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Horizontal Capacity Coordination for Risk Management and Flexibility: Pay Ex Ante or Commit a Fraction of Ex Post Demand?

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Motivated by the dual-sourcing and contracting practices in the semiconductor industry, we study two prevailing types of contracts that deal with horizontal-capacity-coordination issues between two possible sources: an integrated device manufacturer (IDM) and a foundry. IDMs both design and manufacture semiconductor devices, whereas foundries concentrate only on manufacturing. Because production capacity is capital intensive, IDMs often make decisions on whether to manufacture each device internally or subcontract to foundries. Two types of contracts are most frequently used in such settings. Under α-contracts, a fixed fraction α of ex post realized demand is committed to subcontract to the foundry and serves as an incentive for the foundry to build capacity. Under reservation contracts, an ex ante capacity reservation fee is paid to the foundry as an incentive to build capacity. Because of the different nature of incentives under these contracts, it is unclear which type of contract maximizes the IDM's expected profit. Furthermore, IDMs and their customers often prefer dual sourcing to sole sourcing for risk-management purposes. This paper studies the relationship between the two types of contracts, both with and without dual-sourcing constraints and shows the effect of a dual-sourcing preference on contract selection. Our analysis offers supporting rationale for the coexistence of α-contracts and reservation contracts in practice and provides insights on horizontal capacity coordination beyond the semiconductor industry.

Key words: capacity planning and investment; incentives and contracting; risk management; supply chain management
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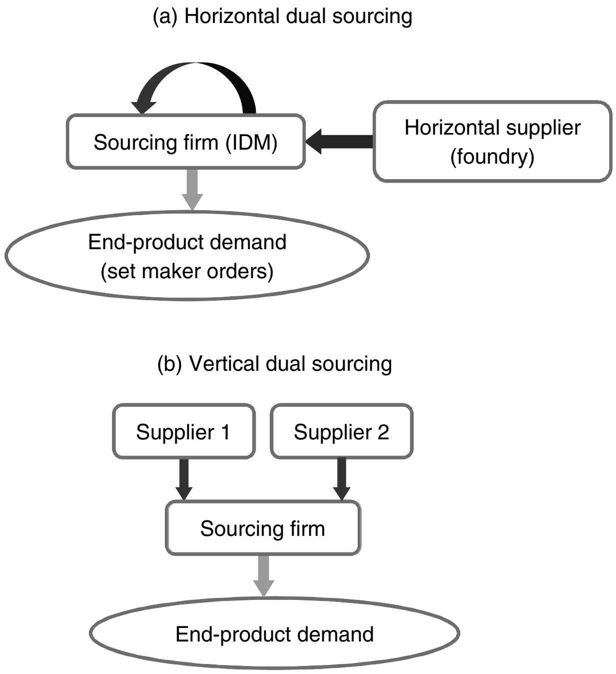
1. Introduction

In this paper, we deal with a special type of dual sourcing, which we refer to as *horizontal dual sourcing*. Even though we are mostly motivated by capacity sourcing, it can apply equally well to standard component sourcing. In our horizontal-dual-sourcing environment, the firm responds to end-product demand using two possible sources. The firm potentially sources the end product (or capacity) from another firm (supplier) not competing in the end-product market while at the same time the sourcing firm has the capabilities to meet a portion of the end demand if desired and appropriate investments have been made in advance. The fundamental challenge in this setting is how to coordinate the needed investments, in capacity or inventories, between the firm and its horizontal supplier to ensure the firm's profitability and risk-management concerns. Dual sourcing, as compared with sole sourcing, increases the resilience of the sourcing firm to disruptions resulting from natural disasters, terrorism, large-scale fires, supplier quality, or default occurrence. For the purposes of our paper, risk concerns are alleviated when nonzero capacity (inventory) investments are made from both the firm and its supplier (viable dual-sourcing structure).

The more traditional vertical dual sourcing involves the firm that serves end-product demand sourcing a subset of the needed components and materials from two suppliers. In this case, typically the sourcing firm does not have the internal capabilities or intention to invest in capacity for producing these components. Figure 1 shows a representative depiction and contrast of the "horizontal" and "vertical" dual sourcing.

This paper is an outgrowth of our research project with an integrated device manufacturer (IDM) in

Figure 1 **Horizontal Dual Sourcing vs. Traditional Vertical Dual Sourcing**



the semiconductor industry. IDMs both design and manufacture semiconductor devices. Foundries, on the other hand, concentrate on manufacturing such devices and obtain their orders from both fabless firms and IDMs. IDMs and foundries are in a horizontal relationship, with only IDMs having access to the end market (Figure 1(a)). In 2009, IDMs such as Texas Instruments, Freescale Semiconductor, STMicroelectronics, and Renesas Electronics were estimated to outsource 55%, 23%, 20%, and 10%–20%, respectively, of their production to foundries (IC Insights 2011). We expect horizontal dual sourcing to continue to be an important industry trend for reasons exposed below.

Semiconductor manufacturing capacity is both capital and technology intensive, with capacity investment a risky proposition due to the demand uncertainty and short technology and product life cycles. Because of the significant capacity installation time, capacity is committed well before the actual demand is realized. Conservative capacity investment with high capacity utilization is necessary to sustain profitable operations. Thus, IDMs facing frequent such capacity outlays often follow a mixed-capacity expansion strategy: build some of their own manufacturing capacities and then subcontract the remaining requirements to foundries. In this case, dual sourcing is arranged voluntarily by the IDM to share the capacity investment risk with the foundry, secure extra capacity, and increase the flexibility in response to demand surge.

On the other hand, dual sourcing is sometimes a requirement for an IDM that is imposed by the IDM's customers, which are themselves established companies, often referred to as *set makers* that produce automobiles, household electronics products, cellular phones, and so on. In most cases, risk management is the motivating rationale for such imposed requirements. For example, as a consequence of the strong and extensive earthquake in east Japan on March 11, 2011, a Renesas Electronics' plant was damaged, and its production was shut off until the end of May 2011. This plant supplies microcontroller units (MCUs) to Toyota, with some of these MCUs solely sourced from it. Toyota's production and entire global supply chain were affected considerably. Some critical MCUs for automobiles are categorized as application-specific standard products. Although they are part of standard catalogues, the MCUs require both extensive embedded programming and fine tuning of parameters specific to the device design and its use. Therefore, it is difficult for Toyota to adopt MCUs with similar specification from other firms as substitutes. It also takes considerable time and resources for any semiconductor company to convert a specific product design into a stable process recipe for a specific plant and ramp up production in it. Toyota sole sourced in the past the MCUs from the Renesas Plant. After the earthquake, and in response to Toyota requests, Renesas Electronics announced in June 2011 that it became feasible to second source the MCUs at two of their other plants and from a foundry, GlobalFoundries, and that it would be able to source 50% from the second sources and 50% from its recovered plant by October 2011 (Nikkei Electronics 2011).

In this paper, we study contractual issues in horizontal-dual-sourcing settings. More specifically, we investigate how a sourcing manufacturer (e.g., an IDM) should structure the second sourcing contract, that is, decide the type of contract and the values of contract parameters, with a supplier (e.g., a foundry) in the horizontal-dual-sourcing context. Under this context, we focus on two representative contracts in the semiconductor industry and analyze how the sourcing structure (sole versus dual) affects contract selection.

The two contracts we study are the ones most frequently used for horizontal capacity coordination in the semiconductor industry. There are fixed commitment contracts, which we call α-contracts, and capacity reservation contracts. Under α-contracts, the IDM guarantees ex ante to the foundry a fixed fraction α of realized demand for $0 \leq \alpha \leq 1$, which provides an incentive for the foundry to commit a certain amount of capacity. To the best of our knowledge, these contracts have not been studied in prior literature. We denote the α-contract with $\alpha = x$ as $\alpha(x)$-contract. In an extreme case, an $\alpha(0)$-contract corresponds to the case where only the demand exceeding the IDM's capacity is ordered to the foundry, and thus we refer to it as an *overflow contract*. In another extreme case, an $\alpha(1)$-contract corresponds to the case where the demand is first assigned to the foundry up to her capacity and then the leftover is assigned to the IDM, and thus we refer to it as a *foundry first contract*. Note that both extreme α-contracts can lead to either dual sourcing or sole sourcing.

Under reservation contracts, the IDM pays a reservation fee for each unit of capacity he reserves from the foundry and then pays a subcontract price per unit when the devices are produced. Capacity reservation contracts have been studied in vertical-sourcing situations (e.g., Erkoc and Wu 2005, Jin and Wu 2007) but have not been studied in the horizontal-dual-sourcing context. The reservation contracts may also lead to dual sourcing or sole souring.

Since the IDM has access to the market demand, he is the first mover who proposes either an α-contract or a reservation contract, whichever maximizes his expected profit. Comparing α-contracts with reservation contracts, it is unclear whether committing a fraction of ex post demand or paying an ex ante reservation fee is more effective as an incentive for the foundry to build capacity. Motivated by such issues, we address the following questions: What contract will be proposed by the IDM and implemented in equilibrium when firms are purely focused on profit maximization? How do firms' risk-management considerations (modeled as a dual-sourcing constraint) affect the contract selection? How do α-contracts and reservation contracts perform in terms of system coordination, both with and without a dual-sourcing constraint?

The rest of this paper is organized as follows. In §2, we review the literature. In §3, we discuss assumptions, notation, and the decision sequence protocol. In §4, we study α- and reservation contracts and derive the equilibrium contract that will be implemented by the firms. In §5, we look into the contract selection problem with a dual-sourcing constraint. In §6, we conclude with a summary of our main results and contributions.

2. Literature Review

There are three streams of literature related to our paper: supply chain contracting with reservation and commitment contracts, capacity expansion, and sourcing strategies. The two types of contracts studied in our paper, α-contract and reservation contract, relate to the commitment and the option/reservation contracts of the supply chain contracting literature. Reservation contracts can be categorized into two groups based on the buyer's motivation for reserving capacity: (1) to reduce cost and (2) to ensure supply. An excellent survey of the reservation contracts literature is Wu et al. (2005). Our work falls into the second category and is closely related to Erkoc and Wu (2005) and Jin and Wu (2007). Erkoc and Wu (2005) study capacity expansion via reservation contracts with a deductible reservation fee in the high-tech industry. They study supply chain coordinating reservation contracts and the effects of capacity cost, market size, and demand variability on the contract parameters. A major difference between our work and theirs is that the IDM (buyer in their paper) not only decides on how much capacity to reserve from the foundry (supplier in their paper) but also decides on how much of his own capacity to establish. Furthermore, our focus is on better understanding the rationale of using a particular type of contract under various scenarios, the associated contract parameters, and capacity decisions. Jin and Wu (2007) extend the model in Erkoc and Wu (2005) from one buyer to two or more buyers. Özer and Wei (2006) study a nonlinear capacity reservation contract as a strategic mechanism to achieve truthful information sharing between a supplier and a manufacturer. They also consider special linear capacity reservation contracts that can coordinate the supply chain under symmetric forecast information. In contrast to our paper, the manufacturer does not have in-house capacity and has to rely solely on the supplier's capacity.

In the supply chain contracting literature, the quantity commitment contract is closely related to an α-contract (e.g., see Tsay 1999, Tsay and Lovejoy 1999, Bassok and Anupindi 2008). Bassok and Anupindi (2008) investigate a buyer's optimal commitment policy in each period over a rolling horizon, with the flexibility to adjust in each period the commitment quantity for the future. Tsay (1999) and Tsay and Lovejoy (1999) consider the case where the buyer commits a minimum purchasing quantity and the supplier commits to delivering a flexible quantity within a reasonable range. In the above papers, the committed quantities do not depend on realized demand, whereas in our α-contract the IDM commits to purchasing from the foundry at least α fraction of the realized demand.

The second literature stream related to our paper is that of capacity expansion and associated investments. Van Mieghem (2003) provides a comprehensive review of the literature for both single- and multiple-period capacity investment problems. Our paper falls into the category of game-theoretic capacity investments involving two agents, each of whom control a subset of the capacity network. Our single-period capacity investment model is able to capture the interaction between the two capacity builders (IDM and foundry) in a horizontal coordination core capacity expansion setting. It differs from single-resource, multiagent capacity models (e.g., Cachon and Lariviere 1999, Armony and Plambeck 2005, Plambeck and Taylor 2005) in that both the IDM and foundry can build capacity. Most multiresource, multiagent capacity models focus on horizontal capacity competition (e.g., Bashyam 1996, Lippman and McCardle 1997), where the two firms build their own capacities to compete for the end-product demand. In our paper, the foundry does not compete with the IDM in the end-product market; however, the foundry is willing to serve as a subcontractor to the IDM's end-product demand.

Van Mieghem (1999) studies contracts between a manufacturer and subcontractor to coordinate production and capacity investments. Both the manufacturer and the subcontractor serve their own markets exclusively. Although both the manufacturer and subcontractor must decide separately on the capacity investment levels, their decisions are simultaneous. In contrast, only the IDM has access to the market demand in our paper. Furthermore, their decisions are sequential with the IDM as the Stackelberg leader. Kostamis and Duenyas (2009) analyze manufacturing decisions to support original equipment manufacturer (OEM) sales in a supplier–OEM chain, and the focus of the study is on the OEM's quantity commitment decision and the supplier's pricing decision in a wholesale price contract setting. Our work differs by focusing on horizontal capacity coordination between the IDM (OEM) and the foundry (supplier) under contractual structures other than wholesale price contracts.

The required sourcing structure (sole versus dual) may play a major role in contract selection. The strategic decision on sole sourcing or dual/multiple sourcing has received substantial attention from both industry (e.g., Lester 2002, Reuters 2011) and academia (e.g., Treleven and Schweikhart 1988, Burke et al. 2007, Li and Debo 2009). This steam of literature focuses on comparing the two sourcing strategies, whereas our paper focuses on better understanding the choice between two risk sharing contracts when an explicit dual-sourcing constraint is imposed. Our analysis provides supporting rationale for the existence of both contract types: Even though one contract type dominates the other in terms of the sourcing firm's expected profit, the other may be more appealing from a risk-management perspective because of the required dual-sourcing structure under certain circumstances.

3. Model Assumptions and Notation

We consider the following problem. The IDM (he) designs a device and sells it for a unit price of p to a set maker. The demand is realized in one period and is expressed as a random variable D; realized demand is denoted as d. Here, $f(t)$ is its probability density function (pdf), where $f(t) > 0$ for $t \geq 0$ and $f(t)$ is differentiable; and $F(t)$ is its cumulative distribution function, where $F(t)$ is differentiable and invertible for $t \geq 0$. Let $\overline{F(t)} = 1 - F(t)$.

Because of the high risk of early capacity investment and the manufacturing efficiency of the foundry (she), the IDM may contract with the foundry for her capacity. The two prevailing types of contracts used in the semiconductor industry are the α-contract (w, α) and capacity reservation contract (w, r, R), where w is the subcontract price the IDM pays to the foundry for a unit of end product, and α is the fraction of the realized demand the IDM guarantees to allocate to the foundry under the contract for $0 \leq \alpha \leq 1$. For the capacity reservation contract, r is the unit capacity reservation fee, and R is the reservation quantity that the IDM secures from the foundry. Hereafter, we refer to the reservation contract via its parameters (w, r), and it is understood that the IDM sets a capacity reservation level R as part of his capacity decisions.

Of the two types of contracts, the IDM proposes one to the foundry. We show, in §4.2, that when the foundry commits positive capacity, she always earns a positive expected profit under α-contracts, but she may earn an arbitrarily-close-to-zero expected profit under reservation contracts. Therefore, we model the situation where the foundry is able to insist on the α-contract type if the IDM proposes an undesirable reservation contract to her. The foundry's limited say in the contracting stage is equivalently captured by her participation constraint: The foundry accepts the proposed contract only if she earns at least her expected profit under the IDM's profit-maximizing (PM) α-contract. We refer to a reservation contract that leads to its expected profit for the foundry greater than or equal to that under the IDM's PM α-contract, as a *viable* reservation contract. If a viable reservation contract does not exist, or if viable reservation contracts exist but the IDM's expected profit under any of them is less than that under his PM α-contract, then the IDM proposes to the foundry his PM α-contract; otherwise, the IDM proposes a viable reservation contract that maximizes his expected profit.

After the contract is determined, but before the demand is realized, the IDM and foundry need to commit their production capacities K_s and K_f, respectively. They expend the ex ante capacity costs $v_s K_s$ and $v_f K_f$, where v_s and v_f are the variable capacity costs of the IDM and foundry, respectively. Let Ω denote the capacity equilibrium (K_s, K_f) of the Stackelberg capacity game under α-contract. Let Θ denote the capacity and capacity reservation equilibrium (K_s, R, K_f) under reservation contract. After the demand D is realized, it is allocated for production to the IDM and foundry according to the agreed upon contract terms, and they determine their production quantities to maximize the ex post profits subject to the capacity constraints. Let c_s and c_f denote the variable production costs of the IDM and foundry, respectively. The ex ante expected profits of the IDM and foundry are denoted by Z_s and Z_f, respectively. The unit penalty cost incurred at the IDM for any unsatisfied device demand is normalized to 0. We assume at the end of the period the capacity has no salvage value.

In the analysis of our capacity game, we assume the IDM shares with the foundry the realized demand information. Implementation of an α-contract presumes truthful revelation of such information, and such contracts are legally enforceable. For our analyzed business-to-business settings, verification of truthful revelation of sales is straightforward when the demand is greater than the total capacity built by the IDM and foundry because all of the IDM's and foundry's capacities are used. In such an instance, sales equal the total capacity, and thus the actual demand information is nonconsequential and untruthful revelation of demand information serves no purpose. When the demand is less than the total capacity, all demand is met, and thus sales equal the actual demand. The demand seen by the IDM in our business-to-business setting is orders from set makers, which are in most cases generated and recorded by their enterprise resource planning (ERP) systems. If necessary, within a court of law, such information becomes available directly or is indirectly verifiable through access to their accounting documents. But in most cases, truthful demand information sharing is driven by built trust due to long-term business relationships between the IDM and foundry within a symbiotic industry network.

The other needed assumption in the analysis of the game is the full information of the IDM's and foundry's cost structures. We again argue that IDMs need to exert substantial effort to effectively manage long-term relationships with foundries through careful monitoring of the foundries' process capabilities and qualities, and thus they end up working with only a few foundries. This allows IDMs to have a good understanding of the foundries' cost structures. Furthermore, some third parties, for example, iSuppli, provide for products, such as integrated circuit (IC), cost evaluators that accurately estimate the cost and price involved in IC procurement. Thus, the cost structures in such settings tend to be common knowledge among experienced firms.

Throughout this paper, to avoid uninteresting pathological cases, we assume $p > c_s + v_s$ and $w > c_f + v_f$. Based on the current business reality in the semiconductor industry, with foundries focusing on manufacturing efficiencies, it is reasonable to assume that the foundry has a total cost advantage over the IDM, i.e., $c_f + v_f < c_s + v_s$. We summarize the information sharing and decision sequence protocol in Table 1. Step 1 corresponds to the contracting stage, and Steps 2–5 correspond to the capacity game. The resulting contract implemented by the IDM and foundry out of the protocol is called an *equilibrium contract*. In §4, we first characterize the IDM's PM α-contract, and then we check whether there is a viable reservation contract that is preferred by the IDM to his PM α-contract, emerging as the equilibrium contract. In §5, we revisit such analysis and results when risk-management concerns lead to an explicit dual-sourcing constraint.

Table 1 Information Sharing and Decision Sequence Protocol

Step 0.	The IDM and foundry share for a particular device the information on its unit price to a set maker, p, the cost structures c_s, v_s, c_f, v_f, and the demand pdf, $f(\cdot)$.
Step 1.	The IDM as the Stackelberg leader proposes either an α-contract (w, α) or a reservation contract (w, r) to the foundry to maximize his expected profit. The foundry either accepts the proposed contract or insists on an α-contract type if the proposed one is an undesirable reservation contract to her. In the latter case, the IDM proposes an α-contract that maximizes his expected profit.
Step 2.	The IDM determines his own capacity commitment, K_s (and the amount of reserved capacity R for the reservation contract).
Step 3.	Observing the IDM's capacity decision, the foundry determines her own capacity commitment, K_f ($K_f \geq R$ for the reservation contract).
Step 4.	The demand D is realized.
Step 5.	The IDM decides on his production quantity and places a production order with the foundry taking into account contractual demand allocation constraints.

4. α-Contract and Capacity Reservation Contract

4.1. α-Contract

An α-contract is specified by the parameter pair (w, α). We first analyze the capacity equilibrium for a given α-contract. There are two cases. For $w \leq c_s$, the IDM first uses the foundry's capacity if available, which is equivalent to the case $\alpha = 1$. For $w > c_s$, the IDM prefers to use his own capacity first. However, because of the early commitment of allocating α portion of realized demand d to the foundry, the IDM has to use the foundry's capacity first up to $\min[\alpha d, K_f]$, and the rest demand is met through the IDM's capacity, if available. The expected profits of the IDM and foundry under these two cases are derived in Proposition 1.

Proposition 1. (a) *If $w > c_s$, the expected profits for the foundry and IDM under α-contracts are as follows*:

If $\alpha \geq K_f/(K_s+K_f)$,

$$Z_f = (w-c_f)\alpha \int_0^{K_f/\alpha} \overline{F(t)}\,dt - v_f K_f, \tag{1}$$

$$Z_s = (p-c_s+\alpha(c_s-w)) \int_0^{K_f/\alpha} \overline{F(t)}\,dt + (p-c_s)\int_{K_f/\alpha}^{K_s+K_f} \overline{F(t)}\,dt - v_s K_s. \tag{2}$$

If $\alpha \leq K_f/(K_s+K_f)$,

$$Z_f = (w-c_f)\alpha \int_0^{K_s/(1-\alpha)} \overline{F(t)}\,dt + (w-c_f)\int_{K_s/(1-\alpha)}^{K_s+K_f} \overline{F(t)}\,dt - v_f K_f, \tag{3}$$

$$Z_s = (p-c_s+\alpha(c_s-w)) \int_0^{K_s/(1-\alpha)} \overline{F(t)}\,dt + (p-w)\int_{K_s/(1-\alpha)}^{K_s+K_f} \overline{F(t)}\,dt - v_s K_s. \tag{4}$$

(b) *If* $w \leq c_s$, *the expected profits are a special case of Equations* (1) *and* (2) *by setting* $\alpha = 1$.

Because the IDM's and foundry's expected profit expressions are different for $\alpha \geq K_f/(K_s+K_f)$ and $\alpha < K_f/(K_s+K_f)$, we study each of these cases separately. Our first result, Lemma 1, describes the foundry's optimal capacity decision given the IDM's capacity decision (see Step 3 in Table 1). For notation simplicity, define $K_w \equiv F^{-1}((w-c_f-v_f)/(w-c_f))$ and $K_p \equiv F^{-1}((p-c_s-v_s)/(p-c_s))$.

Lemma 1. (a) *If* $w > c_s$, *then the foundry's optimal capacity* K_f, *given the IDM's capacity decision* K_s, *is expressed as follows*:

$$K_f = \begin{cases} K_w - K_s & \text{for } \alpha \leq (K_w-K_s)/K_w, \\ \alpha K_w & \text{for } \alpha \geq (K_w-K_s)/K_w. \end{cases}$$

(b) *If* $w \leq c_s$, *then* $K_f = K_w$.

If the IDM uses the foundry first to meet all demand (i.e., the case for $w \leq c_s$), then the foundry's desired capacity is her newsvendor critical fractile K_w. But in the α-contract with $w > c_s$, only α fraction of the demand is first allocated to the foundry. Therefore, if the IDM does not build enough capacity (i.e., $K_s \in [0, (1-\alpha)K_w]$, which is equivalent to $\alpha \leq (K_w - K_s)/K_w$), then the foundry will build capacity equal to the difference between K_w and K_s. Otherwise, she will build the capacity of αK_w because only α fraction of the demand is guaranteed. Note that the foundry builds capacity of at least αK_w because she is guaranteed α fraction of the demand.

Anticipating the foundry's capacity decision, the IDM chooses K_s to maximize his expected profit, resulting in a capacity equilibrium $\Omega^* = (K_s^*, K_f^*)$. (The details of derivation of capacity equilibrium Ω^* resulting from the Stackelberg game in Steps 2–5 in Table 1 are characterized in Proposition A1 in the online supplement, available at http://dx.doi.org/10.1287/msom.2013.0435.)

There are three possible capacity equilibria corresponding to (K_s, K_f):

$$\Omega_1 = (0, K_w),$$

$$\Omega_2 = (K_p - \alpha K_w, \alpha K_w),$$

$$\Omega_3 = \left((1-\alpha)F^{-1}\left(\frac{w-c_s-v_s}{w-c_s}\right), K_w - K_s\right).$$

Here, Ω_2 and Ω_3 for $0 < \alpha < 1$ describe dual sourcing of device capacity. However, Ω_2 for $\alpha = 0$ has the IDM as the sole capacity source, and Ω_3 for $\alpha = 1$ has the foundry as the sole source. The foundry is also the sole source when capacity is the same as Ω_1. There are two different critical fractiles to describe the optimal capacity for the IDM: $(p-c_s-v_s)/(p-c_s)$ and $(w-c_s-v_s)/(w-c_s)$. To better interpret them, one has to carefully consider how demand is met through the two capacity sources. Denote the IDM's committed order to the foundry as CF, which is a function of realized demand, d. If $CF(d) \geq K_f$, then the IDM has to satisfy the rest of demand $d - K_f$ from his own capacity. Therefore, the IDM's underage capacity cost c_u is $p - c_s - v_s$ and his overage cost is v_s. If $CF(d) < K_f$, then we have two cases of the IDM's underage cost to consider. First, if the demand is greater than or equal to the total capacity, then one unit of capacity shortage leads to one unit of lost revenue, but it saves one unit of capacity investment and corresponding production costs; hence, $c_u = p - c_s - v_s$. Second, if the demand is less than the total capacity but the IDM's capacity is not enough to meet the demand $d - CF(d)$, then using one less unit of the IDM's capacity requires using one more unit of the foundry's capacity, which has a net cost effect of $w - c_s - v_s$ to the IDM. If w is greater than $c_s + v_s$, then $w - c_s - v_s$ is the IDM's underage cost.

The IDM's PM α-contract is of particular interest because it leads to an expected profit for the foundry corresponding to her participation constraint, and it also determines the IDM's benchmark profit in his contract selection. We first derive the PM α value, α^*, for a given w in Proposition 2. Let $I_f = \int_0^{K_w} F(t)/K_w\,dt$.

Proposition 2. *Among* α-*contracts*, *the PM* α^* *is as follows*:

(a) *If* $w \leq c_s + v_s$, $\alpha^* = 1$.

(b) *If* $w > c_f + (v_f(p-c_s))/v_s$, $\alpha^* = 0$.

(c) *If* $c_s + v_s < w \leq c_f + (v_f(p-c_s))/v_s$, *there exists a threshold* $\hat{w} \in (c_s + v_s, c_f + (v_f(p-c_s))/v_s)$ *such that*

(i) *for* $\hat{w} \leq w \leq c_f + (v_f(p-c_s))/v_s$, $\alpha^* = 0$,

(ii) *for* $c_s + v_s < w < \hat{w}$,

$$\alpha^* = \begin{cases} 1 & \text{for } I_f > (w - c_s - v_s)/(w - c_s), \\ 0 & \text{for } I_f \leq (w - c_s - v_s)/(w - c_s). \end{cases}$$

Proposition 2 implies that for a profit-maximizing IDM, extreme α-contracts ($\alpha^* = 0$ or 1) are optimal. The extreme contract result is interesting and far from obvious because the IDM's profit function is highly nonlinear in α. For low subcontract prices, the IDM prefers to use the foundry's capacity as much as possible. Committing to allocate all demand to the foundry first provides strong incentive for the foundry to build capacity. Thus, for low subcontract prices ($w \leq c_s + v_s$), the full commitment (i.e., $\alpha = 1$) option prevails. If the subcontract price is high, it is not attractive to use the foundry's capacity, so the IDM prefers no commitment (i.e., $\alpha = 0$).

For intermediate values of the subcontract price, the IDM's assessment of the likelihood of a high demand market comes into play. Consider two demand cumulative distribution functions, say $G(\cdot)$ and $H(\cdot)$, with $G^{-1}((w - c_f - v_f)/(w - c_f)) = H^{-1}((w - c_f - v_f)/(w - c_f)) = \eta$. Suppose $G(\cdot)$ is stochastically greater than $H(\cdot)$ over $[0, \eta]$, then $G(\cdot)$ leads to a smaller I_f than $H(\cdot)$. Therefore, under $G(\cdot)$, which indicates a stochastically larger market demand, condition $I_f \leq (w - c_s - v_s)/(w - c_s)$ is more likely to be satisfied, and Proposition 2 implies it is more likely $\alpha^* = 0$. This means that for a high likelihood of large demand, the IDM builds most of the needed capacity and uses the foundry only for overflow demand. For a low likelihood of large demand, the IDM might use the full commitment contract ($\alpha^* = 1$) even when the subcontract price is greater than its total cost per unit.

If it is optimal for the IDM to fully commit, then the equilibrium capacity pair is $\Omega^* = (\max[K_p - K_w, 0], K_w)$. This implies dual sourcing is the outcome if K_p is greater than K_w; otherwise, sole sourcing from the foundry is the outcome. If the IDM does not commit any ex post demand to the foundry, then it is optimal for him to build capacity either up to his critical fractile level $F^{-1}((w - c_s - v_s)/(w - c_s))$ assuming the excess demand will be met through the foundry's capacity (dual sourcing) or up to his critical fractile level K_p assuming the excess demand is lost (sole sourcing using his own capacity).

Proposition 2 maps w to the optimal α. As such, the search of the IDM's PM α-contract reduces to a one-dimensional search over w by setting α to the corresponding optimal value. Although the optimal w has no closed-form solution, we can numerically derive it for the purpose of our study. One may wonder whether the IDM's PM α-contract can achieve the centralized system performance (for the details of the centralized capacity profile, refer to Result A1 in the online supplement). Proposition 3 addresses this question.

Proposition 3. *The IDM's PM α-contract fails to coordinate and thus to implement the centralized system capacity profile.*

To understand the underlying reasons for Proposition 3, let us consider two cases: For $(p - c_f)/v_f > (p - c_s)/v_s$, which means the foundry is the one with a larger margin over capacity cost, the foundry's desired capacity level according to the incentive provided by the IDM ($\alpha F^{-1}((w - c_f - v_f)/(w - c_f))$) never catches up with the system's preference for the foundry's capacity ($F^{-1}((p - c_f - v_f)/(p - c_f))$); for $(p - c_f)/v_f \leq (p - c_s)/v_s$, an α-contract exists with $w = (v_f c_s - c_f v_s)/(v_f - v_s)$ and $\alpha = 1$ that can coordinate and achieve the first-best system performance; however, this α-contract is costly for the IDM because it requires a high w to provide adequate incentives to the foundry to build the system's desired capacity level. For such high w, it is shown that the IDM earns a larger expected profit by solely relying on his own capacity. Thus, the IDM's PM α-contract fails to coordinate.

4.2. Capacity Reservation Contract

In analyzing the reservation contract, we need to consider three cases—$w - r > c_s$, $c_s < w \leq c_s + r$, and $w \leq c_s$—accounting for the fact that the reservation fee per unit of capacity is refunded as soon as one unit of demand is allocated to the foundry. For the first R units of demand, the IDM needs to compare $w - r$ and c_s, where $w - r$ is the additional fee that the IDM pays if he sources from the foundry, and c_s is the production cost that the IDM incurs for his own production. Therefore, condition $w - r > c_s$ implies that the IDM prefers to use his own capacity first. When $w \leq c_s$, the foundry's capacity is always used first. When $c_s < w \leq c_s + r$, the foundry's capacity is used first up to R, and then the IDM's capacity; thereafter, any remaining requirements will be met through the leftover capacity at the foundry. Proposition 4 derives the expected profits of the IDM and foundry under these three cases, respectively.

Proposition 4. *The expected profits for the foundry and IDM under reservation contracts are as follows:*

For $w > c_s + r$,

$$Z_f = (w - c_f)\int_{K_s}^{K_s+K_f} \overline{F(t)}\,dt - v_f K_f + r\int_{K_s}^{K_s+R} F(t)\,dt, \tag{5}$$

$$Z_s = (p - w)\int_{K_s}^{K_s+K_f} \overline{F(t)}\,dt + (p - c_s)\int_0^{K_s} \overline{F(t)}\,dt - v_s K_s - r\int_{K_s}^{K_s+R} F(t)\,dt. \tag{6}$$

For $c_s < w \le c_s + r$,

$$Z_f = (w - c_f)\left(\int_0^R \overline{F(t)}\,dt + \int_{K_s+R}^{K_s+K_f} \overline{F(t)}\,dt\right) - v_f K_f + r\int_0^R F(t)\,dt, \quad (7)$$

$$Z_s = (p - w)\left(\int_0^R \overline{F(t)}\,dt + \int_{K_s+R}^{K_s+K_f} \overline{F(t)}\,dt\right) + (p - c_s)\int_R^{K_s+R} \overline{F(t)}dt - v_s K_s - r\int_0^R F(t)\,dt. \quad (8)$$

For $w \le c_s$,

$$Z_f = (w - c_f)\int_0^{K_f} \overline{F(t)}\,dt - v_f K_f + r\int_0^R F(t)\,dt, \quad (9)$$

$$Z_s = (p - w)\int_0^{K_f} \overline{F(t)}\,dt + (p - c_s)\int_{K_f}^{K_s+K_f} \overline{F(t)}\,dt - v_s K_s - r\int_0^R F(t)\,dt. \quad (10)$$

The foundry's capacity decisions are as follows:
For $w > c_s$,

$$K_f = \begin{cases} R & \text{for } R + K_s \ge K_w, \\ K_w - K_s & \text{for } R + K_s < K_w. \end{cases}$$

For $w \le c_s$,

$$K_f = \begin{cases} R & \text{for } R > K_w, \\ K_w & \text{for } R \le K_w. \end{cases}$$

Recall that $\Theta = (K_s, R, K_f)$ represents capacity and capacity reservation equilibrium of the Stackelberg capacity game between the IDM and foundry for a given reservation contract. According to our obtained results, a reservation contract (w, r) leads to a unique capacity and capacity reservation equilibrium, Θ^*. The details of the equilibrium results are presented in the online supplement. (Propositions A2, A3, and A4 in the online supplement present the equilibrium results under the cases $w > c_s + r$, $c_s < w \le c_s + r$, and $w \le c_s$, respectively.)

According to these results, there are seven possible equilibria Θ_i, $i = 1, 2, \ldots, 7$, as follows:

$$\Theta_1 = (0, 0, K_w),$$

$$\Theta_2 = \left(0, F^{-1}\left(\frac{p - w}{p - w + r}\right), R\right),$$

$$\Theta_3 = \left(F^{-1}\left(\frac{w - c_s - v_s}{w - c_s}\right), 0, K_w - K_s\right),$$

$$\Theta_4 = \left(F^{-1}\left(\frac{w - c_s - v_s}{w - c_s - r}\right), F^{-1}\left(\frac{p - w}{p - w + r}\right) - K_s, R\right),$$

$$\Theta_5 = (K_p, 0, 0),$$

$$\Theta_6 = \left(K_p - R, F^{-1}\left(\frac{c_s + v_s - w}{c_s + r - w}\right), R\right),$$

$$\Theta_7 = (K_p - K_w, 0, K_w).$$

Among all capacity and capacity reservation equilibria, there are two critical fractiles for the optimal level of capacity reservation: $(p - w)/(p - w + r)$ and $(c_s + v_s - w)/(c_s + r - w)$. This is because of two possible cases for the impact of the IDM's capacity reservation quantity on the system's total capacity. In the first case, the reservation quantity affects the total capacity. The IDM's underage cost of not reserving enough capacity is $p - w$ and the overage cost is r, leading to critical fractile $(p - w)/(p - w + r)$. In the second case, the total capacity is independent of the IDM's capacity reservation decision. Building one more (less) unit of capacity by himself means reserving one less (more) unit from the foundry. Correspondingly, his underage capacity reservation cost is $c_s + v_s - w$ and overage cost is $r - v_s$, leading to critical fractile $(c_s + v_s - w)/(c_s + r - w)$.

The IDM's capacity decision has three critical fractiles. In addition to the same two fractiles $(p - c_s - v_s)/(p - c_s)$ and $(w - c_s - v_s)/(w - c_s)$ under α-contracts, there is an additional fractile $(w - c_s - v_s)/(w - c_s - r)$ (in Θ_4) that is unique to a reservation contract. In Θ_4, the total of the IDM's built capacity and the reservation capacity is up to a fixed critical fractile level. Building one more unit of capacity by himself means reserving one less unit from the foundry. So his overage cost of building excess capacity is $v_s - r$ instead of v_s, and his underage cost is $w - c_s - v_s$.

In the contracting stage, we need to check whether the IDM's PM reservation contract is viable. The IDM's PM reservation contract and the firms' expected profits can be derived from an existing result in Wu et al. (2013). Wu et al. (2013) focus their study on coordinating reservation contracts (reservation contracts that lead to the first-best system performance and implement the centralized capacity investment and production decisions) and have characterized them for various cost structures as shown in Result 1. Let $MOC_s = (p - c_s - v_s)/v_s$ and $MOC_f = (p - c_f - v_f)/v_f$. Let K_{cs}^u and K_{cf}^u denote the centralized capacity investments at the IDM and foundry, where the superscript "u" is used to contrast the unconstrained centralized capacities (K_{cs}^u, K_{cf}^u) from the centralized capacities with a dual-sourcing constraint in §5.2.1.

Result 1 (Wu et al. 2013). There exist the following reservation contracts with $K_{cf}^u = R$ that coordinate the IDM's and foundry's capacity investment and production decisions.

(a) Assume $MOC_s \ge MOC_f$ holds. Then set $w = c_f + v_f + \xi$ and $r = v_f - (\xi(v_f - v_s))/(c_s + v_s - c_f - v_f)$ for $(c_s - c_f - v_f)^+ < \xi < c_s + v_s - c_f - v_f$.

The expected profits for the foundry and IDM are

$$Z_f^c = \frac{\xi}{c_s+v_s-c_f-v_f} \cdot\left((c_s-c_f)\int_0^{K_{cf}^u}(1-F(x))\,dx-(v_f-v_s)K_{cf}^u\right),$$

$$Z_s^c = Z_{cs}-Z_f^c,$$

where

$$Z_{cs} = (p-c_f)\int_0^{K_{cf}^u}(1-F(x))\,dx + (p-c_s)\int_{K_{cf}^u}^{K_{cs}^u+K_{cf}^u}(1-F(x))\,dx - v_f K_{cf}^u - v_s K_{cs}^u.$$

The corresponding capacity investments are

$$(K_{cs}^u, K_{cf}^u) = \left(K_p - F^{-1}\left(\frac{c_s+v_s-c_f-v_f}{c_s-c_f}\right), F^{-1}\left(\frac{c_s+v_s-c_f-v_f}{c_s-c_f}\right)\right).$$

(b) Assume $MOC_f > MOC_s$ holds. Then set

$$w = c_f+v_f+\xi \quad \text{and} \quad r = v_f - \frac{\xi v_f}{p-c_f-v_f} \quad \text{for } 0<\xi\le c_s+v_s-c_f-v_f.$$

The expected profits for the foundry and IDM are

$$Z_f^c = \frac{\xi}{p-c_f-v_f}Z_{cs},$$

$$Z_s^c = \left(1-\frac{\xi}{p-c_f-v_f}\right)Z_{cs},$$

where

$$Z_{cs} = (p-c_f)\int_0^{K_{cf}^u}(1-F(x))\,dx - v_f K_{cf}^u.$$

The corresponding capacity investments are

$$(K_{cs}^u, K_{cf}^u) = \left(0, F^{-1}\left(\frac{p-c_f-v_f}{p-c_f}\right)\right).$$

Result 1 shows that for any parameter setting, a continuous range of reservation contracts exists that can coordinate capacity investment and production decisions. Under the usual case of $c_f+v_f \ge c_s$, the foundry's (IDM's) profit can be arbitrarily close to 0 (the system's profit). In fact, by setting $w=c_f+v_f$ and $r=v_f$, the IDM can extract the coordinated system's whole profit and leave the foundry with zero profit. However, under α-contracts, the foundry earns positive expected profit whenever she builds positive capacity, because she has the option of not committing any capacity. Thus, the IDM's PM reservation contract $(w=c_f+v_f, r=v_f)$ that leads to zero profit for the foundry is not viable. In the following, we investigate whether other coordinating reservation contracts exist that are viable and also lead to larger expected profits for the IDM compared with his PM α-contract.

4.3. Reservation Contract Emerging as Equilibrium Contract

Because it is intractable to analytically compare expected profits under the IDM's PM α-contract with those under coordinating reservation contracts, we conduct numerical studies in advancing the argument that there are viable coordinating reservation contracts that often emerge as equilibrium contracts.

In our numerical study, we use scaled representative parameter settings in our studied semiconductor industry: $p=1{,}300$, $D\sim N^T(500, 200^2)$ with the negative part truncated, $c_s+v_s=600$, and $c_f+v_f=\delta(c_s+v_s)$ with $\delta=70\%$, 80%, and 90%, respectively. The three values of δ correspond to three cases of cost-efficiency difference between the IDM and foundry. Furthermore, we consider three scenarios of cost structure for both the IDM and foundry. The variable capacity cost is the ex ante capacity preparation cost, which is expended before the demand is realized. On the contrary, the variable production cost is incurred ex post. The lower the proportion of the ex ante capacity cost, the more flexible the cost structure is. Scenario 1, referred to as the standard case (S), uses equal variable capacity cost and variable production cost (i.e., $v_i=c_i$, $i=s,f$). Scenario 2, the flexible case (F), uses 30% variable capacity cost out of the total production cost (i.e., $v_i/c_i = 3/7$, $i=s,f$). Scenario 3, the inflexible case (IF), uses 70% variable capacity cost out of the total production cost (i.e., $v_i/c_i=7/3$, $i=s,f$). Considering all possible combinations of total cost difference and cost structures (i.e., standard, flexible, inflexible) both for the IDM and foundry leads us to evaluate 27 different scenarios. Table 2 illustrates nine of them with a standard IDM's cost structure. In the third column of the table, we derive the IDM's PM α-contract, and the associated IDM's and foundry's expected profits, respectively. In the fourth column, we derive the coordinating reservation contract that gives the foundry the same expected profit as under the PM α-contract. Compared with the IDM's PM α-contract, under each of the 27 representative parameter settings, a coordinating reservation contract exists that guarantees the foundry the same expected profit but gives the IDM strictly greater expected profit. This coordinating reservation contract is the one the IDM should propose in Step 1 of Table 1. This result is confirmed to be robust under a range of profit margins, with p varying from 800 to 1,600.

To sum up, for all studied practical parameter settings, coordinating reservation contracts are equilibrium contracts if the IDM is a pure profit maximizer. However, risk-management considerations might drive preference for dual sourcing and certain capacity profiles, leading to an implementation of a contract other than the PM one. In an ideal case,

Table 2 The IDM's Profit-Maximizing α-Contract and the Equilibrium Reservation Contract

Total cost difference (%)	Cost structure	IDM's PM α-contract (w, α), $[Z_s, Z_f]$	Equilibrium (reservation) contract (w, r), $[Z_s, Z_f]$
10	(S, F)	(567, 1), [296.9 K, 5.4 K]	(552, 159), [330.1 K, 5.4 K]
10	(S, S)	(564, 1), [293.6 K, 3.7 K]	(549, 267), [312.6 K, 3.7 K]
10	(S, IF)	(564, 1), [292.0 K, 3.0 K]	(549, 366), [300.3 K, 3.0 K]
20	(S, F)	(524, 1), [316.7 K, 11.1 K]	(505, 140), [357.4 K, 11.1 K]
20	(S, S)	(522, 1), [310.0 K, 8.5 K]	(500, 234), [341.3 K, 8.5 K]
20	(S, IF)	(521, 1), [306.3 K, 7.2 K]	(498, 329), [327.4 K, 7.2 K]
30	(S, F)	(478, 1), [340.2 K, 16.5 K]	(456, 121), [385.5 K, 16.5 K]
30	(S, S)	(477, 1), [330.1 K, 13.5 K]	(451, 203), [370.6 K, 13.5 K]
30	(S, IF)	(476, 1), [324.3 K, 11.8 K]	(448, 285), [357.4 K, 11.8 K]

the equilibrium contract adopted by the IDM and foundry leads to dual sourcing and a desirable capacity profile. Result 1 shows that under $MOC_s \geq MOC_f$, dual sourcing is indeed the resulting sourcing structure. However, in the more frequent cases with the foundry having a more flexible cost structure, i.e., $MOC_f > MOC_s$, coordinating reservation contracts that emerge as equilibrium contracts lead to sole sourcing. In such cases, there is a need to make a trade-off between profit and risk exposure (indirectly captured via resulting sourcing structure: sole (risky) or dual (hedge)) in selecting a contract. In the next section, we explicitly incorporate the consideration of dual sourcing in contract selection.

5. Contract Selection with a Dual-Sourcing Constraint

For risk-management purposes, the IDM or the IDM's customer prefers both the IDM and the foundry to build positive capacity, say $K_s \geq a$ and $K_f \geq b$ ($a, b > 0$). This way one source (let us say, IDM) has some available capacity if the other source (foundry) is disrupted, due to a natural disaster or a large-scale fire, for example.

5.1. α-Contracts with a Dual-Sourcing Constraint

With an explicit dual-sourcing constraint, the IDM solves the following optimization problem to derive his constrained PM α-contract:

$$\max_{w,\alpha,K_s} \; Z_s \quad \text{s.t. } K_s \geq a, \; K_f \geq b, \tag{11}$$

where Z_s is represented in Equations (2) and (4). For a subcontract price w, $K_w = F^{-1}((w-c_f-v_f)/(w-c_f))$ is the maximum capacity the foundry is willing to build. Thus, w must be greater than a threshold so that the foundry is willing to build above b units of capacity (i.e., $K_w > b$). For $w \leq c_s$, the IDM always prefers to allocate the demand to the foundry first, and thus the value of α is irrelevant. For $w > c_s$, which is the relevant case, we characterize in Proposition 5 the constrained PM α value for a given w by solving problem (11).

Proposition 5. *Assume the IDM is required to meet the dual-sourcing constraint: $K_s \geq a$ and $K_f \geq b$. Let $\tilde{\alpha} = \min[1, \max[b/K_w, \alpha^o]]$, where α^o satisfies*

$$F(\alpha^o K_w + a) = \frac{p - w(1-I_f) - c_s I_f}{p - c_s}. \tag{12}$$

Then for a given w, the PM α^* is specified as follows:

(a) $a + b > K_w$:

$$\begin{cases} K_w > K_p\colon\ \alpha^* = \tilde{\alpha}, \\ K_w \leq K_p\colon\ \begin{cases} a+b \geq K_p\colon\ \alpha^* = \tilde{\alpha}, \\ K_w < a+b < K_p\colon \\ \qquad \begin{cases} I_f > \dfrac{w-c_s-v_s}{w-c_s}\colon\ \alpha^* = \tilde{\alpha}, \\ I_f \leq \dfrac{w-c_s-v_s}{w-c_s}\colon\ \alpha^* = \tilde{\alpha} \text{ or } \dfrac{b}{K_w}; \end{cases} \end{cases} \end{cases}$$

(b) $a + b \leq K_w$: $\alpha^* = 0$ *or* $\tilde{\alpha}$.

The corresponding capacity equilibrium (Ω^*) is specified as follows:

If $\alpha^* = \tilde{\alpha}$ or b/K_w, $\Omega^* = (\max[a, K_p - \alpha^* K_w], \alpha^* K_w)$.

If $\alpha^* = 0$,

$$\Omega^* = \left(\max\left[a, F^{-1}\left(\frac{w-c_s-v_s}{w-c_s}\right)\right], \; K_w - \max\left[a, F^{-1}\left(\frac{w-c_s-v_s}{w-c_s}\right)\right]\right).$$

In contrast to the case without dual-sourcing constraint, where only extreme value α-contracts are profit maximizing, Proposition 5 shows that both extreme and intermediate value α-contracts can be profit maximizing for the IDM. The value α^o is optimal for the IDM when the IDM's capacity constraint is binding (i.e., $K_s^* = a$). In the definition of α^o in (12), $1 - I_f$ indicates the probability of using the foundry's capacity when the foundry's built capacity is αK_w, and I_f indicates the probability of using the IDM's capacity. The capacity commitment underage cost is $p - w(1-I_f) - c_s I_f$ and the overage cost is $(w-c_s)\cdot(1-I_f)$. This explains the definition of α^o. If w and a are large enough, α^o can be less than 1. Thus, in circumstances where the firms have no control over the subcontract price and this price is high, dual-sourcing concerns may lead to the use of intermediate value α-contracts.

If w is low, then α^o is greater than 1 if a is not large enough. In this case, a full commitment contract is used in most cases. An overflow contract ($\alpha(0)$-contract) can be profit maximizing only when the total capacity constraint $a+b$ is less than the foundry's critical fractile K_w. In this case, the foundry will be willing to build $K_w - a$, which is already greater than b; thus, no commitment is needed. But if the total capacity has to be above K_w, the IDM will always commit at least b/K_w portion of ex post demand to the foundry so that the foundry builds capacity $\alpha K_w = b$.

The above analysis of the optimal α value is for a given w. When the IDM chooses both w and α, a trade-off between low price and low commitment of ex post demand appears. This is because larger values of w and α both serve as incentives for the foundry to build capacity; as one incentive becomes stronger, the other can be weaker. In fact, $dw/d\alpha^o < 0$ can be shown analytically under uniform demand distribution. Under a normal distribution, $dw/d\alpha^o < 0$ holds for all the used parameter settings in our numerical study. Given such a trade-off between w and α, the results in Table 2 show that the option of offering a low price with full commitment prevails for the IDM ($\alpha^* = 1$) when there is no dual-sourcing constraint. To see if the results continue to hold in the presence of a dual-sourcing constraint, we need to search for the optimal w in problem (11) by setting α to the corresponding optimal value.

5.2. Equilibrium Contract with a Dual-Sourcing Constraint

Following a parallel analysis to that in §4.3, we are in search of viable reservation contracts that lead to larger expected profits for the IDM compared with the IDM's constrained PM α-contract. If no such reservation contract is found, the constrained PM α-contract emerges as the equilibrium contract.

We focus on the case where the IDM's customer requires the total capacity to be at least the unconstrained optimal level for the system of the IDM and foundry. We refer to it as Assumption T.

Assumption T: *The capacity constraint satisfies*

$$a+b \ge K_{cs}^u + K_{cf}^u = \max\left[K_p, F^{-1}\left(\frac{p-c_f-v_f}{p-c_f}\right)\right].$$

This assumption can be justified from two aspects: First, the IDM's customer benefits from a larger capacity built in the system; thus, it is always desirable for a customer to impose a lower bound of the total capacity. Second, the required minimum total capacity maximizes the total expected profit of the IDM and foundry in the absence of a dual-sourcing constraint, which makes it reasonable for the IDM's customer to impose this requirement.

To derive the equilibrium contract type in the presence of a dual-sourcing constraint, our first step is to check, in §5.2.1, whether the IDM's PM α-contract with a dual-sourcing constraint can coordinate the first-best system performance. If so, no viable reservation contract can strictly outperform the PM α-contract in terms of the IDM's expected profit. Thus, the coordinating PM α-contract is proposed by the IDM, emerging as the equilibrium contract. If the PM α-contract cannot coordinate the first-best system performance, we further investigate, in §5.2.2, whether a viable reservation contract exists that outperforms the PM α-contract for the IDM.

5.2.1. Coordinating Profit-Maximizing α-Contract Emerging as Equilibrium Contract. To check whether the IDM's PM α-contract is coordinating, we derive centralized capacity investment decisions in the presence of the dual-sourcing constraint in Proposition 6, where K_{cs}^u and K_{cf}^u indicate the unconstrained (no dual-sourcing constraint) centralized capacities. Proposition 6 focuses on the nontrivial cases with at least one firm's capacity constraint binding.

Define K_f^o, K_f^1, and K_s^o such that

$$p-c_f-v_f-(c_s-c_f)F(K_f^o)-(p-c_s)F(a+K_f^o)=0, \quad (13)$$

$$p-c_f-v_f-(p-c_f)F(a+K_f^1)=0, \quad (14)$$

$$p-c_s-v_s-(p-c_s)F(K_s^o+b)=0. \quad (15)$$

Proposition 6. *With the dual-sourcing constraint $K_s \ge a$ and $K_f \ge b$, the centralized capacity investments are specified as follows*:

(a) *If $MOC_f > MOC_s$ and $c_s > c_f$, then* $(K_{cs}, K_{cf}) = (a, \max[b, K_f^o])$.

(b) *If $MOC_f > MOC_s$ and $c_s \le c_f$, then* $(K_{cs}, K_{cf}) = (a, \max[b, K_f^1])$.

(c) *If $MOC_s \ge MOC_f$, then*

$$(K_{cs}, K_{cf}) = \begin{cases} (a, b) & \text{if } a \ge K_{cs}^u \text{ and } b \ge K_{cf}^u, \\ (a, \max[b, K_f^o]) & \text{if } a \ge K_{cs}^u \text{ and } b < K_{cf}^u, \\ (\max[a, K_s^o], b) & \text{if } a < K_{cs}^u \text{ and } b \ge K_{cf}^u, \end{cases}$$

where

$$K_{cs}^u = F^{-1}\left(\frac{p-c_s-v_s}{p-c_s}\right) - F^{-1}\left(\frac{c_s+v_s-c_f-v_f}{c_s-c_f}\right) \quad \text{and}$$

$$K_{cf}^u = F^{-1}\left(\frac{c_s+v_s-c_f-v_f}{c_s-c_f}\right).$$

The dual-sourcing constraint forces the IDM to build a capacity of at least a. Given that the IDM builds a units of capacity, K_f^o and K_f^1 denote the foundry's unconstrained centralized capacity levels for $c_s > c_f$ and $c_s \le c_f$, respectively. Similarly, K_s^o denotes the IDM's unconstrained optimal capacity level for the system given the foundry builds b units of capacity.

Because the centralized production decision is to allocate the demand to the foundry first (for $c_s > c_f$) or to the IDM first (for $c_s \le c_f$), only extreme value α-contracts may coordinate the system. For $c_s \le c_f$, an $\alpha(0)$-contract can coordinate the production decision, but it is unable to coordinate the capacity investment decision because no incentive is provided for the foundry to build the centralized capacity level $\max[b, K_f^1]$.

For $c_s > c_f$, an $\alpha(1)$-contract can coordinate the production decision. It is an interesting question to investigate whether an $\alpha(1)$-contract can coordinate the centralized capacity investment decisions while maximizing the IDM's expected profit. We know that it fails to coordinate in the absence of the dual-sourcing constraint (see Proposition 3), but this may change when we impose the dual-sourcing constraint, as our discussion below indicates.

Let us consider the following two scenarios. In the first (second) scenario, the foundry's capacity constraint is (is not) binding in the centralized decision making (i.e., $b \ge K_f^o$ $(b < K_f^o)$). Therefore, the centralized system has the foundry build b (K_f^o) units of capacity. To replicate the centralized foundry's capacity, the IDM needs to propose contract parameters w and α that provide the foundry with the exact incentives to build the centralized capacity level. If the centralized foundry's capacity is K_f^o with $K_f^o > b$, it is unlikely the IDM's preferred foundry's capacity is exactly the system's preferred level K_f^o.

Whereas if the centralized foundry's capacity is binding (i.e., $b \ge K_f^o$ so that $K_{cf} = b$), then as long as the IDM's unconstrained preference for the foundry's capacity is less than b, the IDM has to guarantee the foundry's capacity reaches b by providing enough incentives. In this case, the capacity constraint at the foundry makes it easier to align the IDM's preference for the foundry's capacity with what is optimal for the centralized system. This provides an opportunity for α-contracts to coordinate the centralized capacity investments. Furthermore, the system's desired foundry's capacity level decreases if the IDM is required to build a capacity level higher than his system-optimal level in the absence of a dual-sourcing constraint. Notice that K_f^o and K_f^1 defined in Equations (13) and (14) are strictly less than $F^{-1}((p - c_f - v_f)/(p - c_f))$. Given a lower foundry's capacity in the coordinated system, it becomes feasible for the IDM to replicate this capacity using an α-contract. Proposition 7 shows formally that the dual-sourcing constraint alters the coordinating capability of α-contracts under certain circumstances.

Table 3 The IDM's Profit-Maximizing α-Contract Is Coordinating $(b \ge K_f^o)$

Total cost difference (%)	Cost structure	(a, b, K_f^o)	IDM's PM and coordinating α-contract
10	(S, S)	(215, 430, 421)	(691, 1), [261.5 K, 45.3 K]
10	(S, IF)	(205, 410, 409)	(720, 1), [251.4 K, 51.3 K]
20	(S, S)	(225, 450, 442)	(638, 1), [281.0 K, 49.6 K]
20	(S, IF)	(215, 430, 429)	(668, 1), [270.3 K, 56.4 K]
30	(S, F)	(245, 490, 488)	(535, 1), [320.0 K, 39.0 K]
30	(S, S)	(235, 470, 466)	(583, 1), [301.8 K, 53.2 K]
30	(S, IF)	(230, 460, 448)	(630, 1), [283.4 K, 67.3 K]

Proposition 7. *In the presence of dual-sourcing constraint $K_s \ge a$ and $K_f \ge b$, if $c_s > c_f$, $dw/d\alpha^o < 0$, Assumption T holds and the demand has an increasing generalized failure rate, then there exists a threshold $\hat{b} > K_f^o$ so that the IDM's constrained PM α-contract coordinates the centralized capacity and production decisions for $b \ge \hat{b}$.*

Proposition 7 gives a sufficient but not necessary condition for the IDM's constrained PM α-contract to be coordinating. However, $c_s > c_f$ is a necessary condition. Among the nine cost scenarios in Table 2, seven satisfy the condition $c_s > c_f$, as summarized in Table 3. Under a range of dual-sourcing constraints satisfying Assumption T and $b \ge K_f^o$, the IDM's constrained PM α-contract is coordinating. Table 3 presents one set of such examples with $b/a = 2$. Of course, there are other combinations of (a, b), such as $b/a = 1$, that lead to similar results.

If the IDM's constrained PM α-contract is coordinating, then no viable reservation contract can strictly outperform it in terms of the IDM's expected profit, and the PM α-contract will emerge as the equilibrium contract. Thus, the result of Proposition 7 offers a theoretical foundation to explain the extensive use of α-contracts in practice, particularly so for an industry with pervasive risk-management concerns.

5.2.2. Noncoordinating PM α-Contract Emerging as Equilibrium Contract. In contrast to the case of $b \ge K_f^o$, the IDM's PM α-contract is generally not coordinating under the condition of $b < K_f^o$, as shown in Table 4. For all the parameter settings in Table 4, it is optimal for the IDM to just offer incentives to the foundry to build b units of capacity, which is less than the system optimal level K_f^o. When the IDM's constrained PM α-contract is not coordinating, we need to check whether viable reservation contracts exist that lead to larger expected profits for the IDM compared with the PM α-contract. We first search among

Table 4 The IDM's Profit-Maximizing α-Contract Is Not Coordinating ($b < K_f^o$)

Total cost difference (%)	Cost structure	(a, b, K_f^o)	IDM's PM α-contract (w, α), $[Z_s, Z_f]$	Coordinating α-contract (w, α), $[Z_s, Z_f]$
10	(S, S)	(215, 410, 421)	(668, 1), [270.2 K, 36.7 K]	(680, 1), [265.8 K, 41.1 K]
10	(S, IF)	(205, 400, 409)	(705, 1), [256.6 K, 46.1 K]	(720, 1), [251.4 K, 51.3 K]
20	(S, S)	(225, 430, 442)	(615, 1), [290.2 K, 40.3 K]	(629, 1), [284.9 K, 45.7 K]
20	(S, IF)	(215, 420, 429)	(663, 1), [275.9 K, 50.8 K]	(668, 1), [270.5 K, 56.3 K]
30	(S, F)	(245, 470, 488)	(518, 1), [326.8 K, 31.9 K]	(533, 1), [320.8 K, 38.2 K]
30	(S, S)	(235, 450, 466)	(559, 1), [311.4 K, 43.4 K]	(578, 1), [304.0 K, 51.0 K]
30	(S, IF)	(230, 440, 448)	(599, 1), [296.0 K, 54.8 K]	(610, 1), [291.6 K, 59.3 K]

coordinating reservation contracts. Throughout this subsection, we focus on the cases of $MOC_f > MOC_s$ and $c_s > c_f$ (i.e., the foundry has a more flexible cost structure and lower unit production cost) because these are the more likely cost structures in practice. Hereafter, we refer to them as the *superior foundry cost* cases. The coordinating reservation contracts are derived in Proposition 8.

Proposition 8. *If Assumption T and $b < K_f^o$ hold, then under the superior foundry cost case, the reservation contracts (w, r) with $r = w - c_f - (w - c_f - v_f)/F(K_f^o)$ and $c_f + v_f \le w \le c_f + v_f + (c_s - c_f)F(K_f^o)$ coordinate the centralized capacity and production decisions.*

Because the IDM's proposed reservation contract is viable only if it leads to a larger expected profit for the foundry compared with the IDM's constrained PM α-contract, we check whether the coordinating reservation contract with the largest foundry's profit is viable. It is shown that among coordinating reservation contracts specified in Proposition 8, the foundry's expected profit increases in w. Thus, we compare the foundry's expected profit under the IDM's PM α-contract with that under the coordinating reservation contract with $w^* = c_f + v_f + (c_s - c_f)F(K_f^o)$ and $r^* = w^* - c_f - (w^* - c_f - v_f)/F(K_f^o)$.

Table 5 shows that even the foundry's largest profit among all coordinating reservation contracts is much smaller than that under the IDM's PM α-contract. This implies no coordinating reservation contract is viable.

Note that in the absence of a dual-sourcing constraint, the IDM's PM α-contract is dominated by a range of coordinating reservation contracts. However, an explicit dual-sourcing requirement alters the result. Under reservation contracts, and with the IDM having to build at least a units of capacity, the subcontract price and reservation fee should be low enough so that he finds it optimal to reserve the centralized capacity level at the foundry. Such low subcontract price and reservation fee are necessary to induce the system optimal capacity profile, but unfortunately lead to very low expected profit for the foundry. In contrast, under the IDM's constrained PM α-contract, the IDM should offer to the foundry high enough w and α so that the foundry would be willing to build at least b units of capacity to satisfy the dual-sourcing constraint.

Although no coordinating reservation contract is viable, we still need to search for noncoordinating reservation contracts that might be viable and preferred by the IDM before declaring the α-contracts as equilibrium contracts for dual-sourcing cases. We check reservation contracts with $w > c_s + r$ and $w \le c_s + r$, respectively.

A reservation contract must strictly improve the system profit to possibly outperform the IDM's PM α-contract. Under all the IDM's PM α-contracts in Table 4, the capacity constraints are binding, i.e., $K_s = a$ and $K_f = b$. Proposition 9 shows that any reservation contract with $w > c_s + r$ also leads to binding capacity profile ($K_s = a, K_f = b$). However, the demand is allocated to the IDM first under reservation contracts with $w > c_s + r$, which is not consistent with the allocation rule under the centralized

Table 5 No Coordinating Reservation Contract Is Viable Due to the Foundry's Participation Constraint

Total cost difference (%)	Cost structure	(a, b, K_f^o)	IDM's PM α-contract (w, α), $[Z_s, Z_f]$	Coordinating reservation contract (w^*, r^*), $[Z_s, Z_f]$
10	(S, S)	(215, 415, 421)	(674, 1), [268.2 K, 38.7 K]	(550, 250), [303.9 K, 3.0 K]
20	(S, S)	(225, 430, 442)	(615, 1), [290.2 K, 40.3 K]	(503, 203), [323.6 K, 7.1 K]
20	(S, IF)	(215, 420, 429)	(663, 1), [275.9 K, 50.8 K]	(536, 236), [310.0 K, 16.8 K]
30	(S, F)	(245, 470, 488)	(518, 1), [326.8 K, 31.9 K]	(423, 123), [358.0 K, 1.0 K]
30	(S, S)	(235, 450, 466)	(559, 1), [311.4 K, 43.4 K]	(459, 159), [342.5 K, 12.5 K]
30	(S, IF)	(230, 440, 448)	(599, 1), [296.0 K, 54.8 K]	(488, 188), [329.5 K, 21.3 K]

system with $c_s > c_f$. Thus, reservation contracts with $w > c_s + r$ lead to a strictly lower system profit than the IDM's PM α-contract.

Proposition 9. *If Assumption T holds, then under the superior foundry cost case, no reservation contract with $w > c_s + r$ can improve the system profit over a contract that results in a binding dual-sourcing constraint.*

To improve the system profit, it is necessary to drive the foundry's capacity closer to the system's optimal level K_f^o. To achieve this, Proposition 10 gives the conditions that reservation contracts have to satisfy.

Proposition 10. *If $a + b > K_p$ and $b < K_f^o$ hold, then under the superior foundry cost case, the reservation contracts (w, r) that satisfy* (i) *$w < c_s + r$ and* (ii) *$w\overline{F(b)} + (c_s + r)F(b) < p - (p - c_s)F(a + b)$ are candidates to improve the system profit over a contract that results in a binding dual-sourcing constraint.*

Condition (ii) in Proposition 10 guarantees the subcontract price and reservation fee are low enough that it may be optimal for the IDM to reserve a capacity level greater than b and closer to K_f^o. Such a low subcontract price and reservation fee might be less attractive for the foundry compared with the IDM's PM α-contract. This is indeed the case for the parameter settings in Table 5: Among all (w, r) that satisfy conditions (i) and (ii) in Proposition 10, it has been confirmed that none lead to a larger foundry's expected profit compared with the IDM's PM α-contract. That is, all the IDM's PM α-contracts in Table 5 emerge as equilibrium contracts. Note that none of these equilibrium contracts are system coordinating.

The minimum capacity required at the foundry b is close to the centralized capacity level K_f^o in Table 5. On the other hand, if b is much less than K_f^o, there is a greater potential to improve the system profit by using the candidate reservation contracts to push the foundry's capacity closer to the centralized level, and thus candidate reservation contracts specified in Proposition 10 may be viable and preferred by the IDM, emerging as equilibrium contracts. For example, for the total cost difference of 10% and cost structure (S, S), if we change the dual-sourcing constraint from $(a, b) = (215, 415)$ to $(215, 380)$ (the total capacity drops from above the centralized total capacity $(F^{-1}((p - c_f - v_f)/(p - c_f)) = 628)$ to below it), then we can find a viable reservation contract that leads to a strictly larger expected profit for the IDM than the PM α-contract. In such cases, the equilibrium contract is a reservation contract.

6. Concluding Remarks

To the best of our knowledge, this paper is the first to study contracting issues in horizontal settings with both the supplier and manufacturer being able to build core capacities and having to horizontally coordinate their capacity expansion. It studies two prevailing types of contracts used in the semiconductor industry between IDMs and foundries: fixed commitment α-contracts and capacity reservation contracts. The IDM has access to the market demand and hence serves as the Stackelberg leader that proposes either an α-contract or a reservation contract to the foundry. This paper shows that under α-contracts the foundry always earns a positive expected profit when she commits positive capacity, but she may earn an arbitrarily-close-to-zero profit under reservation contracts. Therefore, the foundry's say in the contracting stage is captured by a participation constraint: A contract is acceptable, or "viable," to the foundry only if it leads to her expected profit that is greater than or equal to that under the IDM's PM α-contract.

The IDM's PM α-contract is an extreme one with $\alpha = 0$ or 1. However, such a PM α-contract fails to coordinate and achieve the first-best system performance. Instead, a range of coordinating reservation contracts exists that are viable and lead to strictly greater expected profits for the IDM compared with his PM α-contract. As a result, a reservation contract emerges as the equilibrium contract if the IDM is a pure profit maximizer and no explicit dual-sourcing requirements are imposed.

When risk-management concerns lead to an explicit imposition of dual-sourcing capacity profiles, these results have to be revisited. It is shown that the dual-sourcing constraint enhances the coordinating capability of α-contracts. The IDM's PM α-contract in the absence of a dual-sourcing constraint fails to coordinate because the IDM never offers a high enough wholesale price to provide adequate incentives for the foundry to build the centralized capacity level. With an explicit dual-sourcing constraint, the centralized foundry's capacity is reduced because the IDM has to build some of its own. This makes it possible for α-contracts to provide adequate incentives via a reasonable wholesale price to the foundry to build the needed capacity. Furthermore, the capacity constraint at the foundry also helps coordination when the constraint at the foundry is binding in the coordinated system. In such a situation, the IDM has to provide enough incentives for the foundry to build the centralized capacity even though the IDM's unconstrained preference for the foundry's capacity is lower. Thus, the IDM's PM α-contract coordinates under certain circumstances with the dual-sourcing constraint. When the IDM's PM α-contract is coordinating, it emerges as the equilibrium contract because compared with it no viable reservation contract can lead to a strictly larger expected profit for the IDM. This analysis offers strong supporting rationale for the effectiveness of α-contracts when risk-management concerns have to be balanced with profit maximization.

In situations where the foundry's capacity constraint is not binding in the coordinated system, the IDM's PM α-contract is not coordinating. Nevertheless, if the foundry's centralized capacity level is not much greater than her capacity constraint, both coordinating and noncoordinating reservation contracts that lead to larger system profits compared with the PM α-contract lead to lower profits for the foundry, and thus are not viable. This is because under coordinating reservation contracts or reservation contracts that improve the system profit over the IDM's PM α-contract, w and r must be low enough for the IDM to be willing to reserve the centralized foundry's capacity or a capacity level close to it, wheras under the IDM's PM α-contract, w must be high enough for the foundry to build the constrained capacity level. In such cases, the IDM's PM α-contract, although it is not coordinating, may emerge as the equilibrium contract. In contrast, if the capacity constraint at the foundry is much lower than her centralized capacity, there is greater potential to improve the system profit by pushing the foundry's capacity closer to the centralized level. As a result, viable reservation contracts may exist that improve the IDM's expected profit over his PM α-contract.

Although our problem is motivated by the semiconductor industry—an important industry in its own right—nothing prevents our analysis from being used to better understand horizontal-capacity-coordination issues in other industries.

Supplemental Material

Supplemental material to this paper is available at http://dx.doi.org/10.1287/msom.2013.0435.

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