the previous subsection, we observed that the regions of responsibility are determined by $c/c'$ and $w/w'$, while uncertainty and magnitudes of costs and prices (for fixed $c/c'$, $w/w'$) do not have any effect. The magnitude of the loss resulting from the misallocation of responsibility, on the other hand, depends on uncertainty, and the scale of costs and prices, as well as the factors that delineate the regions.

**Effect of Uncertainty:** Misallocation of responsibility is more costly to the supply chain when uncertainty is high $\left(\frac{\partial \Delta \Pi_{T}}{\partial \sigma_{o}} > 0\right)$.

**Effect of Cost Structure:** Keeping the cost ratio, $c/c'$, constant, the cost of misallocation is increasing in production costs $\left(\frac{\partial \Delta \Pi_{T}}{\partial c'} > 0\right)$.

**Effect of Pricing:** The higher the difference between the ratio of prices paid by the OEM under expediting and regular production, $w/w'$, and the ratio of the associated costs, $c/c'$, the higher is the profit differential in favor of CM responsibility $\left(\frac{\partial \Delta \Pi_{T}}{\partial z_{o}} < 0\text{ if } z_{o} < z_{c}; \frac{\partial \Delta \Pi_{T}}{\partial z_{o}} > 0\text{ if } z_{o} > z_{c}\right)$. This is because of an increase in the double marginalization effect. As long as the ratio of prices is constant, the magnitudes of wholesale prices $w$ and $w'$ have no effect on the profit differential.

**Effect of Information Differential:** As the difference in information accuracy between the OEMs and CM becomes more pronounced (R increases), OEM ownership of responsibility becomes more desirable from the supply chain perspective $\left(\frac{\partial \Delta \Pi_{T}}{\partial R} < 0\right)$.

**Effect of Operational Flexibility:** As the number of OEMs served by the CM (therefore the operational flexibility of the CM) increases, supply chain profit differential per OEM increases as a result of better pooling $\left(\frac{\partial \Delta \Pi_{T}/M}{\partial M} > 0\right)$. However, when $\Delta \Pi_{T} < 0$, it is possible that the cost of misallocation increases even more when new customers are added $\left(\frac{\partial \Delta \Pi_{T}/M}{\partial M} > 0\right)$.

We now numerically demonstrate the magnitude of the loss of misallocation as a function of these factors. Table 1 tabulates $\left(\frac{\left|\Delta \Pi_{T}\right|}{\max(E[\Pi_{T}^{1}], E[\Pi_{T}^{2}])} \times 100\%ight)$, the percentage loss incurred because of the misallocation of responsibility. For two different parameter combinations, we examine the effects of pooling, information asymmetry, and double marginalization by tabulating the percentage loss as a function of $R$ and $M$, with and without double marginalization. The numbers marked with the $^*$ symbol are in the region where OEM responsibility is preferred $(R > R_{i}(M))$; otherwise, CM responsibility is optimal for the supply chain.

We observe that the percentage loss because of misallocation can be quite significant under reasonable parameter choices. As expected from the sensitivity discussion above, increasing cost parameters and demand variability both result in increased losses from misallocation. The larger is the difference between $(R, M)$ and $(R_{i}(M), M)$, the higher is the cost of misallocated. This cost is more pronounced when the responsibility is misallocated to the OEM, because not only pooling benefits are eliminated, but double marginalization is introduced as well.

### 5. Individual Profits

In §4, we considered the impact of the location of decision rights and risk on the total supply chain prof-
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\[
\text{Let } OSL\sigma_{oi}/w/c = \text{OSL\sigma}_{oi}/w/c \text{ denote the expected value in this range, and}
\]

Notes. Parameter sets (a) and (c) have no double marginalization, while (b) and (d) do.

\[
\begin{align*}
R & \quad 1 \quad 3 \quad 5 \quad 7 \quad 10 \\
(b) & \quad 0.7\% \quad 2.0\% \quad 2.4\% \quad 2.6\% \quad 2.8\% \\
1 & \quad 0.0\% \quad 1.3\% \quad 1.7\% \quad 1.9\% \quad 2.1\% \\
2 & \quad 1.3\%\ast \quad 0.6\% \quad 1.1\% \quad 1.4\% \quad 1.7\% \\
3 & \quad 2.3\%\ast \quad 0.0\% \quad 0.7\% \quad 1.1\% \quad 1.4\% \\
4 & \quad 3.1\%\ast \quad 0.5\%\ast \quad 0.3\% \quad 0.7\% \quad 1.1\% \\
5 & \quad 3.8\%\ast \quad 0.9\%\ast \quad 0.0\% \quad 0.5\% \quad 0.9\% \\
(c) & \quad 0.0\% \quad 11.6\% \quad 14.6\% \quad 16.1\% \quad 17.5\% \\
2 & \quad 12.8\%\ast \quad 5.4\% \quad 10.2\% \quad 12.6\% \quad 14.6\% \\
3 & \quad 22.6\%\ast \quad 0.0\% \quad 6.5\% \quad 9.6\% \quad 12.3\% \\
4 & \quad 30.9\%\ast \quad 4.8\%\ast \quad 3.2\% \quad 7.0\% \quad 10.2\% \\
5 & \quad 38.2\%\ast \quad 9.0\%* \quad 0.0\% \quad 4.6\% \quad 8.3\% \\
(d) & \quad 0.0\% \quad 11.6\% \quad 14.6\% \quad 16.1\% \quad 17.5\% \\
2 & \quad 12.8\%\ast \quad 5.4\% \quad 10.2\% \quad 12.6\% \quad 14.6\% \\
3 & \quad 22.6\%\ast \quad 0.0\% \quad 6.5\% \quad 9.6\% \quad 12.3\% \\
4 & \quad 30.9\%\ast \quad 4.8\%\ast \quad 3.2\% \quad 7.0\% \quad 10.2\% \\
5 & \quad 38.2\%\ast \quad 9.0\%* \quad 0.0\% \quad 4.6\% \quad 8.3\% \\
\end{align*}
\]

\[
\text{Let } \Pi^c_{oi} \text{ denote the profits the CM expects to make under Scenario I. As the CM’s revenues are affected}
\]

by the OEM’s forecast errors, we need to make an assumption on the CM’s belief concerning the OEM’s

accuracy to calculate $\Pi^c_{oi}$. We assume that the CM belief about the accuracy of the OEM forecast $\sigma^c_{oi}$

drawn from a distribution with a support on $[0, \sigma^c_{oi}]$; this is consistent with the modeling assumption

that the CM believes the OEM is at least as accurate as she is, but does not know the exact accuracy of the OEM.

Let $\hat{\sigma}^c_{oi}$ denote the expected value in this range, and $\hat{R} \doteq \sigma^c_{oi}/\hat{\sigma}^c_{oi}$ the CM’s belief about her informational

disadvantage. If $a \doteq \hat{R}/R > 1$ ($a < 1$), then the CM is pessimistic (optimistic) about her own forecasts, she

overestimates (underestimates) the accuracy of OEM forecasts.

**Proposition 3.** The following is true for individual profits of the OEM and CM:

(i) **OEM profits are higher under CM responsibility:** $E[\Pi^c_{oi}] < E[\Pi^c_{oi}]$.

(ii) **CM prefers Scenario I to II, i.e.,** $E[\Pi^c_{oi}] > E[\Pi^c_{oi}]$,

unless $(-\phi(z_0)(w' - c') - \sigma_{oi}(c - c'w'/w'))/c\phi(z_0) > \sqrt{R}/\sqrt{M}$.

(iii) **The CM under/overestimates her expected profit in Scenario I:** $E[\Pi^c_{oi}] < E[\Pi^c_{oi}]$.

OEMs prefer Scenario II under which the CM holds the responsibility. The reason is straightforward: In Scenario II, the OEM fills all the demand and avoids paying the extra charges related to high-demand realizations, whereas in the first scenario, he has to assume the cost of uncertainty.

The CM, for her part, prefers that the OEMs bear the demand risk by committing to capacity over a large portion of the parameter space. One reason for the CM’s unwillingness to take responsibility is the same as that for the OEM: the cost of uncertainty. However, the CM has a further disincentive. In Scenario I, the CM makes (even higher) profits when the OEM demand exceeds the initial commitment as the OEM makes an extra payment for every purchase above commitment. Therefore switching from Scenario I to II implies a loss in revenues for the CM. Bearing risk becomes even less attractive for the CM if she overestimates OEM inaccuracy. There also exists

| Table 1 Percentage Loss Incurred Because of the Misallocation of Responsibility ($\max(\mathbb{E}[\Pi_{II}], \mathbb{E}[\Pi_{I}]) \times 100\%$) |
|-----------------|-----------------|-----------------|
| $R$ | 1 | 3 | 5 | 7 | 10 |
| (a) | 0.0% | 1.3% | 1.7% | 1.9% | 2.1% |
| (b) | 0.7% | 2.0% | 2.4% | 2.6% | 2.8% |
| (c) | 0.0% | 11.6% | 14.6% | 16.1% | 17.5% |
| (d) | 2.9% | 14.1% | 17.1% | 18.6% | 19.8% |
a range of parameters where the CM prefers to be in charge, despite the associated risk. This happens when the cost arising from double marginalization is high, and informational disadvantage of the CM is low relative to her scale.

6. Risk Premiums

In this section, we investigate whether a per unit price premium can be used to induce the right party to bear the risk. For simplicity, we assume that the OEMs are identical.

We start our analysis by constructing thresholds beyond which the OEM and CM are willing to bear the risk. It was shown that \( E[\Pi_i^c] < E[\Pi_i^o] \); that is, the OEM would not want to operate under Scenario I (where he takes responsibility), but would prefer Scenario II to be in effect (where the CM takes responsibility). Let \( w^* > w \) be the wholesale price if the CM were to take responsibility, and define \( \delta = w^* - w \) as the risk premium. Equating the profits for OEM \( i \) under Scenarios I and II, one can find a wholesale price \( w^* \) and a corresponding premium \( \delta_o \) to make the OEM indifferent between bearing the risk or not. Solving \( E[\Pi_i^c(w)] = E[\Pi_i^o(w^*)] \) for \( w^* \) yields

\[
\delta_o = w^* \phi(z_o) \frac{\sigma_o}{\mu_i}. \tag{3}
\]

OEM \( i \) would prefer to keep the responsibility only if CM responsibility were coupled with a wholesale price premium of \( \delta > \delta_o \). Any premium over the threshold would make Scenario II prohibitively expensive for the OEM. A similar threshold can be found for the CM by equating the expected profit under Scenario I from the CM perspective to its expected profit under Scenario II as follows:

\[
\delta_c = \frac{\sigma_c \sqrt{R}}{\mu_i} \left( \frac{c' \phi(z_c) + w^* \phi(z_o) - z_o (c - c' w/w^*) + c' \phi(z_c)}{\sqrt{R}} \right). \tag{4}
\]

A premium \( \delta > \delta_c \) is sufficient to convince the CM to take the risk. Three regions are defined by the threshold pair \((\delta_c, \delta_o)\). In the first region, where \( \delta < \delta_{\text{min}} = \min(\delta_c, \delta_o) \), the premium is too low. Neither the OEM, nor the CM is willing to be responsible: The CM does not receive sufficient compensation to take the responsibility, whereas the OEM prefers CM responsibility, because her cost to the OEM is low. In the third region, where \( \delta \geq \delta_{\text{max}} = \max(\delta_c, \delta_o) \), both parties are willing to be responsible. The compensation for the CM is more than sufficient to induce it to take over the risk. However, the OEM prefers to bear the risk since the cost of not doing so is too high. Finally, in the intermediate region, \( \delta_{\text{min}} < \delta < \delta_{\text{max}} \), both parties prefer the party with the lower of the thresholds to be responsible.

Recall that the regions of responsibility are defined by the line \( R_1(M) \): The supply chain profits are higher when the capacity decision is taken by the OEM (CM) above (below) this line. For ease of exposition, define the following:

\[
g = c' \phi(z_c); \quad k = w' \phi(z_o); \quad l = z_o (c - c' w/w^*) + c' \phi(z_c).
\]

Given these, we can rewrite the condition that separates the OEM and CM responsibility regions as \( R_1(M) = (l/g) M \). It is also possible to obtain a line \( \{ (R, M) | \delta_o = \delta_c \} \) that separates regions where one of the parties has a lower premium threshold, therefore is convinced first

\[
R_2(M) = \left( \frac{k - (k - 1)/\sqrt{R}}{g} \right)^2 M.
\]

Below this curve, \( \delta_c < \delta_o \), and there exists a range of \( \delta \) values for which CM responsibility is preferred by both parties. \( \delta_i > \delta_o \) above the curve and there exists a range of \( \delta \) values for which OEM responsibility is preferred by both parties.

Figure 1 illustrates when premiums are useful in improving the profits for the supply chain and the

![Figure 1](image-url)
parties involved for the case, where \( R_2(M) < R_1(M) \); a complete tabulation of possible results is given in Table 2. OEM responsibility is optimal for the supply chain and OEM risk ownership is preferred by both parties for any \( \delta \in (\delta_o, \delta_c) \) in region PO. Similarly, CM responsibility leads to higher supply chain profits and any \( \delta \in (\delta_o, \delta_c) \) leads to CM responsibility in region PC. However, there also exists a region where the use of premiums is ineffective: In region IP-NE, the premium induces one party to bear the risk, but it is the wrong party because of the CM’s imperfect information regarding OEM’s accuracy. When the CM underestimates OEM accuracy, she overestimates her own profits in Scenario I, and therefore requires a higher premium for operating in Scenario II. As a result, there exists a premium under which both parties prefer OEM responsibility, even though the OEM is not the right party. Conversely, the CM may overestimate OEM accuracy, and therefore underestimate her own Scenario I profit. In this case, she is willing to accept taking risk in exchange for a premium that would not be acceptable under more accurate information.

Is the loss significant in regions IP-NE? Table 3 shows the maximum percentage profit loss possible in the presence of premiums for a set of model parameters. For any \( M \), the highest loss is experienced at \((M, R_2(M))\): this is the farthest point from \( R_1 \) for given \( M \) inside the wedge defined by \( R_1 \) and \( R_2 \). \((M, R)\) combinations within the wedge closer to \( R_1 \) result in a lower loss, and loss is zero on \( R_1 \). The figure suggests that the maximum loss is highest when the CM margin, the level of uncertainty, and the cost of capacity are high and there is double marginalization. However, overall, the maximum loss in IP-NE is not significant. We conclude that premiums are largely effective in aligning individual pref-

### Table 2  Conditions Under Which the Regions PO, PC, and IP-NE Arise Depending on Various Parameters

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### Table 3  Maximum Percentage Expected Loss for a Set of Model Parameters (\( c'/c = 1.1; \mu = 100; \tau = 100 \))

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<th>( a )</th>
<th>( \sigma )</th>
<th>( c )</th>
<th>( w )</th>
<th>( w'/w )</th>
<th>Max. % Loss</th>
<th>( a )</th>
<th>( \sigma )</th>
<th>( c )</th>
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<th>Max. % Loss</th>
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Ülkü, Toktay, and Yücesan: Risk Ownership in Contract Manufacturing
erences with the supply chain optimal assignment of responsibility.

7. Both CM and OEM Bear the Risk
In this section, we allow both the OEM and the CM to bear risk. When the OEMs commit to purchasing quantity $\sum_{i=1}^{M} K_i$, demand risks faced by the CM are effectively eliminated. Nevertheless, the CM may prefer to deviate from this commitment to improve its profits. Let us call this Scenario III.

We start by assuming that the productive resource is not delivered to the OEM unless there is demand for it, a reasonable assumption when unused resource is worthless for the OEM at the end of the period. This is valid, for instance, for capacity and material with no salvage value. Given this assumption, the CM can reallocate unused resource to customers with high demand. At the end of the section, we discuss the effect of relaxing this assumption.

**Lemma 3.** The optimal regular capacity maximizing each OEM's own profit based on the signal $s_i^{c}$ is $K_i^{e} = \mu_i + z_c\sigma_i$. The total capacity built at the CM is $K_c^{e} = \mu_c + z_c\sigma_c$. The expected supply chain profit in Scenario III is given by

$$E[\Pi_{T}^{III}] = (r - c) \sum_{i=1}^{M} \mu_i - c'\sigma_i\phi(z_c). \quad (5)$$

**Proposition 4.** Let $\Pi_{c}^{III}$ denote the profit the CM expects to make in Scenario III. The following is true for OEM, CM, and supply chain profits:

(i) $E[\Pi_{c}^{II}] < E[\Pi_{c}^{III}]$ when $\sqrt{R/M} < R_3(M) = ((z_c(c/c' - \frac{w}{w'}) + \phi(z_c))\phi(z_c)\sqrt{\sigma}M $.

(ii) The supply chain is indifferent between Scenarios II and III for any $R, M$.

(iii) The OEM is indifferent between Scenarios I and III for any $R, M$.

(iv) CM profits are always higher in III compared to II: $E[\Pi_{c}^{II}] < E[\Pi_{c}^{III}]$.

It follows from the first part of Proposition 4 that the CM does not deviate from OEM commitments unless she has a sufficiently large number of customers to offset her information disadvantage. Otherwise, her profit is lower in expectation. In other words, no decision may be the best decision in some cases. Note that this threshold is equal to $R_3(M)$ divided by $\sqrt{\sigma}$ if the CM feels that her forecasts are much worse than those of the OEM, she is less likely to deviate from firm OEM orders.

From the supply chain perspective, Scenarios II and III are equivalent. The CM makes her own capacity decision to maximize her own profits, while still fulfilling OEM demand up to the preordered capacity $K_i$ at regular price $w$. Thus it is the CM who ultimately determines supply chain profits in Scenario III. Since the information sets and economic parameters $(c/c')$ are the same in Scenarios II and III, capacity choice and supply chain profits are also identical. On the other hand, from the OEM perspective, Scenarios I and III are equivalent, because his profits are not affected. Finally, the CM always prefers Scenario III to II. While the CM makes a decision and faces a risk under both scenarios, she is guaranteed a certain revenue under Scenario III.

Table 4 illustrates how the results regarding premiums change with the inclusion of CM ability to deviate from commitments. We see that premiums are still helpful; the regions PO, PC, and IP-NE continue to exist even if the CM can deviate from OEM commitments.

Two new regions emerge. In the first region, $S$, provision of premiums is unnecessary: optimal supply chain profits are achieved regardless of the final agreement between the OEM and the CM. In this region, the OEM prefers Scenario II, the CM prefers Scenario III, and there is no possibility of improving one party's profit without hurting the other. In the second one, IP-CD, CM deviation makes it impossible to reach the supply chain optimal solution. In this region, OEM responsibility is preferable for the supply chain, and there exists a range of premiums at which the OEM would be willing to bear the responsibility. However, the CM is overconfident in her own accuracy ($a < 1$), and therefore prefers to deviate from OEM commitments.

We started with the assumption that the productive resource is not delivered to the OEM unless there is demand for it, and therefore the excess can be reallocated to OEMs in need. When physical delivery is required, the incentive for deviating from the commitment is weaker: the CM can only deviate upward from the commitment, and cannot reallocate the unused portion of the productive resource for another customer. Deviation occurs in a smaller
Table 4  When the CM Is Allowed to Deviate from OEM Commitments, $PC$, $PO$, $IP-NE$ Continue to Exist

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<th>III</th>
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Notes. There are regions where there is no need for premiums $S$, and where CM deviation makes it impossible to achieve supply chain optimal $IP-CD$.

region than that specified by the first part of Proposition 4. From the perspective of the OEM, Scenarios I and III are still identical. On the other hand, parts (ii) and (iv) of Proposition 4 are not true anymore: The supply chain profits differ in Scenarios II and III, and the CM may prefer Scenario II to III in certain cases.

8. Robustness of Results to Model Assumptions

The previous analysis makes several simplifying assumptions about the supply chain structure. In this section, we investigate the robustness of our results to these assumptions.

Nature of productive resources. Recall that we defined $M$ as the number of OEMs that use the same productive resource. If the production process or material under consideration is specific to each OEM, then $M = 1$; whereas $M > 1$ for flexible production capacity and generic material. We implicitly model cases where the productive resource at the CM is perfectly flexible and can be used for all customers when $M > 1$. If there is a cost of switching between different customers and products, then models from the transshipment literature that assign costs to transferring material between facilities can be used. The existence of such costs favors the scenario where the OEMs bear the risk.

Risk neutrality. In this paper, we consider operational risk, the expected cost of uncertainty that results from over- or underinvestment, rather than financial risk, commonly represented in the finance literature as the variance in returns.

The basic trade-off between information and pooling does not change with the inclusion of financial risk. A risk-averse decision maker would order a smaller quantity than a risk-neutral one because of the disutility of variance in profits (Eeckhoudt et al. 1995). Assume that utility is separable in the expectation and variance of utility (Chen and Federgruen 2000). Pooling at the CM decreases variability, and therefore reduces the disutility because of variance. As the number of OEMs served increases, the initial capacity built by the CM gets closer to the risk-neutral optimum. On the other hand, information asymmetry works in the opposite direction, distancing the CM capacity from the risk-neutral supply chain optimal.

The CM and OEM differ in salvage values. In this paper, salvage values at the OEM and CM are normalized to zero. However, the OEM and CM may have access to different markets, creating a salvage value differential. If the OEM (CM) were in a better position to use excess capacity, then the region of responsibility for the OEM (CM) would expand.

Estimating $R$ in practice. The aim of this paper is to investigate the impact of the location of decision making and of risk bearing on the total cost of uncertainty. The perspective is that of an omniscient observer. We show that there is no single answer that is valid for all supply chains. To measure the relative accuracies of the two parties, historical forecast accuracies could be used. A third party could examine the internal forecasts of the parties for specific product lines to develop this measure. However, the manner in which
the location that will bear the risk might be determined in practice is not straightforward. Even though it may be possible to measure the accuracies of the OEM and CM when there is no impact on the two firms (as in the case of a benchmarking study), the two parties may not be willing to share this information with a third party when decision making is involved.

**Correlated demand.** The profit differential $\Delta \Pi_f$ would decrease (increase) with positive (negative) demand correlation, leading to the contraction (expansion) of the CM responsibility region. Results would stay the same qualitatively.

9. Conclusions

As discussed in §1, this research was motivated by the desire to reconcile two conflicting points of view brought up by industrial participants during the Supply Chain Forum on Contract Manufacturing organized at INSEAD. Both OEMs and CMs were reticent to bear the risk arising from demand uncertainty. Some consultants and OEM managers claimed that contract manufacturers should bear the costs of demand uncertainty because they are better able to manage this uncertainty by pooling resources across several customers. CMs claimed that OEMs are better able to manage demand uncertainty because they are better informed about end-customer demand.

To address this issue, we compared individual and supply chain profits under two scenarios that assign all uncertainty-related costs to the party that makes the initial capacity decision. In the first scenario, the decision responsibility and the resulting risks are assumed by the OEMs; in particular, OEMs commit to a purchase quantity before demand realization and are responsible for any expediting costs above this quantity. In the second scenario, the decision responsibility and the resulting risks are assumed by the CM: The CM builds a certain level of resource before the realization of the demand and is responsible for any expediting costs. Finally, we also considered the possibility that both the OEM and CM may take a certain level of risk. The managerial insights generated by our analysis are discussed below.

There is no unique place to assume risk in the supply chain. From a supply chain point of view, there is no unique location where it is always better to assume risks. A larger pool of customers favors CM responsibility because of operational flexibility. However, if the OEMs are much better informed about future demand, then the OEM ownership is preferable. The higher is the impact of double marginalization, the higher is the information advantage that justifies OEM responsibility. When individual profits are considered, though, the parties are unwilling to take responsibility.

It may be preferable for an OEM, rather than the CM, to own generic resources. If the CM does not have a sufficiently good understanding of end demand, it is preferable for the OEM to bear the risks. This is so even if the resource under consideration is a generic one, and despite the ability of the CM to pool demand.

The supply chain may benefit from the separation of risk ownership and production capability. One of the primary drivers of outsourcing is the transfer of risks to a third party, and risk ownership is usually bundled with the manufacturing service from a CM. We find that bundling of production capability and risk ownership is beneficial for the parties only when the CM has sufficiently good information about demand in the end markets.

**How important is the correct allocation of responsibility?** The cost associated with the misallocation of decision rights is especially high in volatile markets with a high cost of acquiring the productive resources. The presence of double marginalization and a large gap between informational difference and pooling efficiency further raise the importance of correct allocation.

The best decision for the CM may be no decision. Even when the CM has the opportunity to make a capacity decision, there are instances where she prefers not to exercise it. When the CM perceives that she has low visibility of the end market, she prefers to rely on the committed orders by the OEM, rather than take her own decisions.

Simple cost-plus contracts eliminate double marginalization. Two sources of inefficiency are considered in this paper: double marginalization and information asymmetry. We show that simple cost-plus contracts with equal percentage margins for regular and expedited production eliminate one of these sources, double marginalization. This partly explains why such simple contracts are prevalent in practice.
By not negotiating on risk, parties leave money on the table. Our interviews indicate that negotiations between contract manufacturers and OEMs are based on price; the location of risk bearing is not a dimension of the negotiation process. In many cases, profits can be increased for all by shifting the location of risk bearing in conjunction with premiums or discounts. We provide a simple solution to the conflict between the suppliers and OEMs, who would both prefer to avoid the responsibility.

Premiums are largely effective. With a premium-based scheme, it is always possible to determine a range of premiums for which one party is willing to take the responsibility and the other is willing to yield it. However, because of information asymmetry, for some supply chain configurations, the party who takes responsibility is not necessarily the one under which supply chain profit is maximized. Nevertheless, we find that premiums are effective when inefficiency because of misallocation is high. When alignment through premiums is not possible, the loss is usually insignificant. We conclude that premium-based schemes are largely effective, even in the presence of information asymmetry.

This series of insights provides a better understanding of certain industry practices and OEM-CM arrangements, which are discussed next.

Various arrangements between OEMs and CMs are observed in practice regarding risk ownership. For example, in assembling Apple’s computers, Solectron has the responsibility to purchase materials and performs assembly in accordance with Apple’s forecasts. On the other hand, the OEMs ship the components to the Flextronics plant in Mexico that assembles photocopy machines.

While there may be other practical reasons for this difference, our model provides one possible explanation for it. In the case of Solectron, the product in question is a computer. Because it is a high-volume consumer product, sales data is readily available, which may reduce the information asymmetry between the CM and OEM. In addition, many of the components can be used in other products. Therefore our model would recommend that the contract manufacturer own the components. On the other hand, a photocopier is a more idiosyncratic product and for parties other than the OEM, it is harder to forecast the market demand. Thus the information gap between the OEM and CM is presumably larger. In addition, the components used in photocopiers are more specific and can be used in few other products. Therefore, one can expect the OEM to be responsible for the components that are used in this product.

It is possible for CMs to produce generic white box products, which are then sold under a different brand—that of a store chain, mobile operator, or another OEM. Some OEMs write contracts disallowing this practice because of the competition it creates on the end-product market, while others allow it (EBN 2002). Our model explains why some OEMs may choose to allow this practice as follows: White box production increases the alternative uses of CM resources, thereby increasing their salvage value. This makes the supply chain more efficient and allows the transfer of risk to the CM at a lower price.

Our interviews with industry experts suggested that even in the presence of information asymmetry regarding demand, a premium-based scheme can be implemented. With nonidentical forecasts, it is hard to attach a dollar value to risk and agree on it. Nevertheless, each firm can determine the price threshold at which it would still be willing to take the risk based on its own information. Transaction prices would then be determined through a negotiation process. When the CM resources allocated to the OEM are small, it is easier for the CM to accept bearing risk, but when the OEM is one of the CM’s few customers, or the resource is OEM specific, then the risk premium needs to be higher.

Our results suggest that when demand correlation among the CM’s customers is high, CM responsibility is not desirable. For example, the telecommunications supply chain, where CM responsibility grew significantly leading up to the 2001 downturn, was saddled with significant levels of excess capacity and inventory (BusinessWeek 2001), which may not have been the case if the OEMs had borne part or all of that risk.

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Therefore, the expected total supply chain profit is
\[ E[\Pi_1] = (r - c) \sum_{i=1}^{M} \mu_i - \sum_{i=1}^{M} \sigma_i (\phi(z_o)c' + z_o(c - c'w/w')) . \]  

\[ \Delta \Pi_1 = E[\Pi_1^1] - E[\Pi_1^2] \]

\[ = \sum_{i=1}^{M} \sigma_i (\phi(z_o)c' + z_o(c - c'w/w')) - c'\sigma_c \phi(z_o) . \]

Therefore, \( \Delta \Pi_1 \) is preferable when \( \Delta \Pi_1 < 0 \).

\[ \Delta \Pi_1 = \sum_{i=1}^{M} \sigma_i (\phi(z_o)c' + z_o(c - c'w/w')) - c'\sigma_c \phi(z_o) < 0 \]

\[ \frac{\phi(z_o)c' + z_o(c - c'w/w'))}{c'\phi(z_o)} < \frac{\sigma_c}{\sum_{i=1}^{M} \sigma_i} . \]
With identical OEMs,
\[ \frac{\sigma}{\sum_{i=1}^{M} \sigma_{i}} = \frac{\sqrt{RM\sigma_{i}}}{M\sigma_{i}}, \text{ where } R = \frac{\sigma^{2}}{\sigma_{i}}. \]

Therefore OEM responsibility is preferable when
\[ R_{1}(M) = M \left( \frac{\phi(z_{c})c' + z_{c}(c - c'w/w')}{{c'}^{2}} \right)^{2} < R. \]

**Proof of Proposition 3.**
(i) From the proofs of Lemmas 1 and 2, we have the expected OEM profit under each scenario: \( E[\Pi_{i}^{1}] = (r - w)\mu_{i} - w\sigma_{i}\phi(z_{c}) \) and \( E[\Pi_{i}^{II}^{}} = (r - w)\mu_{i}. \) Therefore
\[ \Delta \Pi_{i} = E[\Pi_{i}^{1}] - E[\Pi_{i}^{II}^{}} = -w\sigma_{i}\phi(z_{c}) < 0. \]

(ii) From the proofs of Lemmas 1 and 2, we have the expected CM profit under each scenario as follows:
\[ E[\Pi_{i}^{I}^{}] = (w - c)\sum_{i=1}^{M} \mu_{i} + (\phi(z_{c}))(w' - c' - z_{c}(c - c'w/w')) \sum_{i=1}^{M} \sigma_{i}, \]
\[ E[\Pi_{i}^{II}^{}] = (w - c)\sum_{i=1}^{M} \mu_{i} - c'\sigma_{i}\phi(z_{c}). \]

When the first term is negative, \( \Delta \Pi_{i}^{I} < 0. \) If it is positive, then \( \Delta \Pi_{i}^{I} > 0 \) if
\[ \frac{-\phi(z_{c})(w' - c' - z_{c}(c - c'w/w'))}{c'\phi(z_{c})} > \frac{\sigma_{c}}{\sum_{i=1}^{M} \sigma_{i}} = \frac{\sqrt{R}}{\sqrt{M}}. \]

(iii) In calculating the expected Scenario I from the CM perspective, we need to take the expectation over the CM’s belief concerning the OEM’s profit, \( \sigma_{c}. \) Since expected profit is linear in \( \sigma_{c}, \) the perceived expected profit can be written in terms of the CM’s point estimate of OEM accuracy, which is \( \tilde{\sigma}_{c}. \)
\[ E[\Pi_{i}^{III}] = (w - c)\sum_{i=1}^{M} \mu_{i} + (\phi(z_{c}))(w' - c')\tilde{\sigma}_{c} \text{ and } E[\Pi_{i}^{III}] = (w - c)\sum_{i=1}^{M} \mu_{i} + (w' - c')\phi(z_{c})\sum_{i=1}^{M} \sigma_{i}. \]

Therefore
\[ E[\Pi_{i}^{III}] - E[\Pi_{i}^{III}] = (w' - c')(\sum_{i=1}^{M} \tilde{\sigma}_{c} - \sigma_{c}) \leq 0. \]

**Proof of Lemma 3.** From the OEM’s perspective, Scenario III is identical to I in information sets and the economic parameters. Therefore the capacity chosen by the OEM and the resulting profit remain the same as well as follows:
\[ K_{i}^{*} = \mu_{i} + z_{c}\sigma_{i}, \]
\[ E[\Pi_{i}^{III}](K_{i}^{*})] = \mu_{i}(r - w) - w\sigma_{i}\phi(z_{c}). \]

The CM profit in Scenario III is given by
\[ \Pi_{c}^{III}(K_{c}, D) = \sum_{i=1}^{M} (wK_{i}^{*} + w(D_{i} - K_{i}^{*})) - cK_{c} - c'(D - K_{c})^{+}. \]

Revenue is independent of capacity choice, therefore the CM sets capacity to minimize expected cost, \( K_{c} = \mu_{c} + z_{c}\sigma_{c}, \) which is equal to that in Scenario II. Therefore the supply chain profit in Scenario III is also the same as that in II as follows:
\[ E[\Pi_{c}^{III}] = (r - c)\sum_{i=1}^{M} \mu_{i} - c'\sigma_{c}\phi(z_{c}). \]

**Proof of Proposition 4.**
(i) CM’s expected profits in Scenarios I and III, respectively, are
\[ E[\Pi_{c}^{II}^{}] = (w - c)\sum_{i=1}^{M} \mu_{i} + (\phi(z_{c}))(w' - c' - z_{c}(c - c'w/w')) \sum_{i=1}^{M} \tilde{\sigma}_{c}, \]
\[ E[\Pi_{c}^{III}] = (w - c)\sum_{i=1}^{M} \mu_{i} + (w' + w) \sum_{i=1}^{M} \phi(z_{c})\tilde{\sigma}_{c} - c'\phi(z_{c})\sigma_{c}. \]

Therefore, \( \Pi_{c}^{III} > E[\Pi_{c}^{II}] \)
\[ w' \sum_{i=1}^{M} \phi(z_{c})\tilde{\sigma}_{c} - c'\phi(z_{c})\sigma_{c} > (\phi(z_{c})(w' - c') - z_{c}(c - c'w/w')) \sum_{i=1}^{M} \tilde{\sigma}_{c}, \]
\[ c'\phi(z_{c})\sigma_{c} < (\phi(z_{c})c' + z_{c}(c - c'w/w')) \sum_{i=1}^{M} \tilde{\sigma}_{c}. \]

Assume that all OEMs are identical. With \( \sqrt{R} = \sigma_{c}/\tilde{\sigma}_{c} \) and \( a = R/\sqrt{R}, \)
\[ \frac{\sqrt{M}\sigma_{i}}{\sqrt{R}} = \frac{\sqrt{M}}{\sqrt{R}} \frac{\sqrt{R}}{\sqrt{M}} = \frac{\sqrt{M}}{\sqrt{M}} < \frac{\sqrt{\sqrt{R}}}{\sqrt{M}}, \]
\[ \frac{\sigma_{c}}{\sum_{i=1}^{M} \tilde{\sigma}_{c}} < \frac{\phi(z_{c}) + z_{c}(c/c' - c'w/w')}{\phi(z_{c})}. \]

(ii) From Lemmas 2 and 3, it follows that \( E[\Pi_{c}^{II}] = E[\Pi_{c}^{III}] \). Therefore Scenarios II and III are equally desirable when \( R_{1}(M) > R \).

(iii) From Lemmas 1 and 3, \( E[\Pi_{i}^{III}] = E[\Pi_{i}^{III}] = (r - w)\mu_{i} - w\sigma_{i}\phi(z_{c}). \)

(iv) \[ E[\Pi_{i}^{III}] = (w - c)\sum_{i=1}^{M} \mu_{i} + (\phi(z_{c}))(w' - c' - z_{c}(c - c'w/w')) \sum_{i=1}^{M} \sigma_{i}, \]
\[ E[\Pi_{i}^{III}] = (w - c)\sum_{i=1}^{M} \mu_{i} - c'\sigma_{i}\phi(z_{c}). \]

Therefore the CM always prefers Scenario III to II. □
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