R&D OPTION STRATEGIES

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R&D OPTION STRATEGIES

This paper uses an integrated real options and game-theoretic framework for strategic R&D investments to analyze two-stage games where the growth option value of R&D depends on endogenous competitive reactions. In this model firms choose output levels endogenously and may have different (asymmetric) production costs as a result of R&D, investment timing differences or learning. The model illustrates the trade-off between the flexibility value and the strategic commitment value of R&D that interacts with market structure via altering the competitor's equilibrium quantity or changing the market structure altogether (e.g., from Cournot equilibrium to Stackelberg or monopoly). Comparative statics provide rich results for competitive R&D strategies depending on uncertainties in market demand and in the outcome of R&D, on whether R&D benefits are proprietary or shared, on imperfect or asymmetric information with signaling, on learning or experience cost effects, and on competition in R&D versus cooperation via a joint research venture.

R&D OPTION STRATEGIES

We consider various extensions to the standard investment problem under uncertainty. The standard NPV rule is typically applied to one-stage investment problems (e.g., building a plant or commercializing a new product), taken immediately or never, without any strategic considerations. The early real options literature (e.g., McDonald & Siegel, 1986) highlighted the value of the option to “wait and see” under demand uncertainty, justifying deferral of even positive-NPV projects. A part of the strategy literature instead focused on the benefits of investing early, e.g., by preempting competitive entry (Dixit, 1979, 1980) or generating learning experience cost effects through cumulative production (Majd and Pindyck, 1993). An alternative way to lower future production costs is to invest in R&D to develop a more cost-efficient production process. Now the R&D investment problem involves a two- (or multi-) stage analysis, with the first stage (research) effectively being a (compound) option on the latter stage (commercialization); the latter stage is discretionary, and hence must be valued as an option since management would proceed (and pay the commercialization cost) only if the first stage is successful, but not otherwise. This growth option value can justify taking negative-NPV investments. (The firm may even choose the optimal timing of investing in R&D, trading off the benefits of future cost savings against the option value of waiting under demand uncertainty.)

But more importantly, there is a strategic benefit to early investment commitment in terms of improving a firm’s relative competitive position (e.g., via a cost advantage) and influencing the competitor’s behavior. The problem then involves a tradeoff between the option value of waiting and the strategic benefits of early commitment --even from the perspective of a single firm (Baldwin, 1987). The value of these strategic benefits may depend on whether the firm can keep them proprietary or whether they are diffused to the industry (Kester, 1984). But in a dynamic environment, the competitor is probably faced with a similar opportunity, to make an R&D investment early or wait, taking each other’s behavior into account. Further, each firm can decide to invest in R&D independently (i.e., compete in R&D), or both firms may do so jointly (collaborate via a joint research venture).

An R&D investment may generally involve the resolution of multiple sources of uncertainty. Besides the market demand uncertainty, there may be technical uncertainty concerning the outcome of each firm’s R&D effort, that also may influence the investment decision of two competing firms. Each firm’s decision would then depend on whether it has complete or incomplete information about the resolution of the other's technical R&D uncertainty (success); in case of asymmetric information, each firm also faces a decision of whether to signal truthful information or not.

This paper combines the real options framework with game-theoretic industrial organization principles to model the above complexities and derive economic implications that may help explain strategic investment behavior under uncertainty. Our basic model examines a two-stage game where the option value of R&D depends on endogenous competitive reactions. We consider a sequence of investment decisions by a pioneer firm involving a first-stage strategic (R&D) investment commitment that can influence its strategic position (relative future production costs) vis-à-vis its competitor in the second stage, and subsequent productive investment (commercialization) decisions by either competitor. The model illustrates the tradeoff between flexibility value of waiting and the strategic commitment value of R&D that interacts with market structure via altering the competitor's equilibrium quantity or changing the market structure altogether (e.g., from Cournot Nash equilibrium to Stackelberg leadership or monopoly). We then extend the basic model by developing various competitive strategies depending on uncertainty in market demand and a stochastic outcome of the R&D effort, on proprietary or shared benefits of R&D, imperfect or asymmetric information with signaling, learning or experience cost effects, and R&D competition versus cooperation via a joint research venture.

There is a diverse literature related to the various aspects of this investment problem, besides the standard real options literature.[1] Baldwin (1982) finds that optimal sequential investment may require a positive premium over NPV to compensate for the loss of future investment opportunities. Dixit (1989) discusses a firm's entry and exit decisions under uncertainty, while Pindyck (1988) discusses the effect of flexibility in deferring irreversible investment and capacity choice on the value of the firm. Competitive interaction and growth option value were discussed qualitatively in Kester (1984).[2] Kulatilaka and Perotti (1992) find that, in a

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[1] The rapidly growing real options literature includes Kester (1984), McDonald and Siegel (1985, 1986), Titman (1985), Trigeorgis and Mason (1987), Dixit (1989), Pindyck (1988, 1991), Trigeorgis (1991, 1993), Ingersoll and Ross (1992), Kulatilaka and Perotti (1992), Grenadier and Weiss (1995), and others. The books by Dixit and Pindyck (1994) and Trigeorgis (1996) provide a nice treatment of real option investment under uncertainty.

[2] As Kester (1984), Trigeorgis (1991a, Kulatilaka and Perotti (1992), Grenadier (1996) and others have also pointed out, an options approach to strategic investing should be seen from the perspective of competitive market structure. Williams (1993) and Grenadier (1996) use game theory to model exercise strategies for real estate development. Competitive strategies using basic option and game-theory principles are developed in Smit and Ankum (1993). We refer to the book by Tirole (1992) for an excellent overview of strategic aspects of investment behavior in IO.

duopoly setting, the market share and value of early investment by a first mover increases with higher uncertainty.

In the IO literature, Dixit (1979, 1980) and Spence (1977, 1979) provide various treatments of investments (such as building excess capacity) designed to preempt competitive entry. The degree of information possessed by competitors and competitive signals can also influence productive investment. Early work on signaling effects in the context of preemptive strategies can be found in Spence (1977, 1979). McGahan (1993) models the effect of incomplete information about demand on a firm's commitment value and finds that incomplete information about demand reduces the incentive to invest in capacity early on. Spatt and Sternbenz (1985) analyze preemption under learning and the influence of the number of competitors on market equilibrium. Majd and Pindyck (1993) show that production is beneficial in reducing the future cost of production and quantify the effect of learning on option value, providing an incentive to invest early on. Learning, being an alternative (to R&D) for reducing future production costs, is an important factor influencing the timing of R&D investment and subsequent capacity commitment in a competitive context.[3]

In energy, Pindyck (1980) notes that a monopolist will intensify exploratory activity for exhaustible resources later relative to a competitive industry. In R & D, Dasgupta and Stiglitz (1980) show that an incumbent firm can preempt potential competitors by spending excessive amounts on R & D; they also find that a monopolist would delay innovation whereas the threat of competition may induce a firm to innovate earlier. Reinganum (1983) argues that entrants stimulate innovation both through their own provocative behavior and through their provocation of incumbent firms. Baldwin (1987) discusses the tradeoff between preemption and flexibility value for new product introductions and shows that an entrant is more likely to innovate than a monopolist.

Another interesting question of current importance is whether firms should independently compete or cooperate in R&D. Fudenberg and Tirole (1984, 1985) examine the effect of tough and accommodating positions on second-stage value when firms are strategic substitutes or complements. Tirole (1992, pp. 413) remarks that, surprisingly, there has been very little work done on the subject of joint research ventures in view

[3] In this model we expand the results of Majd and Pindyck (1993) by comparing the effect of learning with an extra strategic benefit to a cost-saving R&D investment in an interactive competitive setting.

of their potential importance. Among the few exceptions, Ordover and Willig (1985) and Grossman and Shapiro (1986) recognize that joint R&D ventures may help rivals avoid competition in the R&D market.[4]

A number of the results in this paper provide incremental contributions over previous work. First, contrary to standard option valuation, we find that the value of an R&D investment opportunity may no longer increase monotonically with demand uncertainty (or with maturity and other option parameters) because strategic preemption may cause value discontinuities (e.g., higher variability may shift demand below the critical demand investment threshold into a different zone where it may be unprofitable for the competitor to operate).[5] The sign and magnitude of this effect on R&D value depends on the proprietary or shared nature of the investment, on technical R&D uncertainty, on the degree of incomplete information, the existence of learning effects, and on the willingness to compete or form joint research alliances. Second, we show that the effect on R&D value can be opposite for proprietary than for shared investments. Third, the presence of technical R&D uncertainty in the outcome of each firm's R&D effort reduces the strategic (preemption) value of R&D (since R&D may fail) and mitigates the value discontinuity due to preemption. Fourth, under incomplete information about the outcome of the competitor's R&D effort, signaling strategies (about when to truthfully inform the competitor or not) can be devised in a way that benefit the innovator as well as the competitor. Fifth, if a firm can alternatively reduce future costs via learning experience effects, there is an incentive to invest early; however, there is also an extra strategic preemption benefit of early R&D investment since preemption can eliminate the competitor's learning advantage. Finally, besides reducing (sharing) the research costs, collaboration in R&D enables firms to more fully appropriate the flexibility value from waiting and avoid the competitive pressure to invest prematurely (a prisoner's dilemma), despite any potential sacrifice of strategic (e.g., preemption) value.

The remainder of the paper is organized as follows: Section 1 describes the basic two-stage R&D investment game within an integrated real options and industrial organization framework and discusses how the valuation works. Section 2 deals with proprietary vs. shared investments and discusses critical demand zones

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[4] The classic examples of the attrition game between JVC, Sony and Philips in the development of the video-recorder in the 1980s, where all three introduced different systems with the losers getting badly damaged, compared to the agreement to adopt a common standard in the introduction of the CD player among the same players a decade later, illustrate the increasing importance of R&D cooperation in today's competitive environment.

[5] Higher uncertainty generally increases the deferral or flexibility value which is lost when making an early R&D investment commitment, but it may either increase or decrease strategic value (from influencing a competitor's equilibrium output),

and sensitivity results. The comparative statics investigation continues in section 3 with technical R&D uncertainty, stochastic reaction functions and asymmetric information. Section 4 examines the impact of learning cost effects, while section 5 examines competition vs. cooperation in R&D. The last section concludes and discusses various implications.

1. A Real Options and Industrial Organization Framework

This section describes the two-stage competitive R&D investment problem under demand uncertainty, assuming a duopoly market structure. Each of two competitors faces a decision as to whether and when to make an R&D investment as well as follow-up commercialization investment decisions. The firms compete in the commercialization stage, and may also compete (or collaborate) in the research stage. The type of competition in each of the two stages affects the equilibrium production, optimal investment strategy and upfront R&D investment value. The basic two-stage game is described next, followed by a description of the end-node equilibrium payoff values and the valuation of competitive R&D strategies; this section ends with a base-case illustration. In subsequent sections we investigate how the outcome of these games and therefore R&D value is influenced by the proprietary or shared nature of the R&D investment, by technical R&D uncertainty and asymmetric information/signaling, learning cost effects, and the possibility of collaboration in the R&D stage.

The Basic Two-stage Game

Consider an R&D investment by firm A (or B) involving the development of a new, cost-efficient technological process that can influence the firm's relative competitive position (vis-à-vis firm B) via lowering its operating costs ($c_A < c_B$) in a later stage of the market. The value of firm A's strategic R&D investment (requiring an outlay K_A) is determined relative to the base case of no R&D (i.e., continue using the existing technology, with $c_A = c_B$). In addition to market demand uncertainty, the innovation strategy may also involve technical uncertainty in that with probability η_i or $(1-\eta_i)$ the R&D effort by firm i (i = A, B) may succeed or fail. This technical R&D uncertainty is unrelated to market movements and is therefore of a non-systematic nature (i.e., it is not priced).

[Exhibit 1 about here]

possibly by a higher amount; a jump in value may even result as uncertainty increases, shifting from one demand zone (e.g., Cournot Nash equilibrium) to another (e.g., Stackelberg or monopoly), depending on initial demand.

The alternative actions by each firm i (i = A, B) to make the strategic R&D investment (K_A or K_B) or to defer (D) are shown by the tree branches in the first stage (panel A) of Exhibit 1. Either firm A or B can decide to make a strategic R&D investment (shown by squares,). If both firms decide to invest simultaneously (K_A, K_B), technical uncertainty gets resolved with probability of R&D success η_A or η_B, possibly resulting in asymmetric future production costs ($c_A \neq c_B$). Under low demand realization (low commercialization potential) both firms may choose to defer (D, D) maintaining symmetrical costs, whereas only one firm alone may invest in R&D (K, D or D, K) at intermediate levels of demand.[6]

The commercialization-phase (stage 2) market structure is also assumed to result in a duopoly under quantity competition, where either of the two competing firms (A or B) may invest (I) in subsequent production capacity (using either the existing or the new technology from R&D) or defer investment (D) during either of two sub-periods (1 and 2). The dynamics of market demand in the second stage are represented by nature's (θ) random up (u) or down (d) moves, according to the linear demand function

$$P(Q, \theta_t) = \theta_t - (Q_A + Q_B), \tag{1}$$

where θ_t is the demand shift parameter, P is the market price, and Q_i is the production quantity of firm i (i = A, B).[7] The resolution of *market demand uncertainty* θ in the second stage is shown by circles (o) in Exhibit 1 (panel B). The second-stage (commercialization) game is similar to the first-stage duopoly (R&D) game described above, except for the two sub-periods that allow for potential investment timing differences among the firms. When both firms decide to invest (produce) *simultaneously* in the second stage (I, I), the game ends in a Cournot Nash equilibrium (C); when both firms choose to defer (D, D) under low realizations of demand, nature (θ) moves again and the game is repeated; finally, when one firm invests first in a *sequential* game, acting as a Stackelberg leader (S^L) --or in some cases a monopolist (M)-- market demand is revealed again and the competitor may then decide to invest later --as a Stackelberg follower (S^F)-- or to abandon (A).

Equilibrium Payoff Values

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[6] The first-stage R&D game may thus result in a second-stage commercialisation phase (panel B of Exhibit 1) with asymmetrical production costs (e.g., at K, D or D, K with R&D success), with lower but symmetric costs (e.g., at KK when both succeed in R&D), or with the same base-case costs of the existing technology (e.g., at DD, or in case of technical R&D failure at KK, KD or DK).

[7] We later examine robustness of our results to different specifications of the functional form of the demand and cost functions (e.g., an isoelastic demand curve of the form $P = \theta.Q^{-1/\eta}$) and find that they are essentially the same.

In this section we describe the equilibrium payoff values *at the end* of the last stage of our investment problem. These terminal equilibrium payoff values are a non-linear function of the evolution of exogenous market demand (θ). For example, for high levels of demand the early investor captures a greater market share than new entrants; for intermediate levels of demand the early investor may delay or deter potential entrants and capture Stackelberg leadership or monopoly rents; for very low levels of demand the early investor may not find it profitable to invest in the follow-up commercial project. The different market structure games in the commercialization stage (see bottom of Exhibit 1 and Table 1) briefly are as follows:[8]

(i) Cournot Nash Competition (C). If both firms decide to invest in productive capacity (I) in the same period *(simultaneously)*, a Cournot Nash equilibrium is reached when each firm reacts optimally to the other firm's expected quantity (as expressed by its reaction function, R), i.e., $Q^*_A = R_A(Q^*_B)$ and $Q^*_B = R_B(Q^*_A)$.[9] Thus, the Cournot Nash equilibrium quantities, Q^*_A and Q^*_B, are on the intersection of the reaction functions of the two firms (shown as outcome C in Exhibit 2).

(ii) Stackelberg Leadership (S). If one firm invests first in follow-up productive capacity and its competitor invests in a later period, a Stackelberg leader/follower game can result. Given that the follower will observe the leader's prior output, the Stackelberg leader will choose that output on the follower's reaction function, $R_B(Q_A)$, that will maximize its own profit value, i.e., max $V_A(Q_A, R_B(Q_A))$ over Q_A (shown as point S in Exhibit 2).

(iii) Monopoly (M). In some cases, the leader may choose an early action (e.g., a high enough quantity) on the follower's reaction curve such that it would become unprofitable for the follower to operate ($\pi_B(Q_A, Q_B) < 0$, or net of the required outlay, $NPV_B < 0$), preempting its entry and earning monopoly profits (π_m).

(iv) Do Not Invest/Defer (D) or Abandon (A). The firm, of course, has the option not to invest in production capacity or to wait if market demand (θ) is low and undertaking the project would thereby result in a negative value. In case the firm does not invest up until the very last stage, or if it decides to abandon, the value of follow-up investment is truncated to 0.

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[8] The symbols C, S, M, A, D at the bottom of Exhibit 1 refer to the different market structure games described herein (and summarized in Table 1). As noted, the state payoff values at the end of the second stage are the outcomes of different market structure games depending on the state of demand (θ), each firm's actions (invest, do not invest/defer) and their timing (simultaneous or lagged, at t = 1 or 2).

[9] A reaction function assigns to every output level of one firm the value-maximizing output of the other (in quantity competition).

[insert Exhibit 2 about here]

In Appendix 1 we present a model that provides closed-form analytic expressions for quantifying the equilibrium quantities (Q*), profits ($\pi*$), and state net project values (NPV*) at the end states (nodes) under the various market structures (e.g., Cournot, Stackelberg or monopoly). The equilibrium quantities and profit values for the various market structures are summarized in Table 1. Appendix 2 derives the equilibrium quantities and profit values under the various market structures with learning experience cost effects by either firm. The equilibrium path to reach these terminal values depends on the evolution of market demand and the outcome of the competitive subgames in the two stages.

Valuation of Competitive R&D Strategies

The equilibrium set of strategies is found by backward binomial valuation, starting with the end-node payoff (equilibrium state net project) values of a given competitive structure summarized in Table 1 and working back through the tree of Exhibit 1. The strategic impact of R&D investment is captured via changing asymmetrically the second-stage production cost structure (i.e., the relative operating costs, c_A vs. c_B) and through its impact on equilibrium payoff values and resulting competitive reactions in the two-stage game of Exhibit 1. We examine (*a*) proprietary vs. shared cost advantage from the R&D investment; (*b*) complete vs. imperfect information concerning the success of each competitor's R&D effort; (*c*) learning cost effects where either firm can achieve future cost reduction by investing in production capacity early (besides reducing future costs by making a first-stage R&D investment); (*d*) competing in R&D vs. cooperating via a joint R&D venture.

In each case above, the competitive strategy of each firm consists of mapping the information set about its competitor's actions and the development of market demand (u or d moves in θ) to an optimal investment action by the firm. The current value of a claim on project value, C, is then determined from its future up and down state values (C_u and C_d) discounted at the risk-free interest rate (r), with expectations taken over risk-neutral (or "certainty equivalent") probabilities (p) (e.g., see Cox, Ross and Rubinstein, 1979, Brennan and Schwartz, 1985):[10]

[10] Firms presumably create value by investing in projects for which the market (present) value of expected cash inflows, V, exceeds the required investment outlay, I. Therefore, we must determine what a project would be worth if it were traded in the financial markets (see Mason and Merton, 1985). Following Majd and Pindyck (1987), we here adopt the assumption of complete markets in which there exist portfolios of securities that replicate the dynamics of the present value of the project caused by changes in equilibrium state profits. In such complete markets, the risk-neutral probabilities can be obtained from:

$$C = \frac{pC_u + (1- p)C_d}{1+ r}. \qquad (2)$$

The market demand parameter θ is assumed to follow a multiplicative binomial process (or random walk) in complete markets, moving up to $\theta_u \equiv u\theta$ or down to $\theta_d \equiv d\theta$ over each period. The upfront strategic R&D investment decision is based on a *strategic* (or *expanded*) NPV criterion (or NPV*) that incorporates not only the direct NPV of expected incremental net cash flows (e.g., cost savings), but also the strategic value from future competitive interactions as well as the option or flexibility value from deferring investment or revising future decisions. That is,

Strategic net present value (NPV*) = [direct NPV + strategic value] + flexibility value (3)

The incremental value of making the strategic R&D investment (vs. the base-case of no R&D investment) may have both a direct effect on the innovating firm's profit value via lowering its own future production costs as well as an indirect or strategic effect via altering the competitor's equilibrium production quantity.[11] The total strategic value in (3) above consists of this *strategic reaction value* (reflecting the impact of competitor's reaction on profit value via incremental changes in equilibrium quantity for a given market structure) and of a *strategic preemption value* from changing the market structure altogether, e.g., from Cournot Nash equilibrium in the

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$$p = \frac{(1 + r) - (d + \delta)}{(u - d)},$$

where u and d represent the multiplicative up or down moves in market demand, r is the risk-free interest rate, and d is the constant asset (dividend-like) payout yield (equal to k/(1+k) for a perpetual project, where k is the risk-adjusted discount rate).

[11] The strategic effect results from the impact of firm A's strategic investment K_A on competitor firm B's optimal second-stage quantity, dQ^*_B/dK_A, and *its* resulting indirect impact on firm A's profit value (for details see Tirole (1990)):

$$\frac{dV_A}{dK_A} = \frac{\partial V_A}{\partial K_A} + \frac{\partial V_A}{\partial Q_B}\frac{dQ_B^*}{dK_A}$$

(commitment effect = direct effect + strategic effect) base case (staying with the existing, costlier process) to a Stackelberg leadership or monopoly equilibrium under the strategic investment alternative.[12]

Base-case Illustration

To illustrate how the valuation works, consider the simplest form of the game where only one of the two firms (pioneer firm A) can make a first-stage strategic R&D investment that results in a deterministic operating cost advantage in the second stage (commercialization). The general first-stage R&D game of Exhibit 1 is here reduced to the special case of a single R&D investment decision by firm A (only), without any technical R&D uncertainty or learning. We assume that pioneer firm A can enhance its relative competitive position by making an early R&D investment of $K_A = 100$ in a more cost-efficient technological process. In the second stage, either firm A or B can invest I = 100 in follow-up production capacity (commercialization projects), depending on subsequent random demand moves (where initial demand is $\theta_0 = 17.5$ and can move up or down with binomial parameters u = 1.25 and d = 1/u = 0.80). The risk-free interest rate (r) is 10% (while the risk-adjusted discount rate in the last stage is k = 13%). If firm A chooses not to make the R&D investment (base case) the two firms would have symmetric second-stage operating costs, based on the old technology, of $c_A = c_B = 5$.

[insert Exhibit 3 about here]

Exhibit 3 illustrates the valuation results (state project values) for the base-case alternative of no R&D in both periods during the commercialization stage of this simplified basic game. The optimal competitive strategies are derived by utilizing the project payoff values summarized in Table 1. For example, in subgame 1 (C) at the bottom of Exhibit 3, when θ = u and both firms defer (D, D) and then θ moves down and both firms invest (I, I), the resulting Nash Cournot equilibrium value (see Appendix 1 eq. A1.7 or first row in Table 1) is:

[12] The strategic value may be positive (e.g., if early investment creates a proprietary cost advantage and/or deters competitive entry), or negative (if early investment proves the market or creates shared benefits that a competitor can exploit). We subsequently refer to the incremental direct NPV (net of the required investment outlay, K) and the total strategic value (reaction value + preemption value) resulting from an early strategic investment commitment as the *net commitment* value.

$$NPV_A = \frac{(\theta_t - 2c_A + c_B)^2}{9k} - I = \frac{(17.5 - 2(5) + 5)^2}{9(.13)} - 100 = 34.$$[13]

When θ = d in period 2, the Cournot equilibrium value is 327. The expected equilibrium value one step earlier (in period 1) is then obtained from these values using eq. (2) (with p = 0.41):

$$\frac{.41(327) + .59(34)}{1.10} = 140.$$

The other values shown in the two boxes of Exhibit 3 in period 1 of the commercialization stage are derived similarly. Note that if θ = u (left box), each firm has a dominating strategy to invest in production capacity (I) regardless of the other's actions (for each firm 303 > 140 if the competitor defers and 143 > 52 if it invests), resulting in a symmetric Cournot Nash equilibrium outcome of (143, 143). For θ = d (right box), however, both firms may choose to defer and obtain (13, 13). Finally, from the backward binomial risk-neutral valuation of eq. (2), the expected equilibrium value for the base-case (no R&D) strategy at t = 0 is:

$$NPV^*_A = \frac{.41(143) + .59(13)}{1.10} = 60.$$

The base-case value of no R&D investment is (by construction) symmetric for both firms, i.e., (60, 60) for firm (A, B). By way of an overview, Table 2 summarizes the breakdown of total value into various components for

[13] In subgame 2 (M) next to it, when firm A invests and B defers, A's monopoly (net) profit value (from eq. A1.11 with q = 0 or second row in Table 1) is:

$$\frac{(\theta_t - c)^2}{4k} - I = \frac{(17.5 - 5)^2}{4(.13)} - 100 = 200.$$

In subgame 3 (S), when θ = u and A invests while B defers (I, D) but then decides to invest in the next period (2) if θ moves up, the resulting Stackelberg leader equilibrium value for A is given by (see Appendix A eq. A1.7 or third row in Table 1):

$$NPV_A = \frac{(\theta_t - 2c_A + c_B)^2}{8k} - I' = \frac{(17.5 \times 1.25)^2 - 2(5) + 5)^2}{8(.13)} - 100 = 380.$$

each of the cases we examine. In the above base case (column 1), total value (60) consists of a base case NPV of 37 and a flexibility value of 23.

[insert Table 2 about here]

2. Proprietary vs. Shared R&D Investment

When one of the firms (e.g., firm A) decides to make a strategic R&D investment, two different strategies can result depending on whether the resulting cost benefits of the second-stage commercialization project are proprietary (asymmetric costs) or shared (symmetric). Consider first the case where making a strategic R&D investment results in a *proprietary* operating cost advantage for firm A during commercialization. Specifically, suppose the second-stage operating cost for firm A is reduced from 5 to 0 ($c_A = 0$) if it invests in R&D (with sure success) while for firm B it remains at 5 ($c_B = 5$) --as compared to the base case ($c_A = c_B = 5$) when neither firm invests in R&D. This upfront R&D investment commitment makes the pioneer firm stronger in the second stage, preempting market share under quantity competition.

[insert Exhibit 4 about here]

Panel A of Exhibit 4 summarizes the valuation results for the first period of the commercialization phase (stage 2) for the proprietary R&D case (the right branch of the tree is the base case of Exhibit 3).[14] The tree is solved by backward induction in a similar fashion as in the base case. [15] The highlighted (bold) branches along each tree indicate the optimal actions along the equilibrium path. Pioneer firm A should make the R&D

[14] Due to space considerations, Exhibit 4 does not show the last period of the second-stage game, which incorporates the equilibrium values for the Cournot (C), Stackelberg leader/follower (S) or monopoly (M) games (summarized in Table 1) in the various states shown in Exhibit 1. These were illustrated in detail for the base-case alternative of no R&D in Exhibit 3. All the numerical values shown in Exhibit 4 are, nevertheless, the expected values derived from backward binomial option valuation based on the entire multi-stage game and the equilibrium payoff values of Table 1.

[15] Consider first the subgame (in the second box) concerning investment in follow-up production capacity, following a decision by A to invest in R&D (K_A) and a downward demand realization ($\theta = d$). In this case, a production capacity investment (I) by firm A dominates deferral (D) since it results in a higher net value for A's follow-up project regardless of whether competitor B decides to invest (I) or defer (D). Knowing that firm A has a dominating strategy to invest, B would defer (obtaining 0 rather than -86). Thus firm A would earn monopoly profits, resulting in net present values of (293, 0) for the follow-up projects of firm A and B, respectively. However, if $\theta = u$ as in the first box, total market demand would be sufficient for a Cournot Nash equilibrium outcome where both firms, regardless of the other's actions, have dominant strategies to invest (I) in subsequent commercialization projects, resulting in values of (517, 21). Using backward binomial valuation results in expected gross investment opportunity values of (350, 8) when firm A invests in R&D. Net of the required outlay of $K_A = 100$, this results in an expanded net present value (NPV*) for A of 250. Since the base-case alternative of no R&D results in values of (60, 60), firm A should make the R&D investment (250 > 60), increasing its expanded NPV by 190 (= 250 - 60) relative to the base case.

investment in stage 1. It should then make a follow-on commercialization investment (I) in the second stage regardless of demand. If market demand moves favorably (θ = u), both firms would invest resulting in a Cournot quantity equilibrium value for the pioneer (517); if demand is unfavorable (θ = d), B would not invest and A's early R&D can result in a monopoly value (293).

The asymmetry introduced in the relative operating costs from the strategic R&D investment clearly influences each firm's reaction function and the end-node equilibrium payoff values. In panel A of Exhibit 2, the proprietary R&D investment causes firm A's reaction function to shift to the right, changing the base-case Cournot equilibrium outcome from C_0 to C_p and increasing firm A's relative market share.[16] Panels B in Exhibits 2 and 4 illustrate the symmetric shared case, where R&D by firm A results in a more cost-effective technology that both competitors can exploit ($c_A = c_B = 0$). In panel B of Exhibit 2, B's reaction function shifts to the right as well, which increases both firms' quantities with equal market share. As a result, the opposite competitive strategy results for the shared case (compared to the proprietary one), as shown in panel B of Exhibit 4. Firm A should not invest in R&D but should rather retain a flexible "wait and see" position, attaining the base-case equilibrium values of (60, 60). Investing in R&D may create a strategic disadvantage for A by paying the cost of creating valuable investment opportunities for competition or by enhancing the competitor's ability and incentive to respond aggressively in the future (resulting in a value of 51 vs. 60 from waiting with an incremental NPV* of -9).

Although an early strategic R&D investment may reduce option or flexibility value, it may have a high or low net commitment value, depending on the strategic effects. The sign of these strategic effects may be positive or negative, depending on whether the benefits are proprietary or shared. The interplay between the loss of flexibility value and the net commitment value of R&D can be seen by examining the breakdown of total value into its various components shown in Table 2 when the R&D investment is proprietary (column 2) or shared (column 3). Column 2 confirms that if firm A makes a proprietary R&D investment (K_A = 100) in a new, more cost-efficient technology the total expanded NPV will be 250, whereas in the base case of waiting (staying with the old, costlier technology) it is 60 (37 for base-case NPV plus 23 in flexibility value). By investing in R&D, firm A generates a net commitment value of +213, consisting of a direct value of +186 from direct reduction in future operating costs, a strategic reaction value via an incremental change in the competitor's output of +82,

[16] The equilibrium quantity (Q*) and profits (π*) are shown in the table at the bottom of Exhibit 2 for the Cournot, Stackelberg leader, and monopoly market structures.

and a strategic preemption effect of +45 from deterring competitive entry in certain states of demand. This net commitment value of +213 more than compensates for the loss in flexibility value of 23 from giving up the option to wait (base case), resulting in an incremental value (difference between the expanded NPVs of the R&D investment alternative of 250 and the base case of 60) of 190 (> 0) that makes investment in R&D worthwhile. In the shared case (column 3) both the sign of the strategic reaction effect (-72) as well as of the difference between the net commitment value and the flexibility loss (14 - 23 = -9) get reversed, so that it becomes preferable to wait rather than invest in R&D.

Sensitivity and Critical Demand Zones

In this section we analyze critical demand zones triggering invest or defer decisions under different market structures and examine the influence of market demand uncertainty and other parameters on the flexibility and strategic components of value. As noted, the second-stage investment payoff is a non-linear function of exogenous demand (θ) as a result of changes in the subgame outcomes (boxes of Exhibit 4). Exhibit 5 shows how the value in the commercialization stage for firm A (NPV^*_A as of t = 1) varies with market demand θ and the resulting subgame equilibria. Panel A shows the critical demand zones for the base-case of no R&D, while panels B and C illustrate the shared and proprietary cases, respectively. In each case, each firm's decision to invest or defer depends on two critical or threshold market demand parameters, θ^*_{INVEST} and θ^*_{DEFER}, separating the spectrum of demand states into three demand zones. In the base-case of no R&D (panel A), for example, if market demand θ exceeds θ^*_{INVEST} (= 16), at the intersection of the curves whereby firm A invests or defers given that B invests, both firms have a dominant strategy to invest resulting in a Cournot equilibrium market structure. If θ declines below θ^*_{DEFER} (= 12), at the intersection of the invest/defer and defer/defer curves, both firms have a strictly dominant strategy to defer. In between there is an unpredictable (mixed equilibrium) zone with no pure dominant strategy when firms are symmetric.[17] In the shared R&D case (panel B) there are three similar demand zones, except that the critical θ values are lower. Both firms would again invest (Cournot) if θ exceeds 10.8, whereas both will defer if θ declines below 7.1. The lower threshold value for θ^*_{INVEST} compared to the base case (10.8 vs.16) reflects the incentive of both firms to invest earlier due to

[17] In this "unpredictable" (or mixed equilibrium) zone, investing by one firm would result in a higher value (compared to the base case where both firms defer) if the competing firm defers or the first-moving firm becomes a Stackelberg leader (ID > DD),

the lower costs resulting from the shared R&D investment; similarly, with lower costs, the region of demand over which both firms would wait is reduced (7.1 < 12).

In panel C, where the benefits of R&D are proprietary to the pioneer firm resulting in an asymmetric cost advantage, the mixed (unpredictable) zone is replaced by a larger zone where the pioneer dominates as a Stackelberg leader or monopolist. Here R&D improves the firm's strategic position via lower relative future production costs, expanding market share and preempting competitive entry. For θ below θ^*_{INVEST} (= 20.8) and above θ^*_{DEFER} (= 8.5), the NPV of the competitor turns negative, giving firm A the ability to preempt its entry and become a Stackelberg leader or monopolist. Since A's proprietary R&D limits B's output and incentive to invest, the critical value θ^*_{INVEST} required for both firms to invest in the proprietary case is higher than in the base-case and the shared investment cases (20.8 > 16 > 10.8). Given A's cost advantage, NPV^*_A in the proprietary case is also higher than in the other cases (for a given θ).

[insert Exhibit 5 about here]

Exhibit 6 presents sensitivity of firm A's value (NPV^*_A at t = 0) to the degree of shared cost advantage for competitor B (at an initial demand of θ_0 = 17.5), with c_B ranging from 0 to 5. Point A corresponds to the base case of no R&D. Point B at 100% (c_B = 0) corresponds with the special case of a fully shared cost advantage (NPV^*_A = 51 as in Exhibit 4 panel B or Table 2 column 3), while with 0% shared benefits (c_B = 5) the fully proprietary case of point C obtains (NPV^*_A = 250 as in Exhibit 4 panel A or Table 2 column 2). The shared R&D investment results in symmetric Cournot Nash equilibria in the second stage. The initial gradual increase in the value of A's R&D investment (moving from B toward C, as the degree of shared cost advantage declines) is due to the positive strategic reaction effect as firm A gets a relatively larger market share (in Cournot equilibrium) as a result of its greater proprietary cost advantage. As the R&D investment becomes more exclusive, firm A can preempt competitive entry at lower demand, changing the market structure from Cournot equilibrium (at high θ) to Stackelberg leadership or monopoly (see also Exhibit 4, panel A). The resulting preemption effect thus causes a jump in value (at about 60% or c_B = 2). The further gradual increase is a result of added strategic reaction value in Cournot equilibrium at higher levels of demand.

[insert Exhibit 6 about here]

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but would result in a lower value if the competitor simultaneously decides also to invest, leading to Cournot equilibrium (II < DD). The firms may equivalently choose to defer.

Exhibit 7 shows sensitivity of NPV^*_A to changes in market demand uncertainty u (panel A) and to the time interval or separation (panel B) for the proprietary R&D case. Compared to the base case of no R&D (lower curve in panel A) where project value increases monotonically with demand uncertainty as expected from standard option theory, the competitive interaction resulting from A's R&D investment (top curve) causes the sensitivity of value to demand uncertainty to vary non-monotonically (i.e., there is a jump when u exceeds 1.19). Given that at initial demand (θ_0 = 17.5) firm A is in the Stackelberg leadership zone due to its proprietary R&D investment (Exhibit 5, panel C), low changes in demand (left region with u below 1.19) maintain Stackelberg leadership for A. But with higher demand uncertainty (beyond the critical level u = 1.19), competition may enter despite higher costs if demand realization turns out high (i.e., if $\theta_1 = u\theta_0$), changing the market structure from Stackelberg to Cournot equilibrium and causing a decline in strategic value and in NPV^*_A.[18]

Panel B shows the sensitivity of NPV^*_A to the time interval (separation or lag) between the R&D and the follow-on commercialization investments. From real option theory the length of time that the project outlays can be deferred again makes an investment opportunity more valuable. However, if there is competitive interaction, the sensitivity of value to maturity time may again change non-monotonically. Although the expanded NPV for a proprietary investment by firm A increases gradually with separation time, it may drop suddenly when the time interval increases beyond a critical level (about 3 periods in panel B of Exhibit 7) resulting in a change in market structure from Stackelberg leadership to Cournot).[19]

[insert Exhibit 7 about here]

[18] This result about a non-monotonic impact of uncertainty is in contrast to earlier findings in the literature. The non-monotonicity in the results depends on the initial parameters and particularly on the initial demand zone and how far away θ_0 is from θ^*_{INVEST} or θ^*_{DEFER}. As a result, calibration of demand is important in deciding on an investment strategy.

[19] Based on real option theory, a higher interest rate (r) also influences flexibility value positively; however, it generally also translates into a higher required return (discount rate) and a lower market value upon investment, other things constant. Similar to Exhibit 7, there may again be a jump when market structure changes (from Stackelberg to Cournot if $\theta_1 = u\ \theta_0$).

3. Technical R&D Uncertainty, Stochastic Reaction Functions and Asymmetric Information with Signaling

This section continues our comparative statics investigation by extending the basic model to incorporate technical R&D uncertainty, first under complete or symmetric information (although the outcome of R&D is uncertain *a priori*, it can be known by both competitors *ex post*), and then under imperfect or asymmetric information (using stochastic reaction functions), with and without signaling.

Technical R&D Uncertainty (Under Symmetric Information)

The proprietary R&D investment in the earlier section (panel A of Exhibit 4 or column 2 in Table 2) can be seen as a special case of assuming sure R&D success under complete (symmetric) information within a more general model that allows technical R&D uncertainty. In addition to market demand uncertainty in the second stage, we now allow for technical uncertainty in the first stage in that with probability η or $(1-\eta)$ the R&D effort may succeed or fail.[20] Exhibit 8 panel A illustrates the sensitivity of firm A's R&D investment value (NPV^*_A) to the probability of A's R&D success (η_A) and its resulting expected cost $E(c_A)$. The earlier proprietary R&D case corresponds to point A ($NPV^*_A = 250$ in column 2 of Table 2) illustrating the extreme case of η_A = 100% and $c_A = 0$. Point B ($NPV^*_A = -40$) illustrates the other extreme case of sure R&D failure and no cost reduction (η_A = 0% and $c_A = 5$),[21] while point C illustrates the case that R&D has a 50% probability of success or failure (with $E(c_A) = 0.5 \times 5 + 0.5 \times 0 = 2.5$). With technical R&D uncertainty, the expected value of A's R&D varies linearly (from point A to C to B) with A's probability of R&D success (η_A from 100% to 0%).

This is in contrast to the case of certain (successful) R&D where the innovating firm can attain a sure cost advantage over its competitor; above a given "threshold" cost advantage ($c_A = 3.75$) firm A can preempt competition (entering a preemption zone under low demand) and the NPV^*_A curve exhibits a discontinuity (jump in value). With technical R&D uncertainty (with the same expected cost reduction, or mean preserving spread), the chance of R&D failure mitigates the strategic preemption effect so that an increasing expected cost

[20] Because technical uncertainty is non-systematic, we can estimate the expected value of the strategic R&D investment using the actual probabilities (.5) while discounting at the risk-free rate (r = 0.10).

[21] For point B, NPV^*_A = Base-case value - K_A = 60 - 100 = -40.

advantage exhibits a smoother increase in R&D value. Effectively, under technical R&D uncertainty the preemption effect (discontinuity) is linearized (averaged out).[22]

The introduction of technical R&D uncertainty results in less commitment (strategic reaction and preemption) value for firm A because it involves a sure expenditure with a probability ($1-\eta_A$) that R&D may fail and both firms may end up with equal (symmetric) operating costs. While net commitment value declines (from 213 in point A, to 56 in C and -100 in B) with lower probability of success (from η_A = 100% to 50% to 0%), option or flexibility value increases (from 0 to 12 to 23) but to a lower degree.

[insert Exhibit 8 about here]

Imperfect/Asymmetric Information and Stochastic Reaction Functions

Panel A of Exhibit 8 is actually a special case of the more general model depicted in panel B where firm B has complete information over the success of firm A's R&D effort (corresponding to points A, B and C on the vertical axis). Under full symmetric (complete) information, competitor B knows whether firm A's R&D effort has succeeded or not, and therefore uses firm A's actual ex-post costs in its reaction function. Under imperfect or asymmetric information, firm A still has complete (private) information about its own R&D success and uses its actual cost in its reaction function (i.e., $c_A = 5$ if R&D fails and $c_A = 0$ if R&D succeeds). However, in simultaneous Cournot competition where firm B doesn't know whether A's costs are low ($c_A = 0$) or high ($c_A = 5$), it now faces a stochastic reaction function (using A's expected quantity), maximizing its expectation of profit values over firm A's being a low or high-cost type, contingent on A's success or failure.[23] This results in the equilibrium values for firm A (NPV^*_A) shown in Panel B of Exhibit 8 under imperfect information (at the mid-point where η_A = 50%, obtaining points A', B', C').

In cases of sequential investment in a Baysian (separating) equilibrium, firm B can observe A's quantity choice in the prior period and can infer whether A is a low-cost or a high-cost type (reducing to the complete information case).[24] The change in value in the first half along the three curves in panel B of Exhibit 8 represents

[22] If successful in its R&D, firm A preempts with a cost advantage of $c_A = 0$ vs. $c_B = 5$, while if its fails it cannot preempt. By taking the expectation the discontinuity is averaged out.

[23] Since A's expected quantity is linear in A's expected cost, the Cournot equilibrium values are equivalently obtained by using B's perceived *expected* cost of firm A. For instance, if firm B has no information whatsoever whether A's effort succeeded or not (using η_A = 50%), B's estimation of A's cost would be $E_B(c_A) = 0.5(5) + 0.5(0) = 2.5$.

[24] The incentive compatibility conditions that firm A will not set a misleading quantity are satisfied.

the impact of imperfect information under R&D uncertainty in case of R&D success (upper curve AA'), failure (lower curve BB') and the expected value using 50% probability of success (middle curve CC').[25] In case firm A's R&D actually succeeds (upper curve with $c_A = 0$), firm A's value declines as firm B's information on A's R&D success becomes more incomplete. This results from overestimation by firm B of A's actual cost (essentially using $E_B(c_A) = 2.5$ rather than 0) which would lead B to set a higher quantity under contrarian competition, hurting A's profit and value (NPV^*_A at A' is lower than at A). By contrast, in case of actual R&D failure (lower curve), the value of A's R&D investment (NPV^*_A) is higher with less complete (imperfect) information (NPV^*_A at B' > B).[26] Interestingly, these opposite biases (i.e., the value reduction due to B's overestimation of A's cost under R&D success and the value increase due to the opposite effect in case of failure) are approximately averaged out when determining the expected value of A's R&D investment with η_A = 50% (middle line at C' = 104 vs. 105 at C). The breakdown of value components under complete vs. imperfect information (with η_A = 50%) is given in columns (4) and (5) of Table 2. If we compare the effect on the value components of the case of complete vs. incomplete information, we see that the value of flexibility and strategic reaction become less important due to the "averaging out" of these opposite effects in firm B's response, effectively from using A's expected rather than actual costs. As we move from point C (perfect, complete information) to C' (imperfect information) there is a negative effect on strategic reaction (31 vs. 41) and on flexibility value (9 vs. 12), which is roughly offset by the higher strategic preemption value (34 vs. 22) because B (by essentially using A's expected cost) may stay out even when A's R&D fails if demand is low.

[25] Note that the case of a 100% probability of R&D success (point A in panel A of Exhibit 8) corresponds to the special case of complete information (vertical axis) on the upper curve of panel B (point A), while 50% (point C) and 0% (point B) correspond to the initial points on the middle (C) and lower curves (B) of panel B (on the vertical axis).

[26] If firm A's R&D fails ($c_A = 5$), firm B will essentially underestimate A's actual cost and set a lower quantity using firm A's expected cost (2.5 rather than 5), resulting in higher values for A (NPV* at B' > B).

Signaling

Under asymmetric (imperfect) information, firm A may have an incentive to provide (partial or misleading) information over the success of its R&D efforts. If its R&D efforts are successful, firm A would have an incentive to communicate/signal this to firm B to induce it to set a lower quantity and soften second-stage competition.[27] By contrast, firm A has an incentive not to inform B in case its R&D efforts are failing so that B, in maximizing its expectation of profit value, would in effect use A's expected cost (2.5) in its reaction function rather than the actual cost (0) under simultaneous Cournot competition. At first glance, firm A thus appears to have an incentive to always tell its competitor that its R&D effort is successful, whether it actually succeeds or not. Of course this is not credible as firm B would not be fooled. If firm A always informs in case of R&D success but keeps silent in case of failure, firm B will infer that no information (silence) implies that A's R&D actually failed and will increase quantity competition accordingly.[28]

It might in fact be better for firm A to inform (tell the truth) in some cases while keeping silent in others (never explicitly lying). Firm A can follow an implicit signaling rule conditioned on the outcome of its R&D effort (success or failure) as well as on the level of market demand θ and the resulting market structure (deviating from the "rule" whenever there are overriding preemption/strategic benefits from telling the truth over keeping silent).[29] Signaling R&D success is costly in that to be credible the innovative firm must disclose sufficient specific details about its R&D innovation (e.g., through the process of registering its patent or through a pubic announcement to the market) that allows firm B to also benefit somewhat, partially reducing its own costs from 5 to 4.5.[30]

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[27] Firm B would essentially adjust its expectation of A's cost from $E_B(c_A) = 2.5$ to 0, causing a shift in B's reaction function to the left and increasing A's market share under a Nash-Cournot equilibrium.

[28] Firm A may try to fool B in believing that its R&D is a success even when it is failing but this is not credible without costly signaling.

[29] A simple version of the basic signaling "rule" is:

- Signal success (tell the truth) in case of R&D success under high demand: $E_B(c_A) = 0$ ($c_B = 4.5$)
- Keep silent in case of R&D success under low demand: $E_B(c_A) = 2.5$, except when B is follower (uses $c_A = 0$)
- Keep silent in case of R&D failure under high demand: $E_B(c_A) = 2.\ 5$, except when B is follower (uses $c_A = 5$)
- Signal failure (tell the truth) in case of R&D failure under low demand: $E_B(c_A) = 5$.

[30] We assume here that firm B cannot discover this conditional signaling rule (e.g., firm A may have superior or lead information on market demand), although it may choose to respond to all signals as being truthful or ignore them altogether (using A's expected cost of 2.5 instead, except when it is a follower and can infer whether A is a low-cost or high-cost type).

In Exhibit 8 (panel B), the rising right part of the upper curve under R&D success (A'A'') reflects an increasing reaction effect for firm A who sets a higher quantity due to its distinct relative cost advantage, despite B's cost decrease from 5 to 4.5 ($c_A = 0$, $c_B = 4.5$). NPV^*_A at A'' (with signaling) is less than at A (no signaling) because of this signaling cost. If R&D fails (at B"), firm A keeps silent at high levels of demand, appropriating the benefit of imperfect information under Cournot competition which is reflected in the relatively flat right part of the lower curve (B'B''). Comparing the case of asymmetric information with signaling to imperfect information (with no signaling) summarized in columns (6) and (5) of Table 2, strategic reaction value is now significantly higher (44 vs. 31) while preemption value is lower (28 vs. 34) as a result of firm B's entry in case of R&D failure. Nevertheless, both firms benefit from this signaling scheme. For firm A the expected NPV* of 108 at C" (average of values at A" and B") with signaling is higher than in the case without signaling (104 at C'). Firm B benefits from going along with this scheme as well, both in case of R&D success and in failure, since its smaller market share in a Cournot equilibrium when not informed is offset by its lower cost when it is informed. When firm A informs in case of success, firm B benefits from the lower cost (4.5 vs. 5); in case of failure under low demand B benefits from knowledge of A's actual higher cost (5) and increasing its own quantity accordingly.

4. Learning Cost Effect

Besides reducing future production costs via making a strategic R&D investment, firms can alternatively achieve cost reduction by investing earlier in production capacity (e.g., see Majd and Pindyck, 1987). With learning, the marginal cost of firm *i* (*i* = A, B) is assumed to decline exponentially with cumulative production $\Sigma Q_{it}\left(= Q_{it} + \Sigma Q_{it-1}\right)$ at a learning rate γ, converging to a floor level c_i^F according to:

$$c_i\left(Q_{it}\right) \equiv c_i^F + c_i^L e^{-\gamma \Sigma Q_{it}} \tag{4}$$

Exhibit 9 shows the impact of a higher learning rate on the value of firm A's investment when both firms can experience learning cost effects under complete information in different cases. Panel A illustrates the base-case of no strategic R&D with learning. Point B, for example, shows that learning at a rate of γ = 10% increases firm

We do not investigate here the case where firm B discovers the signaling rule through repetition; in any case, B is shown to be better off following the rule as well.

A's value to 103 due to future production cost savings, compared to the base case value of 60 with no learning (point A). As higher learning favors early investment, it results in an erosion of flexibility value (from 23 at point A to 0 at B when γ increases from 0 to 10%) while it increases direct NPV value due to cost savings (from 0 to 111, as seen in column (7) of Table 2). NPV^*_A generally rises more steeply at first with a higher learning rate because the cost savings rise more than the flexibility loss.[31]

Panel B shows the case when firm A makes a proprietary R&D investment with certain success (η_A = 100%) that reduces its cost to $c_A = 2.5$ (rather than to 0 as assumed earlier) with additional learning cost savings at a rate γ% (by both firms). Since the learning benefits are relatively higher for firm B (with firm A's cost staring at $c_A = 2.5$ while B's at $c_B = 5$ with both assumed to decline at the same rate), the rate of increase in NPV_A^* is slower. Further, while at a low learning rate firm A can preempt B given its initial strategic cost advantage from its R&D, beyond a critical learning rate ($\gamma^* = 9.5\%$) firm B can no longer be preempted due to its relatively stronger offsetting operating/production cost advantage, resulting in a large downward jump in firm A's value from D' to D".

Panel C illustrates the value of firm A making an *uncertain* proprietary R&D investment with $\eta_A = 50\%$ that reduces its cost to $c_A = 0$ (assuming B has perfect information) with learning by both firms. Since by design $E(c_A) = 2.5$, the value with no learning in the uncertain R&D case (point E in panel C) is the same (NPV^*_A = 105) as in the certain R&D case (point C in panel B). Since higher learning benefits firm B relatively more in case of A's R&D success, this results in a more flattened value for firm A.[32] At a high learning rate beyond a critical threshold (e.g., at point F with $\gamma = 10\%$) firm A may find it optimal to wait rather than invest in R&D (NPV^*_A = 99 with uncertain R&D at F, exceeding 103 with no R&D at B); under R&D uncertainty firm A cannot attain high preemption value while it can potentially benefit more from future production with learning instead of investing in R&D. Compared to the certain R&D case in panel B (mean-preserving spread), the effect of technical R&D uncertainty is to reduce the impact of preemption (jump); it results in lower value due to the inability to take advantage of a strong preemption effect when learning is low (see preemption zone in panel B for $\gamma^* = 9.5\%$), although it may have relatively higher value at higher learning rates (e.g., at $\gamma = 10\%$ F >

[31] The curve changes in a non-smooth fashion (exhibiting a small down jump at a critical rate of $\gamma^* = 4.5\%$) because of changes in subsequent period subgames, such as switching from (defer, defer) to (invest, invest) and a resulting prisoner's dilemma-type loss under low demand as production costs drop (below a critical level) with a higher learning rate.

D''). Compared to the base case in panel A, the impact of learning is to reduce the incentive to make a strategic R&D investment; without (or with less) learning firm A would have invested in R&D instead (e.g., with γ = 0%, NPV^*_A = 105 at E vs. 60 at A).

[insert Exhibit 9 about here]

The breakdown of value components for uncertain proprietary R&D under learning is shown in column (8) of Table 2 (to be contrasted to column 4 without learning). In general, the learning-cost effect has the following influences on value when firm A makes the strategic R&D investment:

(*i*) It has a negative impact on the direct value of the NPV* for firm A through earlier larger production by firm B. The direct value of making an upfront strategic R&D investment under learning by either firm declines since the strategic investment could result in a relatively smaller cost reduction for firm A. (This can be seen by comparing the direct values of 37 for γ = 10% at point F of Exhibit 9 (or column 8 of Table 2) vs. 93 for γ = 0% at point E (column 4 with η_A = 50%).

(*ii*) The strategic reaction value of the R&D investment of firm A declines with learning, compared to the situation without learning (15 for γ = 10% vs. 41 for γ = 0%), since the larger production of firm B results in a lower quantity for firm A. That is, the R&D investment has a smaller impact on competitor B's reaction, because B's cost declines with production under learning. Interestingly, the presence of learning enhances the strategic preemption value of firm A (44 for γ = 10% vs. 22 for γ = 0%) because of the increased difference between the Cournot and the Stackelberg leadership equilibrium values. In the case of learning, the Cournot equilibrium values of firm A decline when firm B learns. Thus, under learning preemption with a strategic investment is valuable as it prevents the competitor from taking advantage of the learning experience cost effects.

(*iii*) Learning-cost effects erode flexibility value (12 for γ = 0 vs. 0 for γ = 10% at point F, where learning results in Cournot equilibria in both states). Under learning, either firm has an incentive to invest earlier rather than wait. In essence, instead of responding to firm A's strategic R&D investment with its own R&D to reduce its cost, firm B can alternatively achieve similar cost reduction by intensifying its productive (commercialization) investment.

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[32] In case of R&D failure the two firms have symmetric costs and learning benefits (as in the base case of panel A) but in case of success firm A here does not derive further benefits from learning. In panel B above, firm A derives learning benefits in case of R&D success as well (with c_A = 2.5 instead of 0).

5. Competition vs. Cooperation in R&D

An interesting question is whether it is better for the two firms to pursue independent, competing R&D activities or whether to cooperate in the first stage via a joint research venture (sharing the R&D costs) and compete instead only in the second stage of commercial production. Instead of both firms independently investing 100 in R&D, they can now contribute $K_A = K_B = K/2 = 50$ each in a joint research venture. Table 2 shows the components of value for proprietary R&D under technical R&D uncertainty in case of R&D cooperation (column 10) vs. first-stage R&D competition (column 9).[33] In general, joint research has the following three influences on value compared to first-stage competition in R&D:

(i) It has a beneficial impact on direct NPV and net commitment value by achieving the same cost savings during commercialization (second-stage production) with a lower first-stage R&D expenditure by each firm (50 vs. 100).

(ii) It enables the two firms to more fully appropriate the flexibility value from waiting (25 vs. 17). There is no sacrifice of flexibility value in this case from an attempt to preempt the market as under direct R&D competition.

(iii) On the negative side, it results in potential sacrifice of strategic preemption (from 11 to 0) and strategic reaction value (from -16 to -32) because the firm cannot acquire a competitive advantage via an early R&D investment. The second-stage game in this case is symmetrical and does not allow the potentially high Stackelberg leadership or monopoly profits that enhance strategic value if one firm invests earlier.

Exhibit 10 graphically illustrates the valuation results for different demand zones in these two cases of R&D competition (panel A) vs. cooperation (panel B). The analysis incorporates technical R&D uncertainty (with η = 50%) and proprietary benefits from monopoly rents in case a firm's R&D succeeds or the competitor's R&D effort fails. As can be seen from Exhibit 10 (panel A), first-stage R&D competition again involves three critical demand zones. At low demand, both firms are better off to defer R&D due to its low commercialization potential. At intermediate levels of demand there is an unpredictable (mixed equilibrium) zone. Here, the R&D investment is lucrative if only one firm invests, but if both invest the R&D investment strategy turns out to have a negative or low NPV*. At higher demand (above $\theta^*_{INVEST} = 16$) the possibility (threat) of each firm pursuing independent R&D activities triggers a simultaneous similar investment by its

[33] In case the R&D benefits are shared it might be better to wait and benefit from the R&D investment of the competitor or cooperate via a joint research venture.

competitor that, like in a prisoners' dilemma, makes both firms worse off compared to the base-case scenario of waiting.[34] In the case of cooperation (panel B), there are only two demand zones with a single, higher investment threshold (θ^{*}_{JOINT} = 21). By cooperating, the two firms can avoid the prisoner's dilemma (in the region between θ^{*}_{INVEST} and θ^{*}_{JOINT}) and can jointly coordinate their actions against exogenous demand uncertainty, more fully appropriating the flexibility value from waiting. Thus the investment threshold (and the defer zone) are larger.

[insert Exhibit 10 about here]

Comparing the two cases presented in the two panels above leads to several interesting observations. Very high states of demand result in Cournot equilibria where both firms invest, so that there is no preemption advantage from competing in R&D. Thus the joint R&D strategy is more appealing (compare the values for Invest/Invest in panel A vs. Invest in panel B for each given θ) because there is no advantage from preemption. The situation is more dynamic at intermediate demand: firms may follow a competing R&D strategy due to high potential profits resulting from high strategic preemption and reaction effects. A firm may acquire monopoly rents as a result of early investment due to a proprietary cost advantage or in case the competitor's R&D effort fails. At lower market demand, simultaneous investment by both firms may result in negative values in case of R&D competition due to prisoner's dilemma; the higher flexibility value (option value of waiting) resulting from coordination in a joint research venture may compensate for the strategic preemption and reaction value benefits of R&D competition.

6. Conclusions

Strategic competitive interactions influence the value of a sequential investment plan under uncertainty. The standard NPV decision rule should be expanded by adding a strategic as well as a flexibility value component to capture these effects. In general, the expanded NPV of a strategic investment is influenced by two main effects:

(i) The net commitment effect: an early strategic investment may not only result in direct incremental future cash flows (the direct NPV), but it may indirectly also impact on value by influencing the competitor's reaction

[34] The Defer/Defer equilibrium outcome (60, 60) actually has a higher value than Invest/Invest (42,42).

(strategic reaction effect) and the resulting competitive equilibrium, in some cases even changing the market structure entirely by deterring entry of rivals (strategic preemption effect).

(ii) The flexibility effect: this arises from management's ability to wait to invest or revise future decisions under demand (or technical) uncertainty. An early strategic investment commitment can improve the firm's strategic position and enhance the value of its future growth opportunities, but it would sacrifice flexibility value.

Based on a combination of real options valuation with basic game-theoretic principles, a number of implications for strategic investment behavior result. Contrary to standard option valuation, we find that the value of an R&D investment opportunity may no longer increase monotonically with demand uncertainty (or with maturity and other option parameters) because strategic preemption may cause value discontinuities. Higher uncertainty generally increases the deferral or flexibility value which is lost when making an early R&D investment commitment, but it may either increase or decrease strategic value (from influencing a competitor's equilibrium output), possibly by a higher amount; a jump in value may result as uncertainty increases, shifting from one demand zone (e.g., Cournot Nash equilibrium) to another (e.g., Stackelberg or monopoly), depending on initial demand.

The sign and magnitude of this effect on R&D value depends on the proprietary or shared nature of the investment, on technical R&D uncertainty, on the degree of incomplete information, the existence of learning effects, and on the willingness to compete or form joint research alliances. Our comparative statics analysis enabled us to develop the following implications for competitive R&D strategies:

(1) In the case of a proprietary R&D investment under quantity competition, the firm should follow an aggressive R&D strategy to become stronger in the second stage. Under quantity competition, its competitor will retreat in the later stage and the pioneering firm can become a leader as demand grows.

(2) When the benefits of R&D are shared and competition would respond aggressively, the firm should not invest immediately but rather follow a flexible "wait and see" strategy. By delaying R&D investment, it prevents its competition from exploiting the resulting shared benefits to grow at its own expense.

(3) Technical uncertainty in the outcome of R&D generally enhances flexibility value and reduces the strategic preemption and commitment value of R&D (compared to the situation of certain proprietary R&D. That is, with the same expected cost reduction (mean-preserving spread), sure R&D success leads to higher preemption value (discontinuity).

(4) Under imperfect (no) information where the competitor in essence uses the expected cost of the pioneer in its stochastic reaction function in case of simultaneous Cournot competition, the value of flexibility and strategic reaction become less important due to "averaging out" in the competitor's response of the opposite biases from misestimating A's actual cost. When signaling is possible, by providing (partial) information over the success of its R&D efforts, the pioneer firm can enhance the strategic reaction and commitment values of R&D. If its R&D efforts are successful, the firm would communicate this to its competitor if demand is sufficiently high resulting in Cournot competition to induce it to set a lower quantity and soften second-stage competition (but may keep silent under low demand); if its R&D fails, firm A may keep silent under high demand (but tell the truth under low demand). Through such a signaling rule contingent on the state of demand and different market structure equilibria, firm A can be better off with signaling (while B is not expected to improve by ignoring the signal).

(5) Learning (generally) triggers earlier investment via reducing future production costs, thereby eroding flexibility value. Specifically, learning-cost experience effects by both firms has the following influences on the value of a strategic R&D investment: *(a) it has a negative impact on direct NPV and on the strategic reaction value for pioneer firm A because the competitor builds up production volume more quickly and benefits more from learning once he enters; (b) the strategic preemption value of R&D investment is higher under learning since preemption can eliminate the competitor's learning advantage; (c) learning erodes flexibility value since either firm has a cost-driven incentive to invest earlier rather than wait.*

(6) When the firms can cooperate in R&D via a joint research venture during the first stage, we have the following three influences on value compared to direct competition in R&D: *(a) a joint research venture enables the cooperating firms to more fully appropriate the flexibility value from waiting.* There is no sacrifice of flexibility value from the pressure to preempt the market as under direct R&D competition; *(b) joint research has a beneficial impact on direct NPV and commitment value compared to R&D competition by achieving the same cost savings during second-stage production with a lower (shared) first-stage R&D expenditure by each firm;* (*c)* on the negative side, *joint research results in potential sacrifice of strategic value because the firm, by accepting symmetry, cannot acquire a competitive advantage (e.g., preempting competition) via an early R&D investment.*

We also analyzed to what extend these results depend on the particular functional forms that we have assumed for the demand and cost functions, and found that the above implications are quite robust. For instance, with a more convex, isoelastic demand function our basic results regarding the value discontinuity due to preemption are still valid, though more pronounced.[35] The strategic effects due to the proprietary nature of R&D benefits, technical R&D uncertainty, or information asymmetries are also preserved but are more amplified under an isoelastic demand, for similar reasons. If we compare a certain cost reduction, other things equal, we observe a similar but larger discontinuity due to the preemption effect of the certain cost reduction. Imperfect information has a positive effect on R&D value: in case of R&D success the leader will preempt, even if the competitor has incomplete information, while if R&D fails the competitor will be preempted if it uses its expected cost in its reaction function. Similarly, under learning, the cost advantage is typically sufficient to preempt the competitor (so that the competitor cannot take advantage of learning). However, for a lower cost advantage of R&D or if R&D fails, learning by the competitor results in a similar but larger impact due to the higher production implied by more convex demand.

Future research may be directed toward evolutionary games, where a changing competitive landscape alters the competitive positions and R&D values. We leave it for future research to empirically test the economic implications of the above analysis in explaining actual firm behavior.

[35] Basically, with only the flexibility to wait and see (without strategic effects), the value (NPV) is convex in demand (or price). Strategic effects (e.g., preemption) introduce a concavity in the value function making the curve non-monotonic (especially in the intermediate region where the competitor waits while the incumbent may earn monopoly or Stackelberg profits). With an isoelastic (convex) demand curve, the price is higher (increases more steeply than under a linear demand curve) when quantity is rather low (or high). Thus, under low (or high) states of demand the strategic effect of a changing market structure allowing the incumbent to earn monopoly or Stackelberg profits while the competitor waits would be stronger (enhancing the concavity and monotonicity in the intermediate demand zones). Since the strategic benefit of investing earlier increases under an isoelastic demand, the threshold below which both firms would wait (θ^*_{DEFER}) would be lower; the higher output levels associated with a more convex demand would also magnify the impact of the cost advantage (as it becomes more difficult for competitors to enter) and the demand threshold above which both firms would invest (θ^*_{INVEST}) would also be higher.

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Appendix 1

This appendix models the equilibrium quantities (Q^*) and net project values (NPV^*) for various market structures under quantity competition. Exogenous uncertainty in future market demand is assumed to be characterized by fluctuations in the demand parameter, θ_t. In the second-stage game, we assume for simplicity a linear demand function of the form:

$$P(Q, \theta_t) = \theta_t - (Q_A + Q_B), \qquad \text{(A1.1)}$$

where θ_t is the demand shift parameter, assumed to follow a lognormal diffusion process (or a multiplicative binomial process in discrete time). Q_A and Q_B are the quantities produced by firms A and B, respectively, and P(Q) is the common market price as a function of total quantity ($Q = Q_A + Q_B$). The total variable production cost for each firm i (i = A or B) is given by:

$$C(Q_i) = c_i\, Q_i + ½\, q_i\, Q_i^2, \qquad \text{(A1.2)}$$

where c_i and q_i are the linear and quadratic cost coefficients (or the fixed and variable coefficients of the marginal cost function, $c_i + q_iQ_i$) for firm i. The second-stage annual operating profits for each firm i are given by:

$$\pi_i(Q_i, Q_j, \theta_t) = P\, Q_i - C(Q_i) = [(\theta_t - c_i) - Q_j]Q_i - (1 + ½\, q_i)\, Q_i^2 \qquad \text{(A1.3)}$$

The gross project value (profit value), V_i, and the net present value, NPV_i, from the second-stage investment for firm i, assuming perpetual annual operating cash flows (profits) and a constant risk-adjusted discount rate k in the last stage, are obtained from[36]

$$V_i = \frac{\pi_i}{k}, \quad \text{and} \quad NPV_i = V_i - I = \frac{\pi_i}{k} - I \qquad \text{(A1.4)(A1.4')}$$

[36] For simplicity, we assume zero taxes and depreciation so that the operating cash flows are equivalent to operating profits.

Under quantity competition, the reaction function of each firm is downward sloping. Maximizing firm i's (i = A, B) own profit value over its quantity given that its competitor produces Q_j (setting $\partial V_i / \partial Q_i$ = 0), each firm's reaction function is given by:[37]

$$R_i(Q_j) = \frac{\theta_t - c_i - Q_j}{2 + q_i} \tag{A1.5}$$

If both firms make a *simultaneous* production capacity investment in the second stage (I, I), a Cournot Nash equilibrium outcome will result. The equilibrium quantities, Q^*_A and Q^*_B, are obtained by equating (being at the intersection of) the reaction functions of the two firms:

$$Q^*_i = \frac{(\theta_t - c_i)(2 + q_j) - (\theta_t - c_j)}{(2 + q_i)(2 + q_j) - 1} \tag{A1.6}$$

In the case that firm i's early strategic investment reduces its cost (c_i) below its competitor's (c_j), then $Q^*_i > Q^*_j$. If we simplify by setting $q_i = q_j = q = 0$, this asymmetric Cournot Nash equilibrium quantity for firm i reduces to $Q^*_i = 1/3(\theta_t - 2c_i + c_j)$. (For example, if A's early strategic investment makes $c_A = 0$, $Q^*_A = 1/3(Q_t + c_B) > 1/3(Q_t - 2c_B) = Q^*_B$). Substituting back into profit value eqs. (A1.3) and (A1.4), again assuming $q_i = q_j = 0$, gives the Cournot Nash equilibrium profit value for firm i (i = A, B) as follows:

$$V^*_i = \frac{(\theta_t - 2c_i + c_j)^2}{9k} \tag{A1.7}$$

In case the pioneering firm does not make an early strategic investment and both firms invest simultaneously in the second stage, a symmetric Cournot Nash equilibrium may result if the firms are otherwise identical ($Q^*_A = Q^*_B = Q^*$, with $c_A = c_B = c$ and $q_A = q_B = q$), yielding:

[37] As illustrated in the example of Exhibit 2 (with $q_i = 0$), if pioneering firm A's early strategic investment (K_A) would create a first-mover cost advantage (reducing c_A below c_B, say to 0) that would result in proprietary benefits and make the firm tougher, its intercept would increase and its reaction curve would shift out to the right, increasing its equilibrium quantity (Q^*_A) while reducing that of its competitor (Q^*_B) --moving from Cournot equilibrium outcome N_0 to N_p. By contrast, if firm A would take an accommodating position resulting in shared benefits with its competitor (e.g., also reducing the competitor's cost c_B, say to 0), B's reaction curve would also shift to the right, increasing its equilibrium output (Q^*_B) to that of outcome N_s.

$$Q^*_i = \frac{(\theta_t - c)}{(3 + q)}, \quad \text{and} \quad V^*_i = (1 + ½\, q)\frac{(\theta_t - c)^2}{(3 + q)^2\, k} \quad (\text{if } \theta_t > c) \qquad \text{(A1.8)(A1.9)}$$

(If q = 0, the symmetric Cournot equilibrium quantity simplifies to $Q_i^* = 1/3(\theta_t - c)$ and $V_i^* = (\theta_t - c)^2/9k$.) Note that each firm i will eventually be profitable, net of its second-stage outlay I, if demand is such that its NPV, determined from eqs. (A1.4') and (A1.7) above, is positive (in this case if $\theta_t \geq 3\sqrt{kI} + 2c_i - c_j$). If demand is too low for either firm to operate profitably they will both wait, whereas if $\theta_t < 3\sqrt{kI} + 2c_j - c_i$ firm j will be unprofitable ($NPV_j < 0$) and firm i can earn monopoly profits.[38] It can be seen from eq. (A1.5), with $Q_j = 0$, that the value-maximizing quantity for a monopolist firm i (points M in Exhibit 2, where $q_i = 0$) is given by:

$$Q_i = \frac{\theta_t - c_i}{2 + q_i} \qquad (\text{with } Q_j = 0) \qquad \text{(A1.10)}$$

The monopolist firm can then set a monopolist price $[\theta_t(1 + q_i) + c_i]/(2 + q_i)$, and enjoy monopoly profit value of:

$$V_i = \frac{(\theta_t - c_i)^2}{(4 + 2q_i)k} \qquad (\text{with } V_j = 0) \qquad \text{(A1.11)}$$

In case firm i invests first and firm j defers investment until next period (I, D), the follower will set its quantity having first observed the leader's output according to its reaction function, $R_j(Q_i)$, as in eq. (A1.5). The Stackelberg leader i will then maximize $V_i(Q_i, R_j(Q_i))$ over Q_i, taking the follower's reaction function $R_j(Q_i)$ as given, resulting in equilibrium quantity and profit value (assuming for simplicity that $q_i = q_j = 0$) for the Stackelberg leader given by:

$$Q_i = \frac{(\theta_t - c_i)(2 + q_j) - (\theta_t - c_j)}{(2 + q_i)(2 + q_j) - 2}, \qquad \text{and} \qquad V_i = \frac{(\theta_t - 2c_i + c_j)^2}{8k} \qquad \text{(A1.12)(A1.13)}$$

[38] It is assumed that the last stage is infinite (steady state) and the possibility of reentry is precluded.

Substituting the leader's optimal quantity from eq. (A1.12) into the follower's reaction function in eq. (A1.5) gives the Stackelberg follower's quantity and profit value (assuming $q_i = q_j = 0$):

$$Q_j = \frac{(\theta_t - c_j)(2 + q_i) - (\theta_t - c_i)}{(2 + q_i)(2 + q_j)}, \quad \text{and} \quad V_j = \frac{(\theta_t - 2c_j + c_i)^2}{16k} \qquad \text{(A1.14)(A1.15)}$$

As expected, the follower's equilibrium quantity and profit value are lower than the leader's ($Q_j < Q_i$, $V_j < V_i$). Further, if demand is low ($\theta_t < 4\sqrt{kI} + 2c_j - c_i$) the Stackelberg follower will be unable to cover its investment outlay I ($NPV_j < 0$) and will not enter; the Stackelberg leader's profit value can therefore improve (from that of eq. (A1.13)) to the monopoly profit value shown in eq. (A1.11) (with $q_i = 0$). The equilibrium quantities and profit values (assuming $q_i = q_j = 0$) for the various market structures above under contrarian quantity competition are summarized in Table 1.

Appendix 2

This appendix derives the equilibrium quantities, profits and reaction functions under various market structures in the case of a proprietary uncertain R&D investment with learning cost effects by either firm. Based on the assumption (in section 4) that marginal costs decline exponentially with cumulative production $\Sigma Q_{it}\left(= Q_{it} + \Sigma Q_{it-1}\right)$ according to:

$$c_i\left(Q_{it}\right) \equiv \frac{\partial C_i}{\partial Q_{it}} = c_i^F + c_i^L e^{-\gamma \sum Q_{it}}, \tag{A2.1}$$

the total cost function for firm i (with learning) is given by:

$$C\left(Q_{it}\right) = c_i^F Q_{it} + c_i^L \int_{\sum Q_{it-1}}^{\sum Q_{it}} e^{-\gamma \sum Q_{it}} dQ_{it}, \tag{A2.2}$$

where c_i^L is that part of the costs on which firm *i* experiences learning-cost savings at an exponential rate γ, c_i^F is the floor level, and ΣQ_{it} is the cumulative production up to and including period t.

The second-stage annual operating profits for firm *i* are then given by:

$$\pi_i\left(Q_{it}, Q_{jt}, q_t\right) = \left[\left(\theta_t - c_i^F\right) - Q_{jt}\right] Q_{it} - Q_{it}^2 - c_i^L \int_{\sum Q_{it-1}}^{\sum Q_{it}} e^{-\gamma \sum Q_{it}} dQ_{it}. \tag{A2.3}$$

The reaction function of firm *i* (from max $\pi_i(Q_i, Q_j)$ over Q_i) is:

$$R_i\left(Q_{jt}\right) \equiv Q_{it}\left(Q_{jt}\right) = \frac{\theta_t - c_i^F - Q_{jt} - c_i^L e^{-\gamma \sum Q_{it}}}{2}. \tag{A2.4}$$

In the simultaneous Cournot Nash equilibrium, by equating the reaction functions of the two firms, the Cournot Nash equilibrium quantities are:

$$Q_{it}^* = \frac{\theta_t - 2c_i^F + c_j^F - 2c_i^L e^{-\gamma \sum Q_{it}} + c_j^L e^{-\gamma \sum Q_{jt}}}{3}. \tag{A2.5}$$

For sequential Stackelberg equilibrium where firm *i* is the leader and firm *j* the follower, maximization of the profit function of firm *i* (A2.3) with respect to Q_{it}, given $Q_{jt}(Q_{it})$, gives:

$$\theta_t - c_i^F - Q_{jt} - \frac{\partial Q_{jt}}{\partial Q_{it}} Q_{it} - 2Q_{it} - c_i^L e^{-\gamma \sum Q_{it}} = 0. \qquad \text{(A2.6)}$$

Given $Q_{jt}(Q_{it})$ from the reaction function of firm *j* in (A2.4), and differentiating with respect to Q_i,

$$\frac{\partial Q_{jt}}{\partial Q_{it}} = \frac{-1 + \gamma c_j^L e^{-\gamma \sum Q_{jt}} \dfrac{\partial Q_{jt}}{\partial Q_{it}}}{2},$$

so that

$$\frac{\partial Q_{jt}}{\partial Q_{it}} = \frac{1}{\gamma c_j^L e^{-\gamma \sum Q_{jt}} - 2}. \qquad \text{(A2.7)}$$

Substituting Q_{jt} from the reaction function in (A2.4) and $\dfrac{\partial Q_{jt}}{\partial Q_{it}}$ from (A2.7) into (A2.6) and solving for Q^*_{it} leads to the Stackelberg leader's equilibrium quantity:

$$Q^*_{it} = \frac{\theta_t - 2c_i^F + c_j^F - 2c_i^L e^{-\gamma \sum Q_{it}} + c_j^L e^{-\gamma \sum Q_{jt}}}{3 + \dfrac{2}{\gamma c_j^L e^{-\gamma \sum Q_{jt}} - 2}}. \qquad \text{(A2.8)}$$

Substituting (A2.8) into (A2.4) results in the Stackelberg follower's (firm *j*'s) quantity, $R_{jt}(Q^*_{it})$:

$$Q^*_{jt} = \frac{\theta_t - c_j^F - c_j^L e^{-\gamma \sum Q_{jt}}}{2} - \frac{\theta_t - 2c_i^F + c_j^F - 2c_i^L e^{-\gamma \sum Q_{it}} + c_j^L e^{-\gamma \sum Q_{jt}}}{6 + \dfrac{4}{\gamma c_j^L e^{-\gamma \sum Q_{jt}} - 2}}. \qquad \text{(A2.9)}$$

In a monopoly where firm *i* produces the total quantity Q_i (and $Q_j = 0$), the profit function in (A2.3) simplifies to:

$$\pi_i(Q_{it}, \theta_t) = (\theta_t - c_i^F) Q_{it} - Q_{it}^2 - c_i^L \int_{\sum Q_{it-1}}^{\sum Q_{it}} e^{-\gamma \sum Q_{it}} \, dQ_{it}. \qquad \text{(A2.10)}$$

Differentiating (A2.10) with respect to Q_{it} leads to the monopolist's equilibrium quantity:

$$Q_{it}^{*} = \frac{\theta_t - c_i^F - c_i^L e^{-\gamma \sum Q_{it}}}{2}. \tag{A2.11}$$