Capacity Leadership

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This paper examines capacity leadership, in which a manufacturer builds capacity early (before it can be utilized) in order to motivate a supplier to build complementary capacity. The supplier anticipates negotiating a higher payment per unit because the manufacturer's capacity costs are sunk. When the supplier's capacity investment is noncontractible and the supplier's bargaining strength is moderately high, capacity leadership by the manufacturer strictly increases both firms' expected profits. The manufacturer's optimal level of early capacity increases as the selling price and demand for the end product increase, capacity costs decrease, or she obtains private information that demand is likely to be high. Even if the supplier's capacity investment is contractible, the manufacturer may achieve greater expected profit through capacity leadership than a contract. These results may help to explain why several manufacturers of renewable energy and energy-efficient products have built capacity early, before it could be utilized.

Key Words: capacity management, noncontractible capacity, Nash bargaining, asymmetric demand information, signaling, environmental sustainability.

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1 Introduction

This paper is motivated by the puzzling observation that manufacturers of solar photovoltaic (PV) cells, wind turbines and recycled carpet have intentionally built capacity early, before it could be utilized. That capacity sat idle while the manufacturer waited for a supplier to build complementary capacity. Worse yet, by making the capacity investment early, these manufacturers sacrificed the option to right-size capacity to realized demand. The supply chains for solar PV, wind turbines and recycled carpet have two key features in common. First, a critical supplier has a long leadtime to build capacity. Second, demand is uncertain and the manufacturer has better information about the demand distribution than does her supplier. In a model with these features, we show that by building capacity early, a manufacturer can motivate a supplier to build more capacity and thus (under specific circumstances) achieve higher expected profit. We call this "capacity leadership".

For example, consider the solar PV supply chain. Solar cell manufacturing is limited by the supply of crystalline silicon. The leadtime to build silicon capacity is approximately two years (Fisher and Rogol 2005, Zuretti 2006). Two years in advance, the demand for solar cells is uncertain as it depends upon government incentives, demand for new electricity generating capacity, and the costs of alternative types of electricity generation capacity, which are better understood by solar cell manufacturers than their suppliers. Silicon suppliers are rightly suspicious of cell manufacturers' optimistic demand forecasts, having been "burned" by unfulfilled promises of demand from semiconductor manufacturers in the late 90's (Bradford and Flynn 2006). In recent years, despite general agreement that a shortage of silicon would limit their production, solar cell manufacturers expanded capacity far in excess and ahead of production. In the US and Europe, BP Solar doubled its production capacity from 100 MW in 2004 to 200 MW in 2006, despite recognizing that silicon to feed the new production facilities would not arrive for at least two years. As expected, its capacity utilization was below 50% in 2006 and 2007 due to the silicon shortage. (BP Financial and Operating Information 2003-2007, Bruns 2007, Carey 2006). Between 2004 and 2006, solar cell manufacturers in China more than doubled aggregate production capacity and operated at capacity utilizations well below 50% due to the silicon shortage (Fisher and Rogol 2005). In the Philippines during the same time period, SunPower also built solar cell capacity ahead of its supply of silicon (SunPower Annual Reports 2005-2007).

In our second example, wind turbine manufacturing is limited by the supply of carbon fiber, gearboxes, and bearings for which the leadtime to build capacity ranges from two to five years. Demand is uncertain for the same reasons as in the solar PV industry. In 2007, turbine manufacturer Gamesa built new production facilities in the US, Spain and Portugal, although it expected to wait up to five years for matching supply, particularly of carbon fiber (BTM Consult et al. 2007).

In our third example, Interface built an innovative facility to mechanically recover nylon from used carpets. Interface intended to rely on a supplier, Universal, to remelt, blend and extrude that nylon into fiber, which Interface would then input into its existing carpet manufacturing facilities. This would require capacity expansion by Universal, with a long leadtime. Demand for any innovative recycled product is uncertain, as consumers have concerns about functionality and durability. Uncertainty in the demand for the recycled carpet was exacerbated by uncertainty regarding the price of oil, the primary input to new carpet, and uncertainty about the color and purity of the recycled nylon. While waiting for Universal to build capacity, Interface built up a huge inventory of recycled nylon, then slowed production and began to sell that nylon for auto parts (with lower value than the intended carpet product). After observing Interface's recycling capacity, Universal made a complementary capacity investment. (Nelson 2008)

Why should a manufacturer employ capacity leadership rather than a contract to motivate its supplier to build capacity? One reason is that contracting far in advance of production may be problematic. Especially in a new sourcing relationship, as a supplier is developing an innovative or complex process, unforseen contingencies may result in costly disputes and difficulties with contract enforcement (Tirole, 1999). If a manufacturer pays in advance for capacity or output, the supplier may be lax in prevention of fires, equipment malfunction, quality problems, etc. The alternative would be to contract for the manufacturer to make a future payment upon delivery of "high quality" output. However, the supplier may be skeptical of enforceability of such a contract, and hence unwilling to build capacity. These impediments to contracting are exacerbated in jurisdictions with weak court systems, such as China.

According to Lubman (1999) and Pereenbohm (2002), for hundreds of years, China has had less law than foreign traders wanted. This contributed to the Opium Wars and, for seven decades thereafter, Western nations and Japan compelled China to enforce foreign laws on its territory. Under Mao, China entirely rejected the use of law for three decades. Since 1978, to support its economic reform, China has developed contract law and a court system. However, the courts do not yet provide reliable, timely enforcement of contracts. Undue influence and corruption arises from the web of personal relationships between local businesses and the local governments that fund the courts and appoint judges. Moreover, the courts have a backlog of cases. According to Master and Tung (2010) a sourcing contract between a Chinese supplier and foreign manufacturer may explicitly adopt the law of another nation and specify that disputes will be resolved through arbitration or litigation outside China. However, courts in China may refuse to enforce a foreign arbitral award or court judgement. Manufacturers should avoid disputes with suppliers by closely tying payment to the delivery and inspection of goods, as opposed to contracting or paying in advance for future supply.

These impediments to contracting are common in the solar PV and wind turbine industries. Those industries are concentrated in China, where many suppliers are new entrants (NREL 2010, Pg. 32; SustainableBusiness.com News, 2010). Since 2007, Chinese production capacity for solar-grade crystalline silicon has increased by more than a factor of 5, and China now produces more silicon-based PV cells (measured in MW, capacity for electric power generation) per year than any other country. China also produces more wind turbines (measured in MW) per year than any other country (Renewable Energy Policy Network for the 21st Century, 2009; Martinot and Junfeng, 2010). The new entrant suppliers struggle to master the complex traditional processes for making crystalline silicon (Sunpower 2006) or the gearboxes and bearings for wind turbines (Global Intelligence Alliance 2010), and some are developing entirely new, innovative processes (NREL 2010, Pg. 30). Their production facilities have been plagued by fires, equipment malfunction, power outages and quality problems (Osborne, 2010; Barron, 2007).

PV cell and wind turbine manufacturers sometimes contract in advance to purchase components from their established suppliers in the U.S. and E.U. (Carey, 2006). However, problems tend to occur if they contract far in advance of production to spur capacity investment from new suppliers, particularly in China. For example, in 2007, PV cell manufacturer Q-Cells signed a 10-year contract to purchase silicon wafers from new entrant LDK Solar. It pre-payed \$244.4 Million (LDK Solar, 2007). In 2009, Q-Cells attempted to terminate the agreement and reclaim its \$244.4 Million because "LDK did not fulfill significant contractual obligations". Q-Cells' right to reclaim the \$244.4 Million in the event of nonperformance by LDK was secured by a German bank (Savitz 2009). However, upon a motion from LDK, the Superior People's Court in Jiangxi Province, China (wherein LDK's production facilities are located) issued a civil order that would prevent any return of payment to Q-Cells (LDK Solar 2009). Q-Cells subsequently agreed to a more flexible delivery schedule and additional payment tied to the market price of silicon (Sibley 2009), which was higher in 2009 than had been expected in 2007 (Osborne, 2010).

In our carpet recycling example, Interface and Universal could have contracted for capacity or future output. Both companies were based in the U.S. Some innovation would be required from Universal, but this was fairly well understood by both parties, which had worked together previously to recycle nylon waste from Interface's manufacturing process. Nevertheless, Interface chose to build capacity early and not to sign a long-term contract with Universal. (Nelson 2008) Consistent with this example, we show that a manufacturer may achieve strictly greater expected profit with capacity leadership than an advance contract, even if contracting is costless and perfectly enforceable.

This paper is organized as follows. After this introduction and a brief review of related literature, §2 formulates our extended newsvendor model of a 2-level supply chain; §3 characterizes the conditions under which capacity leadership increases the manufacturer's expected profit, assuming the supplier's capacity investment is noncontractible. §4 assumes that the supplier's capacity is contractible, and shows that capacity leadership can nevertheless increase the manufacturer's expected profit (though under more restrictive conditions). Assuming asymmetric information about demand, §5 shows how a manufacturer can signal a high demand forecast through capacity leadership. §6 discusses extensions and draws conclusions. Proofs are in the Appendix.

In related literature, Tirole (1999), and Guriev and Kvasov (2005) survey papers in which contracting is imperfect, parties invest in resources, and then they bargain over the use and gains from those resources. Most of these papers employ static two-period models, with simultaneous investments by all parties in the first period followed by resolution of uncertainty and bargaining in the second period. Examples in which the "resource" is capacity or inventory include (Van Mieghem, 1999; Chod and Rudi, 2006; Plambeck and Taylor, 2005; Anupindi et al., 2001; Granot and Sosic, 2003). Exceptions in which one party invests dynamically are (MacLeod and Malcomson 1993, Che and Sakovics 2004, Guriev and Kvasov 2005) and in which two parties invest sequentially are (Demski and Sappington 1991, Nöldeke and Schmidt 1998, Lülfesmann 2005). Van Mieghem (2003) surveys the literature on capacity management, and notes the lack of game-theoretic analyses of the timing of capacity investment. However, two recent exceptions (Pacheco and Zemsky, 2003; Swinney et al, 2010) consider pre-emptive early capacity investment by competing firms. Cachon and Lariviere (2001) and Özer and Wei (2006) examine how a manufacturer "signals" information about the demand distribution by the contract she offers to a supplier. Riley (2001) surveys the signaling literature.

2 Model Formulation

Consider a newsvendor-type model of capacity investments by a supplier and a manufacturer. Both firms know that demand for the manufacturer's end product is a nonnegative random variable ξ with cumulative distribution function $F(\cdot)$. (In an extension in §5, we allow for the manufacturer to have better information about demand than the supplier.) For analytic convenience, we assume in §3 and §5 that F is differentiable, $F(0) = 0$ and $F(x)$ is strictly increasing for $x > 0$.

The supplier's capacity is a complement to the manufacturer's capacity in the sense that maximum output of the end product is $\min\{K_M^E + K_M^L,\, K_S\}$. The leadtime for the supplier to build capacity is long (as in our solar PV, wind, and recycled carpet examples (Zuretti 2006, BTM Consult et al. 2007, Nelson 2008)). Therefore, the supplier must commit to his capacity level K_S before demand is realized. In contrast, the leadtime for the manufacturer to build capacity is short. The manufacturer may build some capacity K_M^E even earlier than the supplier and build additional capacity K_M^L after observing the supplier's capacity investment and the realization of demand. The cost per unit capacity is c_S for the supplier and is c_M for the manufacturer, regardless of whether the manufacturer's capacity investment occurs early or late. The manufacturer's selling price for the end product is $r > c_M + c_S$. Incremental production costs are negligible.

In our base model, the firms cannot contract in advance. Instead, they negotiate a purchase quantity and payment after the supplier has built capacity and demand has been realized. We assume that the firms have common information and therefore they negotiate to an efficient outcome and share the gains from trade, as is standard in the economics literature on incomplete contracts (Tirole 1999). The detailed sequence of events in our base model is:

1. The manufacturer builds "early" capacity K_M^E.

2. The supplier builds capacity K_S.

3. Both firms observe the demand ξ for the manufacturer's end product.

4. The firms negotiate a purchase quantity and payment. The manufacturer purchases $\min\{\xi, K_S\}$ units, pays the supplier

$$\alpha \left[r \min\{\xi, K_M^E + \bar{K}_M^L, K_S\} - c_M \bar{K}_M^L \right], \tag{1}$$

and builds additional, "late" capacity

$$\bar{K}_M^L = [\min\{\xi, K_S\} - K_M^E]^+, \tag{2}$$

where $\alpha \in [0, 1]$ represents the supplier's bargaining strength.

5. The manufacturer produces and sells the end product and earns revenue of $r\min\{\xi, K_M^E + K_M^L, K_S\}$.

In step 4, the purchase quantity is chosen to maximize ongoing total profit and the supplier captures a fraction α of the gain from trade, which is the asymmetric Nash bargaining solution (Muthoo, 2002). The manufacturer's cost for early capacity and the supplier's cost for capacity are sunk, and therefore do not enter into (1). The supplier's bargaining strength α may depend upon beliefs about what is fair or normal, patience for negotiation, personal relationships, previous experience in negotiation, the desire to obtain future business, and market forces, as described in (Porter 1979, Shell 1999, Kagel and Roth 1995, Rubinstein 1982). The manufacturer's late capacity investment $\bar{K}_M^L$ in (2) maximizes her profit. (Throughout the paper, a bar denotes an equilibrium capacity investment, which maximizes a firm's individual expected profit.) In step 2, the supplier's optimal capacity is:

$$\bar{K}_S = \text{argmax}_{K_S \geq 0}\Big\{\alpha E\big[r\min\{\xi, K_M^E + \bar{K}_M^L(K_M^E, K_S), K_S\} - c_M\bar{K}_M^L(K_M^E, K_S)\big] - c_S K_S\Big\}. \quad (3)$$

In step 1, anticipating the supplier's response $\bar{K}_S(K_M^E)$, the manufacturer optimally builds early capacity:

$$\bar{K}_M^E = \text{argmax}_{K_M^E \geq 0}\Big\{(1-\alpha)E\left[r\min\{\xi, K_M^E + \bar{K}_M^L(K_M^E), \bar{K}_S(K_M^E)\} - c_M\bar{K}_M^L(K_M^E)\right] - c_M K_M^E\Big\}. \quad (4)$$

In §4 only, we consider contracting in step 1 as an alternative to early capacity investment for the manufacturer. Let Π_S denote the optimal objective value in (3) at $K_M^E = 0$. Let Π_M denote the objective in (4) at $K_M^E = 0$. These are the firms' "outside options" in the contract negotiation. We assume contracting is costless and perfectly enforceable. Therefore, according to the "split-the-difference" rule for asymmetric Nash bargaining with positive outside options (Muthoo, 2002), the firms negotiate a contract that maximizes their total expected profit and guarantees profit for the supplier equal to his expected profit with no contract, Π_S, plus a fraction $\alpha' \in [0,1]$ of the increase in total expected profit from contracting. The detailed sequence of events under advance contracting is:

1. The firms negotiate a contract for the manufacturer to purchase $K_S^* = F^{-1}\left(1 - \frac{c_S}{(r-c_M)}\right)$ units and pay the supplier

$$\alpha'\left[(r-c_M)E[\min\{\xi, K_S^*\}] - c_S K_S^* - \Pi_S - \Pi_M\right] + \Pi_S + c_S\bar{K}_S. \quad (5)$$

2. The supplier builds capacity K_S^*.

3. Both firms observe the demand ξ for the manufacturer's end product.

4. The manufacturer builds her profit-maximizing capacity $K_M^* = \min\{\xi, K_S^*\}$ and purchases the quantity K_S^* at the contractually-specified price.

5. The manufacturer produces and sells the end product, and earns revenue of $r\min\{\xi, K_S^*\}$.

The term $(r-c_M)E[\min\{\xi, K_S^*\}] - c_S K_S^*$ in (5) is the supply chain optimal expected profit, which is achieved with capacity investments of K_S^* and K_M^* by the supplier and manufacturer, respectively. For brevity of analysis and exposition in §4, we assume $\alpha' = \alpha$, i.e., the supplier's bargaining strength is the same in advance contract negotiation as if the firms waited until after the demand realization to negotiate a price and quantity.

3 Capacity Leadership Under Symmetric Demand Information

Capacity leadership by the manufacturer can motivate the supplier to build more capacity and thus increase the manufacturer's expected profit.

Proposition 1. *In equilibrium, the manufacturer builds capacity early rather than late,* $\bar{K}_M^E > 0$ *and* $\bar{K}_M^L = 0$*, if* $\alpha \in \left(\frac{c_S}{r}, \min\left(\frac{r-c_M}{r}, \frac{c_S}{r-c_M}\right)\right)$*. Then, the manufacturer's early capacity investment* $\bar{K}_M^E$ *increases with* r *and* ξ*, and decreases with* c_M *and* c_S*.*

An increase in the random demand ξ is meant in the sense of first order stochastic dominance. Intuitively, at high levels of α, the manufacturer would be unable to recover her sunk cost in building early capacity and so builds none. At low levels of α, the supplier would be unable to recover his sunk cost in building capacity and so would build zero capacity even if the manufacturer invested in early capacity, which causes the manufacturer to build none. At moderate levels $\alpha \in \left(\frac{c_S}{r}, \min\left(\frac{r-c_M}{r}, \frac{c_S}{r-c_M}\right)\right)$, the supplier matches the manufacturer's early capacity investment, and the manufacturer more than recoups her sunk costs by selling more product. The manufacturer's optimal early capacity level increases as business conditions become more favorable (the market price and size increase or capacity costs decrease).

The proof of Proposition 1 is based on the following structural observation. The firms' equilibrium capacity investments must take one of the following two forms. In the first, the manufacturer builds early capacity and the supplier matches it, so the manufacturer builds zero late capacity:

$$\bar{K}_M^E = \bar{K}_S = \min\left\{F^{-1}\left(1 - \frac{c_S}{\alpha r}\right), \max\left\{F^{-1}\left(1 - \frac{c_S}{\alpha(r-c_M)}\right), F^{-1}\left(1 - \frac{c_M}{(1-\alpha)r}\right)\right\}\right\}$$
$$\text{and } \bar{K}_M^L = 0. \tag{6}$$

In the second, the manufacturer builds only late capacity, to match the minimum of realized demand and the supplier's capacity

$$\bar{K}_M^E = 0,\ \bar{K}_S = F^{-1}\left(1 - \frac{c_S}{\alpha(r-c_M)}\right) \text{ and } \bar{K}_M^L = \min\left\{\xi, F^{-1}\left(1 - \frac{c_S}{\alpha(r-c_M)}\right)\right\}. \tag{7}$$

Hence for $\alpha \in \left[0, \frac{c_S}{r}\right] \cup \left[\frac{r-c_M}{r}, \frac{c_S}{r-c_M}\right]$, the firms build zero capacity. ($F^{-1}(x) \equiv 0$ for $x \in (-\infty, 0)$.) *In short, the manufacturer builds early capacity, late capacity, or none. She never builds both early and late capacity.* The structure (6)-(7) follows from newsvendor logic. The quantity $F^{-1}\left(1 - \frac{c_S}{\alpha(r-c_M)}\right)$ is the optimal capacity for the supplier to build after observing zero early capacity investment by the manufacturer because the supplier's unit "underage" cost is $\alpha(r - c_M) - c_S$ and his unit "overage" cost is c_S. The quantity $F^{-1}\left(1 - \frac{c_M}{(1-\alpha)r}\right)$ is the optimal early capacity for the manufacturer to build if she anticipates that the supplier will match her capacity investment; in that scenario, the manufacturer's unit "underage" cost is $(1 - \alpha)r - c_M$ and her unit "overage" cost is c_M. The manufacturer builds early capacity only if this serves to increase the supplier's capacity. Therefore, if $F^{-1}\left(1 - \frac{c_S}{\alpha(r-c_M)}\right) \geq F^{-1}\left(1 - \frac{c_M}{(1-\alpha)r}\right)$, the manufacturer builds zero early capacity, the supplier builds capacity $F^{-1}\left(1 - \frac{c_S}{\alpha(r-c_M)}\right)$ and the manufacturer builds late capacity equal to the minimum of demand and the supplier's capacity. In contrast, if $F^{-1}\left(1 - \frac{c_S}{\alpha(r-c_M)}\right) < F^{-1}\left(1 - \frac{c_M}{(1-\alpha)r}\right)$ and the manufacturer builds early capacity, the supplier will optimally match the manufacturer's investment up to a maximum level of $F^{-1}\left(1 - \frac{c_S}{\alpha r}\right)$ because, for investment less than or equal to that of the manufacturer, the supplier's unit "underage" cost is $\alpha r - c_S$ and her unit overage cost is c_S. It follows that the optimal level of early capacity investment for the manufacturer is the minimum of $F^{-1}\left(1 - \frac{c_S}{\alpha r}\right)$ and $F^{-1}\left(1 - \frac{c_M}{(1-\alpha)r}\right)$.

Similar results hold in alternative model formulations. Intuitively, incorporating a fixed cost for capacity for either firm would expand the parameter region in which both firms build zero capacity. However, within the parameter region with capacity investment, the equilibrium timing and levels of capacity investment would remain the same. Requiring the manufacturer to build capacity before the realization of demand would expand the parameter region in which the manufacturer builds capacity early (before the supplier); the optimal level of early capacity and corresponding investment for the supplier would still be (6). When demand is a linear function of the price set by the manufacturer, the manufacturer optimally builds either early capacity or late capacity, not both, and the optimal level of early capacity decreases with the costs c_S and c_M, and increases with the intercept and the slope of the demand function.

When the manufacturer builds early capacity, this increases both firms' expected profits. However, total expected profit remains lower than the integrated-optimal level because the supplier still builds too little capacity and, with positive probability, the manufacturer has excess capacity.

4 Contracting as an Alternative to Capacity Leadership

Although the contract maximizes the firms' total expected profit, the manufacturer may prefer capacity leadership.

Proposition 2. *Suppose demand has a binary distribution: $\xi = h$ with probability ρ, otherwise $\xi = l < h$. The manufacturer has strictly greater expected profit with capacity leadership than the contract if*

$$[\alpha\rho r > c_S \geq \alpha(r - c_M)] \cap [(1-\alpha)\rho r > c_M] \cap [h((1-\alpha)c_S + ((1-\alpha)\rho - 1))c_M > -l(1-\alpha)(1-\rho)c_M] \text{ or}$$
$$[\alpha\rho r \vee \alpha(r - c_M) > c_S \geq \alpha(r - c_M)\rho] \cap [(1-\alpha)\rho r > c_M] \cap [h((1-\alpha)c_S + ((1-\alpha)\rho - 1)c_M) > l((1-\alpha)c_S - (1-\alpha)(1-\rho)c_M)].$$

When $l = 0$, those conditions are necessary as well as sufficient, and they simplify to:

$$[\alpha\rho r > c_S > \alpha\rho(r - c_M)] \bigcap [(1-\alpha)\rho r > c_M] \bigcap [c_M < (1-\alpha)(\rho c_M + c_S)]; \qquad (8)$$

The increase in the manufacturer's expected profit from using capacity leadership rather than the contract strictly increases with c_S and ρ, strictly decreases with c_M and α, but does not vary with r.

The binary distribution could represent uncertainty regarding whether or not government will enact policy to stimulate demand. Government policy is a chief source of uncertainty in the demand for solar photovoltaics and other "clean tech" products.

In (8), the first bracketed condition means that if the manufacturer builds early capacity h, the supplier matches it; however, absent early capacity or a contract, the supplier would build zero capacity. The manufacturer has expected revenue $(1-\alpha)\rho r$ per unit capacity, so the second bracketed condition means she has strictly positive expected profit from building early capacity h. The manufacturer earns the same share of expected revenue $(1-\alpha)\rho r$ per unit under the contract, but bears expected cost of $(1-\alpha)(\rho c_M + c_S)$ per unit as opposed to c_M under early capacity investment. Hence the third bracketed condition means that the manufacturer has strictly greater expected profit with capacity leadership than the contract.

Regarding the magnitude of the increase in expected profit from using capacity leadership rather than the contract, invariance with respect to r follows from the aforementioned fact that the manufacturer earns the same share of expected revenue under capacity leadership and the advance contract. An increase in c_S favors capacity leadership because the manufacturer shares the supplier's capacity cost under the advance contract but not under capacity leadership. Conversely, an increase in c_M or α favors contracting because the supplier shares the manufacturer's capacity cost under the advance contract but not capacity leadership, and the supplier's share of the cost increases with α.

In proving Proposition 2, we assumed that contracting is costless and that the manufacturer's outside option Π_M in the contract negotiation does not allow for her to build early capacity after a failed contract negotiation. The latter is justified (in the parameter region where the manufacturer prefers the contract to capacity leadership) by the fact that if the manufacturer had a strictly greater outside option than Π_M the supplier would have strictly lower expected profit under the resulting contract. Therefore the supplier should delay the negotiation or simply refuse to accept contract terms less generous than characterized in Step 1 of §2 until it is too late for capacity leadership by the manufacturer. However, in the parameter region where the manufacturer strictly prefers capacity leadership to the contract characterized in Step 1 of §2, the supplier's expected profit and total expected profit are lower under capacity leadership than the contract. Therefore, a savvy and proactive manufacturer might convince the supplier that capacity leadership is a credible threat (by arguments analogous to the proof of Proposition 2), and thus negotiate a contract that yields greater expected profit for both firms than capacity leadership. In that scenario, capacity leadership would not actually occur, but instead play an important role in determining the terms of the contract. In a numerical study, we have observed that capacity leadership may yield nearly the integrated-optimal total expected profit (especially when ρ is large). When it does so, accounting for the difficulties inherent in contracting would cause the manufacturer to strictly prefer capacity leadership even to a contract with terms reflecting capacity leadership as an outside option.

5 Capacity Leadership Under Asymmetric Demand Information

We adopt Cachon and Lariviere's (2001) model of asymmetric information about demand. The manufacturer and supplier know that demand is $\theta\xi$ where ξ is the random variable with cumulative distribution function $F(\cdot)$, and θ may take value h or l, where $h > l > 0$. The manufacturer knows θ, whereas the supplier assigns a prior probability $\rho \in (0, 1)$ that $\theta = h$ and prior probability $1 - \rho$ that $\theta = l$. We refer to a manufacturer with high demand forecast $\theta = h$ as a *high-type* and, conversely, to a manufacturer with low demand forecast $\theta = l$ as a *low-type*.

The manufacturer would like for the supplier to believe that $\theta = h$ because the supplier's optimal capacity increases with the demand distribution and the manufacturer's expected profit increases with the supplier's capacity. Hence the supplier should not trust what the manufacturer says about future demand. However, a high-type manufacturer might credibly communicate or *signal* $\theta = h$ to the supplier by building a high level of early capacity. The level of early capacity would need to be sufficiently high to deter a low-type manufacturer from making the same investment simply to mislead the supplier into believing $\theta = h$.

In a separating equilibrium, each type of manufacturer chooses a different level of early capacity that signals her type to the supplier. A separating equilibrium is characterized by solving the problem:

$$
\text{(P)} \qquad
\begin{aligned}
&\max_{K\geq 0}\{\Pi_h(K,h)\} \\
&\text{subject to: } \Pi_h(K,h) \geq \max_{K\geq 0}\{\Pi_h(K,l)\} && (9)\\
&\qquad\qquad\quad \Pi_l(K,h) \leq \max_{K\geq 0}\{\Pi_l(K,l)\} && (10)\\
&\qquad\qquad\quad K \notin \operatorname{argmax}_{K\geq 0}\{\Pi_l(K,l)\} && (11)
\end{aligned}
$$

where $\Pi_i(K, j)$ is the expected profit of the manufacturer of type i who builds an early capacity K and is assumed to be of type j by the supplier. Problem (P) partitions the set of feasible early capacity levels $K \geq 0$. The supplier assumes $\theta = h$ upon observing that the manufacturer's early capacity is an optimal solution to (P). Conversely, the supplier assumes $\theta = l$ upon observing that the manufacturer's early capacity is *not* an optimal solution to (P). These posterior beliefs for the supplier are rational in a separating equilibrium in which the high-type manufacturer chooses early capacity as a solution to (P) and the low type manufacturer chooses early capacity to maximize $\Pi_l(K, l)$. Constraint (9) and the objective function ensure that the high-type manufacturer achieves greater expected profit by building early capacity that is a solution to (P) and thus having the supplier believe that $\theta = h$, rather than by building any other level of early capacity that would lead the supplier to believe $\theta = l$. Constraints (10) and (11) ensure that the low-type manufacturer would never build early capacity in the set of optimal solutions to (P); she obtains strictly greater expected profit by choosing a capacity level that is not a solution to (P). Specifically, constraint (11) ensures that the high-type manufacturer and low-type manufacturer choose different early capacity levels in the separating equilibrium. Any separating equilibrium must have early capacity investment for the high-type manufacturer that is a solution to (P) and early capacity investment for the low-type manufacturer that is a maximizer of $\Pi_l(K, l)$, though it could be supported by different beliefs than those described above.

Exactly like under the symmetric information case analyzed in §3, both firms build zero early capacity when $\alpha \in \left[0, \frac{c_S}{r}\right] \cup \left[\frac{r-c_M}{r}, \frac{c_S}{r-c_M}\right]$. Otherwise, there exists a separating equilibrium that is unique in terms of the firms' capacity levels (except in a negligible parameter region[1]).

Proposition 3. *In the separating equilibrium, a high-type manufacturer builds early capacity. The level may be the same or strictly greater than under symmetric information. A low-type manufacturer builds the same amount of capacity at the same time as under symmetric information.*

Having private information that demand is likely to be high motivates a manufacturer to build some early capacity, in order to signal her high forecast and thus motivate the supplier to build more capacity. The manufacturer's early capacity investment is strictly higher than under symmetric information when the supplier's bargaining strength α is high (such that the manufacturer would build only late capacity under symmetric information) or when α is moderate and the manufacturer's capacity cost is low. With a low cost of capacity, the low-type manufacturer is more inclined to imitate a high-type by building early capacity. Hence the high type must build relatively more early capacity to distinguish herself.

6 Discussion

This paper shows how a manufacturer can increase expected profit through capacity leadership: building capacity early, to motivate a supplier to build complementary capacity. Capacity leadership is optimal when the supplier has moderately high bargaining power or the manufacturer has private information that demand will be high and the supplier's capacity is noncontractible. Even if it is contractible, capacity leadership may yield greater expected profit for the manufacturer than a contract. The optimal level of early capacity increases with the selling price and demand for the end product and decreases with the firms' costs of capacity.

In some industries, including airplane manufacturing, a supplier's capacity may be a substitute, rather than complement, for the manufacturer's capacity. Then, under symmetric information, the manufacturer optimally should reduce her own capacity in order to motivate the supplier to build more. However, to signal a high demand forecast, the manufacturer must nevertheless build some early capacity. For example, Boeing has relied on suppliers for increasingly large and complex subassemblies, which reduces its own

[1] If a separating equilibrium exists, it is unique in terms of the firms' capacity levels, except in a parameter region of Lebesgue measure zero. No separating equilibrium exists in a parameter region that is highly restricted but nonempty. Proof and a detailed characterization of these parameter regions is in the first author's doctoral thesis.

final assembly work (Destefani 2004). Amid the downturn in airplane demand following 9/11, Boeing closed plants and cut a third of its assembly-line workers. Boeing's CEO Alan Mulally resisted demands from labor unions to pull work back into Boeing from its suppliers. He argued that a reduction in Boeing's own capacity was necessary to ensure adequate capacity from suppliers in future, when demand would rebound (Wall Street Journal 2006).

In reality, unlike in our model, each firm has some private information about its cost of capacity. A supplier's uncertainty about the manufacturer's cost of capacity favors capacity leadership. The reason is that the optimal early capacity investment for the manufacturer and resulting expected profit are invariant with respect to the supplier's beliefs about the manufacturer's capacity cost; however, in the absence of early capacity investment by the manufacturer, uncertainty causes the supplier to build less capacity, in order to be confident that the manufacturer will match his investment. In contrast, we conjecture that a manufacturer's uncertainty about the supplier's cost of capacity will reduce the optimal level of early capacity and parameter region in which the manufacturer optimally builds early capacity. Intuitively, the manufacturer must build less early capacity to be confident that the supplier will match her investment. Asymmetric cost information might nevertheless favor capacity leadership relative to a contract because a contract negotiated under asymmetric cost information will fail to achieve the integrated-optimal total expected profit.

Our analysis also has ignored the reality of competition for the manufacturer. This is an intriguing but difficult topic for future research. Competition might favor capacity leadership insofar as a manufacturer's early capacity investment deters entry or expansion by competitors. Competition might favor an advance-purchase contract (where feasible) over capacity leadership, in order to prevent competitors from accessing the supplier's capacity. That is not necessarily true, however, because the option to sell to a competitor at a potentially higher price increases the supplier's incentive for capacity investment.

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Appendix

Proof of Proposition 1: The equilibrium is either as in (6) or in (7). The assumption $\alpha < \frac{c_S}{r-c_M}$ implies that $\bar{K}_S = \bar{K}_M^L = 0$ in (7). Therefore, to establish that $\bar{K}_M^E > 0$ and $\bar{K}_M^L = 0$, we will show that the manufacturer achieves strictly positive expected profit by building early capacity according to (6), wherein the assumption $\alpha \in \left(\frac{c_S}{r}, \min\left(\frac{r-c_M}{r}, \frac{c_S}{r-c_M}\right)\right)$ implies $\bar{K}_M^E = \bar{K}_S = \min\{F^{-1}\left(1-\frac{c_S}{\alpha r}\right), F^{-1}(1-\frac{c_M}{(1-\alpha)r})\} > 0$. The manufacturer's expected profit

$$\begin{aligned}
\Pi_M(K_M^E) &= (1-\alpha)E\Big[r\min\Big\{\xi, \bar{K}_S(K_M^E), \max\big[\min(\xi, \bar{K}_S(K_M^E)), K_M^E\big]\Big\} \\
&\quad -c_M\big[\min(\xi, \bar{K}_S(K_M^E)) - K_M^E\big]^+\Big] - c_M K_M^E \\
&= (1-\alpha)rE\left[\min\{\xi, \bar{K}_S(K_M^E)\}\right] - (1-\alpha)c_M E\big[\min(\xi, \bar{K}_S(K_M^E)) - K_M^E\big]^+ - c_M K_M^E \\
&= (1-\alpha)r\int_0^{\bar{K}_S(K_M^E)} \bar{F}(x)dx - (1-\alpha)c_M \mathbb{I}_{(K_M^E \le \bar{K}_S(K_M^E))}\int_{K_M^E}^{\bar{K}_S(K_M^E)} \bar{F}(x)dx - c_M K_M^E.
\end{aligned}$$

Therefore her optimal expected profit with early capacity investment is strictly positive, $\Pi_M(\bar{K}_M^E) > 0$, if and only if

$$(1-\alpha)r\int_0^{\min\left\{F^{-1}\left(1-\frac{c_S}{\alpha r}\right), F^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right)\right\}} \bar{F}(x)dx - c_M \min\left\{F^{-1}\left(1-\frac{c_S}{\alpha r}\right), F^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right)\right\} > 0. \tag{12}$$

In case $F^{-1}\left(1-\frac{c_S}{\alpha r}\right) \geq F^{-1}(1-\frac{c_M}{(1-\alpha)r})$, (12) holds because its left hand side simplifies to

$$
\begin{aligned}
&(1-\alpha)r\int_0^{F^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right)} \bar{F}(x)dx - c_M F^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right) \\
&> (1-\alpha)r\frac{c_M}{(1-\alpha)r}F^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right) - c_M F^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right) = 0,
\end{aligned}
$$

The strict inequality follows from our assumption that $F(\cdot)$ is strictly increasing for $x \in (0,\infty)$ and $F^{-1}(1-\frac{c_M}{(1-\alpha)r}) > 0$. In particular, as $\bar{F}(\cdot)$ is a strictly decreasing function and $F^{-1}(1-\frac{c_M}{(1-\alpha)r}) > 0$, replacing x in $\bar{F}(x)$ with the upper limit of the integral, $F^{-1}(1-\frac{c_M}{(1-\alpha)r})$, gives the strictly lowest value of the integrand $\bar{F}(x)$ within the limits of the integral, $\frac{c_M}{(1-\alpha)r}$. In case $F^{-1}\left(1-\frac{c_S}{\alpha r}\right) < F^{-1}(1-\frac{c_M}{(1-\alpha)r})$, (12) is

$$
(1-\alpha)r\int_0^{F^{-1}\left(1-\frac{c_S}{\alpha r}\right)} \bar{F}(x)dx - c_M F^{-1}\left(1-\frac{c_S}{\alpha r}\right) > 0.
$$

The function $g(K) = (1-\alpha)r\int_0^K \bar{F}(x)\,dx - c_M K$ is strictly concave because $\frac{\partial^2 g(K)}{\partial K^2} = -(1-\alpha)rf(K) < 0$. Its unique maximizer is $K = F^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right)$, and we proved above that $g\left(F^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right)\right) > 0$ and $g(0) = 0$. As $0 < F^{-1}\left(1-\frac{c_S}{\alpha r}\right) < F^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right)$, $g\left(F^{-1}\left(1-\frac{c_S}{\alpha r}\right)\right) > 0$. Therefore (12) holds.

Our assumptions that $F(x)$ is differentiable and strictly increasing in x for $x \in (0,\infty)$ guarantee that $F^{-1}(\cdot)$ has a strictly positive derivative wherever it is positive. Therefore, the result that $\bar{K}_M^E$ increases with r and decreases with c_S and c_M follows from the fact that, in the case $\bar{K}_M^E = F^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right) > 0$: **a)** $\frac{\partial F^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right)}{\partial r} = F^{-1'}\left(1-\frac{c_M}{(1-\alpha)r}\right)\frac{c_M}{(1-\alpha)r^2} > 0$, **b)** $\frac{\partial F^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right)}{\partial c_S} = 0$, **c)** $\frac{\partial F^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right)}{\partial c_M} = F^{-1'}\left(1-\frac{c_M}{(1-\alpha)r}\right)\left(-\frac{1}{(1-\alpha)r}\right) < 0$; and in the case that $\bar{K}_M^E = F^{-1}\left(1-\frac{c_S}{\alpha r}\right) > 0$: **a)** $\frac{\partial F^{-1}\left(1-\frac{c_S}{\alpha r}\right)}{\partial r} = F^{-1'}\left(1-\frac{c_S}{\alpha r}\right)\left(\frac{c_S}{\alpha r^2}\right) > 0$, **b)** $\frac{\partial F^{-1}\left(1-\frac{c_S}{\alpha r}\right)}{\partial c_M} = 0$, **c)** $\frac{\partial F^{-1}\left(1-\frac{c_S}{\alpha r}\right)}{\partial c_S} = F^{-1'}\left(1-\frac{c_S}{\alpha r}\right)\left(-\frac{1}{\alpha r}\right) < 0$. To see that $\bar{K}_M^E$ increases with the demand distribution, let $F_1(\cdot)$ and $F_2(\cdot)$ be two probability distribution functions that satisfy our assumptions for the demand distribution, $F_i(0) = 0$ and $F_i(.)$ is differentiable and strictly increasing over $(0,\infty)$ for $i = 1,2$. $F_1(\cdot)$ first order stochastically dominates $F_2(\cdot)$ if and only if $F_1(x) \leq F_2(x)$ for all $x \in (0,\infty)$, which is equivalent to $F_1^{-1}(x) \geq F_2^{-1}(x)$ for all $x \in (0,1]$. Therefore, given $1-\frac{c_S}{\alpha r} > 0$ and $1-\frac{c_M}{(1-\alpha)r} > 0$, $F_1^{-1}\left(1-\frac{c_S}{\alpha r}\right) \geq F_2^{-1}\left(1-\frac{c_S}{\alpha r}\right)$ and $F_1^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right) \geq F_2^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right)$. ■

Proof of Proposition 2: First suppose that the manufacturer negotiates a contract with the supplier in step 1, instead of building early capacity. The manufacturer's expected profit is

$$
(1-\alpha)\left[((r-c_M)[\rho\min\{h,K_S^*\} + (1-\rho)\min\{l,K_S^*\}] - c_S K_S^*) - \Pi_S - \Pi_M\right] + \Pi_M \tag{13}
$$

where Π_S is the supplier's expected profit in the event that the firms fail to negotiate a contract, the optimal objective value in (3) at $K_M^E = 0$

$$
\Pi_S(\bar{K}_S(0)) = \max_{K_S\geq 0}\left[\alpha(r-c_M)[\rho\min\{h,K_S\} + (1-\rho)\min\{l,K_S\}] - c_S K_S\right] \tag{14}
$$

and Π_M is the manufacturer's expected profit in the event that the firms fail to negotiate a contract, the optimal objective value in (4) at $K_M^E = 0$

$$
\Pi_M = (1-\alpha)(r-c_M)[\rho\min\{h,\bar{K}_S(0)\} + (1-\rho)\min\{l,\bar{K}_S(0)\}]. \tag{15}
$$

The integrated-optimal capacity for the supplier, K_S^* that maximizes (13), is

$$K_S^* = \begin{cases} 0 & \text{if } c_S \geq r - c_M \\ l & \text{if } r - c_M > c_S \geq \rho(r - c_M) \\ h & \text{if } \rho(r - c_M) > c_S > 0. \end{cases} \tag{16}$$

The supplier's capacity that maximizes the right hand side of (14) is

$$\bar{K}_S(0) = \begin{cases} 0 & \text{if } c_S \geq \alpha(r - c_M) \\ l & \text{if } \alpha(r - c_M) > c_S \geq \alpha\rho(r - c_M) \\ h & \text{if } \alpha\rho(r - c_M) > c_S > 0. \end{cases} \tag{17}$$

Capacity leadership may yield strictly greater expected profit for the manufacturer than a contract in step 1 only in the parameter region in which, absent the contract, the equilibrium is of the form (6) with strictly positive early capacity $\bar{K}_M^E > 0$. We will compare the manufacturer's expected profit with the contract versus early capacity investment in step 1 for two cases in which $\bar{K}_M^E = h$.

Case 1 $[\alpha\rho\mathbf{r} > \mathbf{c_S} \geq \alpha(\mathbf{r} - \mathbf{c_M})] \cap [(\mathbf{1} - \alpha)\rho\mathbf{r} > \mathbf{c_M}]$: The equilibrium capacities in the capacity leadership case are $\bar{K}_M^E = \bar{K}_S = h$ and $\bar{K}_M^L = 0$. Putting these into (4), the manufacturer's expected profit with capacity leadership is:

$$(1 - \alpha)[\rho r h + (1 - \rho) r l] - c_M h. \tag{18}$$

By (17), $c_S > \alpha(r - c_M)$ implies that $\bar{K}_S(0) = 0$ and, therefore, Π_S in (14) and Π_M in (15) are zero. Note that $(1 - \alpha)r > c_M$ is equivalent to $\rho(r - c_M) > \alpha\rho r$. By (16), $\rho(r - c_M) > c_S$ implies that $K_S^* = h$. Therefore, the manufacturer's expected profit with the contract (13) is

$$(1 - \alpha)[(r - c_M)\rho h + (r - c_M)(1 - \rho) l - c_S h]. \tag{19}$$

Subcase 1.1 $\mathbf{h}[[\mathbf{1} - (\mathbf{1} - \alpha)\rho]\mathbf{c_M} - (\mathbf{1} - \alpha)\mathbf{c_S}] \leq -\mathbf{l}(\mathbf{1} - \alpha)(\mathbf{1} - \rho)\mathbf{c_M}$**:** The manufacturer prefers the contract to capacity leadership by comparison of (18) and (19).

Subcase 1.2 $\mathbf{h}[(\mathbf{1} - \alpha)\mathbf{c_S} + [(\mathbf{1} - \alpha)\rho - \mathbf{1}]\mathbf{c_M}] > -\mathbf{l}(\mathbf{1} - \alpha)(\mathbf{1} - \rho)\mathbf{c_M}$**:** The manufacturer strictly prefers capacity leadership to the contract by comparison of (18) and (19).

Case 2 $[\min(\alpha\mathbf{r}\rho, \alpha(\mathbf{r} - \mathbf{c_M})) > \mathbf{c_S} \geq \alpha(\mathbf{r} - \mathbf{c_M})\rho] \cap [\mathbf{h}[(\mathbf{1} - \alpha)\rho\mathbf{r} - \mathbf{c_M}] > \mathbf{l}[(\mathbf{1} - \alpha)\rho\mathbf{r} - (\mathbf{1} - \alpha)\mathbf{c_M}]]$ $\cap[(\mathbf{1} - \alpha)\rho\mathbf{r} > \mathbf{c_M}]$: The equilibrium capacities in the capacity leadership case are $\bar{K}_M^E = \bar{K}_S = h$ and $\bar{K}_M^L = 0$. Therefore, the manufacturer's expected profit with capacity leadership is (18).

By (17), $\alpha(r - c_M) > c_S \geq \alpha(r - c_M)\rho$ implies that $\bar{K}_S(0) = l$ and, therefore, Π_S in (14) is

$$[\alpha(r - c_M) - c_S] l,$$

and Π_M in (15) is

$$(1 - \alpha)(r - c_M) l.$$

Note that $(1 - \alpha)r > c_M$ is equivalent to $\rho(r - c_M) > \alpha\rho r$. By (16), $\rho(r - c_M) > c_S$ implies that $K_S^* = h$. Therefore, the manufacturer's expected profit with the contract (13) is:

$$(1 - \alpha)\big[(r - c_M)\rho h + (r - c_M)(1 - \rho) l - c_S h - [(r - c_M) - c_S] l\big] + (1 - \alpha)(r - c_M) l. \tag{20}$$

Subcase 2.1 $\mathbf{h}[(\mathbf{1} - \alpha)\mathbf{c_S} + [(\mathbf{1} - \alpha)\rho - \mathbf{1}]\mathbf{c_M}] \leq \mathbf{l}(\mathbf{1} - \alpha)\mathbf{c_S} - (\mathbf{1} - \alpha)(\mathbf{1} - \rho)\mathbf{c_M}]$**:** The manufacturer prefers the contract to capacity leadership by comparison of (18) and (20).

Subcase 2.2 $\mathbf{h[(1-\alpha)c_S + [(1-\alpha)\rho - 1]c_M] > l(1-\alpha)c_S - (1-\alpha)(1-\rho)c_M]}$**:** The manufacturer strictly prefers capacity leadership to the contract by comparison of (18) and (20).

Combining Subcase 1.2 and Subcase 2.2, we have the sufficient condition for the manufacturer to have strictly greater expected profit with capacity leadership than the contract. For $l = 0$, one may easily verify that if Case 1 and Case 2 fail to hold then $\bar{K}_M^E = 0$. Hence the conditions in Subcase 1.2 and Subcase 2.2 are necessary and sufficient, and they simplify to (8). Substituting $l = 0$ and subtracting the manufacturer's expected profit with the contract (19) from that with capacity leadership (18), we find that the increase in expected profit from using capacity leadership rather than the contract is

$$(1-\alpha)c_S + [(1-\alpha)\rho - 1]c_M,$$

which strictly increases with ρ and c_S, strictly decreases with α and c_M, and does not vary with r. ■

Proof of Proposition 3: Let $\bar{K}_h^E$ and $\bar{K}_l^E$ denote the early capacity investments of a high- and low-type manufacturer, respectively, in a separating equilibrium. $\bar{K}_h^E$ must be an optimal solution to problem (P) and, to satisfy (10) and (11) in problem (P), $\bar{K}_l^E \in \text{argmax}_{K\geq 0}\, \Pi_l(K, l)$, which means that the low-type manufacturer builds the same capacity at the same time as under symmetric information. With any other capacity investment, the low-type manufacturer would have strictly less expected profit.

Under symmetric information, the high-type and the low-type manufacturers build zero early capacity in the same parameter region. In that parameter region, the high-type manufacturer must build a strictly positive early capacity to satisfy (11). Hence to complete the proof, we will restrict attention to the parameter region where both types would build positive early capacity under symmetric information, and prove that the high-type manufacturer builds more capacity under asymmetric than symmetric information. We will employ the following observations.

(i) The supplier's best response to the manufacturer's early capacity K when he believes that the manufacturer is of type η is:

$$K_S^*(K, \eta) = \min\left\{\eta F^{-1}\left(1 - \frac{c_S}{\alpha r}\right), \max\left\{\eta F^{-1}\left(1 - \frac{c_S}{\alpha(r - c_M)}\right), K\right\}\right\}, \tag{21}$$

and therefore:

$$\Pi_\theta(K, \eta) = (1-\alpha)r \int_0^{K_S^*(K,\eta)} \bar{F}\left(\frac{x}{\theta}\right) dx - (1-\alpha)c_M \mathbb{I}_{\{K_S^*(K,\eta)\geq K\}} \int_K^{K_S^*(K,\eta)} \bar{F}\left(\frac{x}{\theta}\right) dx - c_M K. \tag{22}$$

(ii) $\Pi_\theta(K, \eta)$ is increasing in η.

(iii) $$\frac{d\Pi_\theta(K,\eta)}{dK} = \begin{cases} (1-\alpha)c_M \bar{F}\left(\frac{K}{\theta}\right) - c_M < 0 & \text{for } K \in \left(0, \eta F^{-1}\left(1 - \frac{c_S}{\alpha(r-c_M)}\right)\right), \\ (1-\alpha)r\bar{F}\left(\frac{K}{\theta}\right) - c_M & \text{for } K \in \left(\eta F^{-1}\left(1 - \frac{c_S}{\alpha(r-c_M)}\right), \eta F^{-1}\left(1 - \frac{c_S}{\alpha r}\right)\right), \\ -c_M < 0 & \text{for } K \in \left(\eta F^{-1}\left(1 - \frac{c_S}{\alpha r}\right), \infty\right), \end{cases}$$

and $\frac{d^2\Pi_\theta(K,\eta)}{dK^2} = -\frac{(1-\alpha)r}{\theta} f\left(\frac{K}{\theta}\right) < 0$ for $K \in \left(\eta F^{-1}\left(1 - \frac{c_S}{\alpha(r-c_M)}\right), \eta F^{-1}\left(1 - \frac{c_S}{\alpha r}\right)\right)$ and $\alpha \in [0, 1)$.

(iv) For θ, $\eta \in \{l, h\}$, $argmax_{K\geq 0}\, \Pi_\theta(K, \eta)$ is either zero or:

$$K_\theta^+(\eta) \equiv \min\left\{\eta F^{-1}\left(1 - \frac{c_S}{\alpha r}\right), \max\left\{\eta F^{-1}\left(1 - \frac{c_S}{\alpha(r - c_M)}\right), \theta F^{-1}\left(1 - \frac{c_M}{(1-\alpha)r}\right)\right\}\right\}.$$

In the parameter region where the manufacturer optimally builds early capacity, her early capacity is:

$$K_\theta^+(\eta) = \min\left\{\eta F^{-1}\left(1 - \frac{c_S}{\alpha r}\right), \theta F^{-1}\left(1 - \frac{c_M}{(1-\alpha)r}\right)\right\}. \tag{23}$$

(iv) implies that $\text{argmax}_{K\geq 0}\{\Pi_l(K,h)\}$ is either zero or $\min\left\{hF^{-1}\left(1-\frac{c_S}{\alpha r}\right), lF^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right)\right\}$ whereas $\text{argmax}_{K\geq 0}\{\Pi_h(K,h)\}$ is $\min\left\{hF^{-1}\left(1-\frac{c_S}{\alpha r}\right), hF^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right)\right\}$. This motivates us to consider the following three cases, which are mutually exclusive and exhaustive. The following result holds in all cases: By (ii), $\max_{K\geq 0}\{\Pi_l(K,h)\} \geq \max_{K\geq 0}\{\Pi_l(K,l)\}$ and by (i), we observe that $\Pi_l(K,h) \to -\infty$ as $K \to \infty$. Therefore, (10) is satisfied with equality for some $K > 0$, let K_1 denote maximum such value. For each case, we will prove that any solution to (P) is $K_1 > \text{argmax}_{K\geq 0}\{\Pi_h(K,h)\}$ or $\text{argmax}_{K\geq 0}\{\Pi_h(K,h)\}$.

Case 1 $\mathbf{lF^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right) \leq hF^{-1}\left(1-\frac{c_S}{\alpha(r-c_M)}\right)}$: By (iii), $\Pi_l(K,h)$ is strictly decreasing. If $K_1 > \text{argmax}_{K\geq 0}\{\Pi_h(K,h)\} = K_h^+(h)$, then there is no capacity level $K < \text{argmax}_{K\geq 0}\{\Pi_h(K,h)\}$ that satisfies (10). On the other hand, if $K_1 < \text{argmax}_{K\geq 0}\{\Pi_h(K,h)\}$, then $\text{argmax}_{K\geq 0}\{\Pi_h(K,h)\}$ also satisfies (10) and, by (ii), satisfies (9), and given that $K_h^+(h) > K_l^+(l)$, satisfies (11). Therefore, $\text{argmax}_{K\geq 0}\{\Pi_h(K,h)\}$ is the unique optimal solution to problem (P).

Case 2 $\mathbf{hF^{-1}\left(1-\frac{c_S}{\alpha(r-c_M)}\right) < lF^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right) < hF^{-1}\left(1-\frac{c_S}{\alpha r}\right)}$: By the same arguments as in Case 1, we eliminate the cases where K_1 is unique. We will now consider the case where there are multiple capacity levels where constraint (10) is binding. By (iii), $\Pi_l(K,h)$ strictly decreases over $K \in \left(0, hF^{-1}\left(1-\frac{c_S}{\alpha(r-c_M)}\right)\right)$, strictly increases over $K \in \left(hF^{-1}\left(1-\frac{c_S}{\alpha(r-c_M)}\right), lF^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right)\right)$, and strictly decreases over $K \in (lF^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right), \infty)$. Moreover, $\Pi_l(K,h) \to -\infty$ as $K \to \infty$. Therefore, at most three early capacity levels (K_1, K_2 and K_3) can satisfy $\Pi_l(K,h) = \max_{K\geq 0}\{\Pi_l(K,l)\}$ where $K_1 > K_l^+(h)$, $K_l^+(h) > K_2 > hF^{-1}\left(1-\frac{c_S}{\alpha(r-c_M)}\right)$, and $hF^{-1}\left(1-\frac{c_S}{\alpha(r-c_M)}\right) > K_3 \geq 0$. We will analyze the case where all three exist to prove that the optimal solution of problem (P) must be grater than $\text{argmax}_{K\geq 0}\{\Pi_h(K,h)\}$. That this result holds in cases with two early capacity levels K_1 and K_2 follows from essentially the same arguments. K_1 induces a strictly higher objective function value, $\Pi_h(K,h)$, than K_2 and K_3 because by observing the derivatives of $\Pi_h(K,h)$ and $\Pi_l(K,h)$ with respect to K in (iii), $\frac{\partial[\Pi_h(K,h)-\Pi_l(K,h)]}{\partial K} > 0$ if $K < hF^{-1}\left(1-\frac{c_S}{\alpha r}\right)$ and $\frac{\partial[\Pi_h(K,h)-\Pi_l(K,h)]}{\partial K} = 0$ if $K > hF^{-1}\left(1-\frac{c_S}{\alpha r}\right)$, and by definition $\Pi_l(K_1,h) = \Pi_l(K_2,h) = \Pi_l(K_3,h)$. The early capacity levels $K < K_3$ and $K_2 < K < K_1$ do not satisfy (10) due to the aforementioned derivatives of $\Pi_l(K,h)$ with respect to K. The early capacity levels $K_3 < K < K_2$ induce a strictly lower value of $\Pi_h(K,h)$ than K_2 because $\frac{\partial[\Pi_h(K,h)-\Pi_l(K,h)]}{\partial K} > 0$ if $K < hF^{-1}\left(1-\frac{c_S}{\alpha r}\right)$, and the early capacity levels $K_3 < K < K_2$ induce a lower value of $\Pi_l(K,h)$ due to the fact that $\Pi_l(K,h)$ strictly decreases over $K \in \left(0, hF^{-1}\left(1-\frac{c_S}{\alpha(r-c_M)}\right)\right)$, and strictly increases over $K \in \left(hF^{-1}\left(1-\frac{c_S}{\alpha(r-c_M)}\right), K_l^+(h)\right)$. If $K_1 > K_h^+(h)$, then K_1 induces a strictly higher value of $\Pi_h(K,h)$ than the early capacity levels $K > K_1$ because $\frac{\partial[\Pi_h(K,h)-\Pi_l(K,h)]}{\partial K} = 0$ if $K > hF^{-1}\left(1-\frac{c_S}{\alpha r}\right)$, and the early capacity levels $K > K_1$ induce a lower value of $\Pi_l(K,h)$ due to the fact that $\Pi_l(K,h)$ strictly decreases over $K \in \left(K_l^+(h), \infty\right)$. Therefore, K_1 induces the strictly highest value of the objective function $\Pi_h(K,h)$, among all early capacity levels that satisfy (10). Finally, if $K_l^+(h) < K_1 < K_h^+(h)$, then by (iii), $\text{argmax}_{K\geq 0}\{\Pi_h(K,h)\}$ also satisfies (10) and the other constraints in problem (P) by the same arguments as in Case 1. Therefore, $\text{argmax}_{K\geq 0}\{\Pi_h(K,h)\} = K_h^+(h)$ is the unique optimal solution to problem (P).

Case 3 $\mathbf{hF^{-1}\left(1-\frac{c_S}{\alpha r}\right) \leq lF^{-1}\left(1-\frac{c_M}{(1-\alpha)r}\right)}$: By (iv), $K_h^+(h) = K_l^+(h) = hF^{-1}\left(1-\frac{c_S}{\alpha r}\right)$. Therefore, by the same arguments as in Case 2, $K_1 > \text{argmax}_{K\geq 0}\{\Pi_h(K,h)\}$ induces the strictly highest value of the objective function $\Pi_h(K,h)$, among all early capacity levels that satisfy (10). ■