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Disruptive Innovation, Market Entry and Production Flexibility in Heterogeneous Oligopoly

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We develop a model of oligopoly competition involving innovation effort, market entry and production flexibility under demand uncertainty. Several heterogeneous firms make efforts to develop new prototypes; if they succeed, they hold a shared option to enter a new market under stochastic demand. We derive analytic results for the Markov perfect equilibrium accounting for development effort, market entry and production decisions and complement these by numerical analyses. Firm value—which embeds real options—is not convex increasing in demand but exhibits "competitive waves" due to market entries by rivals. A firm with a development advantage ("innovator") exerts greater innovation effort if the market is a niche, whereas another benefiting from economies of scale ("incumbent") invests more if the market is larger. Positive externalities benefit the incumbent in the development stage, whereas the innovator is better off in counteracting negative externalities. Demand volatility raises firm incentives to innovate as it enhances the value of firm market-entry and production flexibility.

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1. Introduction

Disruptive innovations have reshaped many established industries causing incumbents to lose market share or disappear altogether. Some firms are eager to embrace disruptive innovation, while others are inclined to leverage economies of scale from known technologies. This tension between adapting to technological change and maintaining efficient production lies behind Abernathy's (1978) "productivity dilemma." For decades, established original equipment manufacturers (OEMs), such as Ford, Toyota or Volkswagen, have competed on product design and marketing (rather than innovation) to attain economies of scale. These OEMs overlooked three disruptive innovations: electric vehicles (EVs), car sharing, and autonomous driving. Tesla, initially a niche player in the luxury EV segment, is poised to become a mass producer, attaining a market cap larger than Ford's. EVs existed a century before Tesla's roadster (2006). In the 1900s, a third of the cars in NYC, Boston, and Chicago were electric. Yet, by the 1920s, EVs were less viable than Ford's gasoline-powered model T. Uber aspires to make ride-hailing so cheap and convenient that people might forgo car ownership; by 2030, car sharing may account for 25% of global driving (Economist 2016b). This trend is consistent with a general shift towards servicitation (Karmarkar et al. 2015). High-tech conglomerate Alphabet (Google) is leveraging on its computing power to become the leading exponent of autonomous driving (Economist 2016a). Autonomous driving has been technologically feasible since the EUREKA-PROMETHEUS project in

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the early 1990s (Daimler 2016, Dickmanns 2002). However, it was not commercially viable because the sidelining technologies were unreliable and prohibitively expensive. With these hurdles lifted, commercializing the technology may now be around the corner.

Often the emergence of a new dominant product design or category creates a narrow "window of opportunity," which ends when production efficiency (rather than product innovation) becomes the key value driver (Christensen et al. 1998, Klepper 2002, Suarez et al. 2015). As the "window of opportunity" for embracing these disruptive innovations is closing, some OEMs are now undergoing dramatic changes in their strategies, at the risk of accelerating the decline of the "traditional car." Volkswagen announced a radical plan to address these three disruptions (Wall Street Journal 2016). Audi, BMW, and Daimler are building a technology platform for autonomous driving, having acquired HERE's digital mapping capabilities. The OEMs' success in adopting these disruptive innovations will likely determine whether they can sustain or expand their market shares. Automotive experts believe that product differentiation will play a lesser role (Roland Berger Strategy Consultants 2014) with production efficiency becoming the lead to profitability. The key components of the "car of the future," such as electric drives and batteries, will be more generic than those of traditional cars. Autonomous driving optimized for safety and seamless system integration is less likely to enhance driving pleasure, making BMW's "Freude am Fahren" potentially obsolete. Regulators will likely favor simpler, tested basic components. Car sharing and ongoing urbanization in emerging markets are likely to give a push to easy-to-use standardized vehicles, an expected feature of mobility solutions for future smart cities (Qi and Shen 2019). As process innovation and cost efficiency take over, the window of opportunity is closing fast with late movers locked out.

Virtual reality (VR) is another disruptive innovation and product category becoming ripe for market entry. The underlying technology (sensors, algorithms and VR headset) are becoming fairly standard and commoditized. For instance, the sensors used for positional tracking get smaller, better and more affordable. Manufacturers are less likely to differentiate on product design and prices but on economies of scale. As VR headsets become commoditized, the opportunity to enter this new market (following Facebook's, Sony's and HTC's entry) may also be short-lived.

The above two industries facing disruptive innovations have some common features. In both cases, the research phase has reached maturity. Rival firms must next decide whether to develop a prototype meeting certain regulatory requirements and customer demands as well as satisfying some production efficiency criteria. Some degree of uncertainty remains as to whether a specific firm's prototype will meet these hurdles. Some firms may have a headstart in the development phase, e.g., may already have first results from pilot programs. If a prototype proves viable, a firm can decide whether or not to commercialize the innovation and launch the new product category. These market-entry decisions will depend on the state of future demand (which cannot be readily forecast at present) as well as on how many (and which) rivals succeed at developing competing viable prototypes. Product differences are likely to be short-lived as these innovations rest on a common technology base. Consequently, process optimization (attaining economies of scale and cost efficiency) becomes the key success factor in the later stage. Following their market entry, invested firms are able to adjust production in light of realized demand, expanding production if the new product category performs well beyond the niche market of early adopters (e.g., in autonomous driving) or possibly even shutting down production if the market surge was due to a "hype."

We develop a dynamic game to capture the essential features of the above settings. Heterogeneous oligopoly firms facing technological and market uncertainty must decide first on their development efforts and then on their market entry decisions within a narrow window of opportunity. We adopt an asymmetric Cournot model for the production decisions following market entry assuming process optimization prevails over product differentiation in the mid-to-long term. Our framework explores a new territory involving the interplay among technology development, market-entry and flexible production decisions in heterogeneous oligopoly under uncertainty. We present analytic results, which we complement by numerical analyses. Specifically, we derive a closed-form expression for the value of the flexibility to adjust production to stochastic demand in oligopoly, generalizing the Black–Scholes–Merton (BSM) formula (see Black and Scholes 1973, Merton 1973) to accommodate strategic interactions, production flexibility and cost heterogeneity. Firm value expressions reflect sustained current operations as well as upside expansion potential and shut down options. We address the "coordination game" among firms seeking to enter a new market and derive the expected discounted value attained for given development efforts. We then investigate numerically the equilibrium development efforts by several asymmetric rival firms. We show that firm value is not always convex increasing in the state of demand, but may exhibit "competitive waves" close to the rivals' market-entry thresholds (as the payoff drops with each new rival entry). In addition, we investigate to what extent different firm profiles in terms of development and production capabilities influence the firms' choices of upfront technology development efforts. Finally, we examine the effect of positive or negative externalities on firms' development efforts.

2. Literature Review

Our article relates to literature streams on real options, industrial organization, production flexibility, innovation and strategic investment under uncertainty. By contrast, we account for more firms and for heterogeneity among rivals as well as output flexibility with economies of scale in production. Beside making (binary) market-entry decisions, firms have flexibility to continuously adjust their production decisions to demand realization, rather than switch from one "production mode" to another. In our setting, oligopoly firms directly influence the price-setting process with firm profits and values being convex in the state of demand.

Production flexibility enables a firm to limit the downside risk of operations by curtailing or shutting down production while tapping on favorable upside demand surges to expand production. *Real options analysis* (ROA) allows quantifying the firm's flexibility to adapt to exogenous market changes and estimate the value of production flexibility under uncertainty (see, e.g., Dixit and Pindyck 1994, Smith and Nau 1995, Trigeorgis 1996). This is facilitated by capitalizing on an analogy between financial and real options. While strategic interactions are less significant in efficient capital markets, business situations are replete with strategic real options shared with industry rivals. *Industrial organization* (IO) (see, e.g., Tirole 1988) provided prescriptive guidance into how strategic interactions affect firm behavior. ROA and IO were recently brought together—via "option games"—allowing deeper insights into industry dynamics (e.g., Chevalier-Roignant and Trigeorgis 2011, Chevalier-Roignant et al. 2011, Smit and Trigeorgis 2004).

Several articles in operations management discuss how to mitigate business risk with financial or operational hedging (see, e.g., Huchzermeier and Cohen 1996, Kogut and Kulatilaka 1994, Van Mieghem 2003). Kogut and Kulatilaka (1994) analyze a firm with a global manufacturing footprint that can hedge against foreign exchange fluctuations by shifting production among its network of plants under different currency regimes. Such models view *production flexibility* as a switching option among discrete production modes. We consider a broader class of production schedules, ranging from idle operations at low demand to expanding production at high demand.

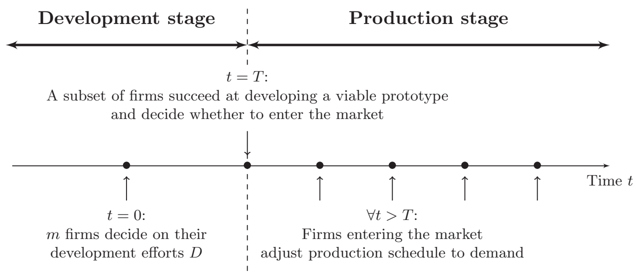
Real options analysis has also proven useful to analyze problems related to development efforts or *innovation investment* (see, e.g., Grenadier and Weiss 1997, Huchzermeier and Loch 2001, McGrath and Nerkar 2004, Oriani and Sobrero 2008, Weeds 2002). McGrath and Nerkar (2004) stress the compatibility of ROA with motives to conduct R&D. Huchzermeier and Loch (2001) consider the role of uncertainty, using ROA to assess R&D flexibility. We here consider development efforts to enhance the value of the option to later commercialize the technology and compete with rivals. Several authors (e.g., Anupindi and Jiang 2008, Kouvelis and Tian 2014, Kulatilaka and Perotti 1998, Swinney et al. 2011, Van Mieghem and Dada 1999) analyze *strategic investment under uncertainty* based on two-stage models where a firm makes a first-stage (e.g., capacity) investment that influences rival behavior in a later stage.

The article closest to ours is Kulatilaka and Perotti (1998) where two firms face a decision to enter a new market, receiving Cournot duopoly profits in a one-shot game. A Stackelberg leader can invest in an efficient production technology reducing future unit cost; such an investment results in greater convexity of second-stage Cournot profits. The authors derive the investment option value in a duopoly. Our paper expands upon this model in several respects. First, we generalize to more than two heterogeneous firms in oligopoly. We further assume firms compete repeatedly *à la* Cournot (rather than one-shot) and incorporate production flexibility. Third, we address the multiplicity of pure-strategy Nash Equilibria (NE) and solve the coordination game at the market entry time. We thus derive a more general value expression for the market-entry option in oligopoly and further examine the incentives of firms to exert innovation efforts.

3. Model Setup and Solution Approach

We consider a game among $m \in \mathbb{N}$ rival firms made up of two stages as shown in Figure 1: a development stage $(0, T)$ and a production stage (T, ∞). We use a filtered probability space $(\Omega, \mathcal{F}, (\mathcal{F}_t)_{t \geq 0}, \mathbb{P})$ to accommodate uncertainty. A firm's success $S_i : \Omega \to \{0, 1\}$ indicates whether (1) *or* not (0) firm i's prototype meets a set of technical, regulatory, and profitability criteria. Firm successes are assumed to be independent events. At the outset ($t = 0$), firm i's probability of success is $\lambda_i = \mathbb{P}(S_i = 1|\mathcal{F}_0)$: firm i may start from scratch (if $\lambda_i = 0$) or enjoy a headstart (if $\lambda_i > 0$). We note $\lambda = (\lambda_i)_i \in [0, 1]^m$ the vector of probabilities. Over the *development stage* $(0, T)$, firm i can exert development effort D_i to improve its probability of success from λ_i to $\Lambda_i(\lambda_i, D)$, where $D = (D_i)_i \in \mathbb{R}^m_+$; firm i's effort is not observed by rivals when they decide on their own efforts $D_{-i} \in \mathbb{R}^{m-1}$. Function $D_i \mapsto \Lambda_i\left(\lambda_i, \begin{pmatrix} D_i \\ D_{-i} \end{pmatrix}\right)$ is concave increasing on $\mathbb{R}_+$ from λ_i to 1; its curvature captures firm i's innovativeness.

Figure 1 Model Setup with Decision Stages



Firm i's innovation success is revealed by market-entry time T. We use upper case $S_i : \Omega \rightarrow \{0, 1\}$ when the success state is unknown and lower case $s_i \in \{0, 1\}$ once it is revealed. We note by $s \in \{0, 1\}^m$ the state of firms' successes. At time T, each rival firm i decides whether to enter the market given demand uncertainty and the threat of rival entry; firm i's decision variable is $\epsilon_i \in \{0, 1\}$ and the market-entry state is $\epsilon \in \{0, 1\}^m$. Market entry is not feasible if firm i fails to develop a viable prototype ($s_i = 0$). Market-entry time T is known from the outset (given an anticipated narrow window of opportunity) and is not part of firms' strategies.[1] When entering the market firm i incurs a firm-specific sunk cost of I_i to set up new production lines and distribution networks and promote the technology. Firms are ranked in terms of increasing market-entry costs: $I_i \leq I_{i+1}$. In a manufacturing industry, an incumbent may leverage on existing production lines and its network of resellers, while market entrants start from scratch. It is meaningful to interpret low-indexed (low-cost) firms as large incumbents and high-indexed (high-cost) firms as smaller start-up entrants.

During the *production stage* ($t > T$), firm i faces affine-quadratic production costs,

$$C_i(q_i) := f_i + dq_i + c_i q_i^2, \quad f_i, d, c_i \geq 0. \tag{1}$$

The cost parameter d in Equation (1) is homogeneous across firms: it represents the (linear) cost incurred to source inputs from competitive suppliers. Firms differ in their ability to exploit economies of scale, as captured by the firm-specific quadratic cost term c_i. Given the assumption $c_i \leq c_{i+1}$, incumbents are better at exploiting economies of scale. Incumbents may also achieve lower fixed production costs f_i owing to economies of scope, so $f_i \leq f_{i+1}$. Overall, incumbents enjoy lower unit costs.

Firm i's profit,

$$\pi_i(x, Q) = p(x, Q)\ q_i - C_i(q_i) \tag{2}$$

depends on the state of demand $x \in \mathbb{R}_+$ and the firms' output decisions $Q \in \mathbb{R}^m$. In line with Kulatilaka and Perotti (1998) and Van Mieghem and Dada (1999), we assume linear demand,

$$p(x, Q) = x - b \sum_{i \geq 1} q_i, \quad b > 0, \tag{3}$$

where the demand intercept $(X_t;\ t \geq 0)$ follows a geometric Brownian motion of the form:

$$dX_t = \mu X_t\ dt + \sigma X_t\ dB_t, \quad X_0 = x\ (>0). \tag{4}$$

Parameter μ ($\geq$0) captures the risk-neutral growth rate, σ (>0) is the (constant) demand volatility, and $(B_t;\ t \geq 0)$ is a standard $\mathbb{P}$-Brownian motion. The sources of uncertainty for market demand and technological development are uncorrelated. The firm can mitigate certain risks through replication or hedging activities, which allows one to adjust the drift of the stochastic process for the underlying riskiness, enabling discounting future risk-adjusted cash-flows at the risk-free interest rate ρ. According to Birge (2000), option-pricing theory offers a rigorous way to incorporate risk aversion in linear cash-flow payoffs without relying on utility functions. If firm profit value risks to suddenly drop (to nil) at a Poisson arrival rate $\varrho \geq 0$—due, for instance, to drastic new regulation or competitive erosion—then the discount rate can be adjusted to $r := \rho + \varrho$ (see, e.g., Merton 1976 or the notion of "exponential decay" in Dixit and Pindyck 1994, pp. 200–204). The variable x is used here to indicate either the demand *state*—known at the time of decision—or the *initial value* of the stochastic demand process $(X_t;\ t \geq 0)$. This second notation for x is used in combination with the conditional expectation operator $\mathbb{E}_x$ under the risk-neutral or equivalent martingale probability measure $\mathbb{P}$.

Firm i's strategy, ϕ_i, amounts to deciding on (i) the innovation efforts D_i during the development stage (0, T); (ii) whether to launch the product at time T, $\epsilon_i \in \{0, 1\}$; and (iii) a production rate $q_i(t)$ considering the demand realization X_t and rivals' output decisions $Q_{-i}(t)$. The Cournot-game structure for (iii) is applicable to our industry examples as product differentiation loses significance as the "window of opportunity" closes and firms play a capacity game (see Kreps and Scheinkman 1983, for the relation between capacity and output decisions).

We solve for the Markov perfect equilibrium of the dynamic game, obtaining a profile of strategies $(\phi_i^\star, \phi_{-i}^\star)$ in the class of Markov or feedback policies that yields a Markov Nash equilibrium (MNE) in each demand state x (see also Fudenberg and Tirole 1991, Ch. 13). When firm i decides at the outset on its efforts D_i over the development period (0, T), it knows the current state of demand x and the initial probabilities of prototype development successes λ. Yet, firm i does not observe rivals' efforts D_{-i} during the development stage but forms beliefs based on the NE concept. At market-entry time T, firm i knows which rivals have successfully developed viable prototypes (the technology state $s \in \{0,1\}^m$). This is reasonable because many rival firms are publicly listed and face pressures to report their achievements to shareholders. Finally, in the production stage ($t > T$), firm i knows the identity of producing rivals (the state $\epsilon \in \{0,1\}^m$) and infers rival outputs from the NE concept. Cost and demand functions (including the intercept dynamics) and the firms' risk preferences are assumed public knowledge.

Our solution approach proceeds backwards. First, we obtain the outputs and profits of all producing firms in MNE. We then derive the value of an invested firm enjoying production flexibility (at market-entry time T), analyze the resulting market-entry game and identify the equilibrium. We express the value of developing a prototype in closed form and determine the (equilibrium) development effort each firm exerts.

4. Product-Market Competition

4.1. Flexible Production Decisions

The MNE, noted $\hat{Q}(x,\epsilon)$ or $\hat{Q}$, is the output vector from which no firm i has an incentive to unilaterally deviate:

$$\hat{\pi}_i(x,\epsilon) := \pi_i(x,\hat{Q}) \geq \pi_i(x,(q_i,\hat{Q}_{-i})), \quad \forall q_i \geq 0,$$

where $\hat{Q}_{-i} \in \mathbb{R}_+^{m-1}$ are the outputs produced by all other rival firms except firm i. We define

$$\Xi(\epsilon) := \frac{\sum_i \epsilon_i \prod_{j\neq i}(b+2c_j)^{\epsilon_j}}{\prod_j (b+2c_j)^{\epsilon_j}} \tag{5}$$

and introduce factor

$$\Theta_i(\epsilon) := \frac{b+c_i}{(b+2c_i)^2}\left[\frac{1}{1+b\Xi(\epsilon)}\right]^2 \mathbb{1}_{\{\epsilon_i=1\}} \tag{6}$$

noting the indicator function by $\mathbb{1}_{\{\cdot\}}$. We next establish in Proposition 1 firm i's equilibrium profit. We use the notation "$\succ$" in $\epsilon' \succ \epsilon$ to signify that $\epsilon'_j \geq \epsilon_j,\ \forall j$ and $\exists j : \epsilon'_j > \epsilon_j$ and $a^+ := \max\{a, 0\}$. Proofs are provided in the online appendices.

PROPOSITION 1. *Firm i's profit in state $(x,\epsilon) \in \mathbb{R}_+ \times \{0,1\}^m$ is*

$$\hat{\pi}_i(x,\epsilon) = \Theta_i(\epsilon)\left[(x-d)^+\right]^2 - f_i. \tag{7}$$

Profit $x \mapsto \hat{\pi}_i(x,\epsilon)$ is convex increasing, but decreases with the number of invested firms $\sum_j \epsilon_j$. Furthermore, (a) $\Theta_i(\epsilon) \geq \Theta_j(\epsilon)$ if $c_i < c_j$, (b) $\Theta_i(\epsilon') < \Theta_i(\epsilon)$ if $\epsilon' \succ \epsilon$, and (c) firm i is worse off if it competes with firms enjoying larger economies of scale.

Firm i will not produce if demand x is lower than the linear cost ($x < d$) though it incurs a fixed cost f_i. If demand is larger ($x \geq d$), firm i's profit grows (with demand x) in a convex manner at a rate driven by $\Theta_i(\epsilon)$ given in Equation (6).[2] A firm benefiting from economies of scale earns more than a disadvantaged rival [due to property (a) in Proposition 1].

Assuming negligible costs in adjusting output, firm value $W_i(x,\epsilon)$ obtains as the expected discounted sum of the profits in Equation (1), that is,

$$\begin{aligned} W_i(x,\epsilon) &:= \max_{q_i(\cdot)\geq 0} \mathbb{E}_x\left[\int_0^\infty e^{-rt}\pi_i\big(X_t,(q_i(t),\hat{Q}_{-i}(t))\big)\,\mathrm{d}t\right] \\ &= \mathbb{E}_x\left[\int_0^\infty e^{-rt}\hat{\pi}_i(X_t,\epsilon)\,\mathrm{d}t\right]. \end{aligned}$$

If firm i operates ($x \geq d$), it makes a *gross* profit value of $\Theta_i(\epsilon)[x-d]^2$. One can give a probabilistic interpretation to

$$w_i(x,\epsilon) := \Theta_i(\epsilon)\left\{\frac{x^2}{r-2\mu-\sigma^2} - 2\frac{xd}{r-\mu} + \frac{d^2}{r}\right\} \tag{8}$$

as the perpetuity value of such gross profits; this interpretation is meaningful only if

$$r > 2\mu + \sigma^2, \tag{9}$$

which is a reasonable assumption given that the drift μ in Equation (4) is the risk-neutral drift (rather than the actual growth rate). We next introduce the parameters[3]

$$\begin{aligned} &\gamma_{A/B} := -\frac{\mu-\sigma^2/2}{\sigma^2} \pm \sqrt{\left(\frac{\mu-\sigma^2/2}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}}, \\ &\gamma_B < 0 < 1 < \gamma_A, \end{aligned} \tag{10}$$

and the function $w_i^{A/B}$ given by

$$\begin{aligned} &w_i^{A/B}(d,\epsilon) \\ &:= \frac{\Theta_i(\epsilon)d^2}{\gamma_A-\gamma_B}\left\{\frac{2-\gamma_{B/A}}{r-2\mu-\sigma^2} - 2\frac{1-\gamma_{B/A}}{r-\mu} - \frac{\gamma_{B/A}}{r}\right\}. \end{aligned} \tag{11}$$

We further note $w_i = w_i^A - w_i^B$. The term $w_i^A(x,\epsilon)$ is the portion of firm i's gross profit perpetuity value attributable to scenarios where future demand X_t exceeds current demand x, while the term $-w_i^B(x,\epsilon)$ captures scenarios where X_t is lower than current demand x. This decomposition of perpetuity value $w_i(x,\epsilon)$ helps distinguish among cases of demand upsurge or contraction. As demand fluctuates, a flexible firm will adjust its production in view of demand realizations, benefiting from demand surges by expanding capacity or reducing its market exposure by contracting or shutting down production should demand fall. Proposition 2 gives the firm value under such production flexibility.

PROPOSITION 2. *Assuming Equation* (9) *holds, if* $\epsilon_i = 1$ *then firm i's value with production flexibility in state* $(x, \epsilon) \in \mathbb{R}_+ \times \{0, 1\}^m$ *is given by*

$$W_i(x,\epsilon) := \begin{cases} -\frac{f_i}{r} + \left(\frac{x}{d}\right)^{\gamma_A} w_i^A(d,\epsilon), & x<d, \\ -\frac{f_i}{r} + w_i(x,\epsilon) + \left(\frac{x}{d}\right)^{\gamma_B} w_i^B(d,\epsilon), & x \geq d. \end{cases} \tag{12}$$

Further, $x \mapsto W_i(x, \epsilon)$ *is convex increasing from* $-f_i/r$ *to* ∞ *and* $W_i(x, \epsilon') < W_i(x, \epsilon)$ *if* $\epsilon' \succ \epsilon$.

Value $W_i(x, \epsilon)$ in Equation (12) is comprised of terms reflecting changes to the production rate in response to changes in demand. If firm i is currently idle ($x < d$), it incurs recurring fixed (e.g., maintenance) cost f_i—having perpetuity value f_i/r—but it also receives perpetual gross profit value should demand x exceed d. The growth (expansion) option value term, $w_i^A(d, \epsilon)(x/d)^{\gamma_A}$, can be interpreted as a forward perpetuity value, $w_i^A(d, \epsilon)$, received at future time $\tau_A(x, d) := \inf\{t \geq 0 | X_t \geq d\}$ and discounted back to the present with the factor $\mathbb{E}_x[e^{-r\tau_A(x,d)}] = (x/d)^{\gamma_A}$. If demand is large ($x \geq d$), firm i receives, beside the perpetuity value of present operations $w_i(x, \epsilon)$ in Equation (8) and the perpetuity of fixed maintenance cost $-f_i/r$, a downside value adjustment, $w_i^B(d, \epsilon)(x/d)^{\gamma_B}$, capturing savings from production shutdown when X_t falls below d.

4.2. Firm Market-Entry Decisions

We next analyze firms' market-entry decisions, noted $\epsilon \in \mathcal{E}(s) := \{\epsilon \in \{0, 1\}^m | \epsilon \preceq s\}$. Let

$$V_i(x,\epsilon) := \Big[W_i(x,\epsilon) - I_i\Big] \mathbb{1}_{\{\epsilon_i = 1\}} \tag{13}$$

be the payoff received by firm i upon market entry.

Equilibrium Market-Entry Choices. Consider first a game between $m = 2$ *symmetric* firms both with viable prototypes [$s = \begin{pmatrix}1\\1\end{pmatrix}$]. The functions $x \mapsto V_1\left(x, \begin{pmatrix}1\\0\end{pmatrix}\right) = V_2\left(x, \begin{pmatrix}0\\1\end{pmatrix}\right)$ and $x \mapsto V_1\left(x, \begin{pmatrix}1\\1\end{pmatrix}\right) = V_2\left(x, \begin{pmatrix}1\\1\end{pmatrix}\right)$ admit unique roots due to the monotonicity of $x \mapsto W_i(x, \epsilon)$ shown in Proposition 2. These roots, noted $\bar{x}\,(0)$ and $\bar{x}\,(1)$, satisfy $\bar{x}\,(0) < \bar{x}\,(1)$. If demand x is sufficient to accommodate entry by both firms ($x \geq \bar{x}\,(1)$), each has a dominant strategy to enter, resulting in MNE $\hat{\epsilon}(x, s) = \begin{pmatrix}1\\1\end{pmatrix}$. If demand is not sufficient for either firm to enter profitably ($x < \bar{x}\,(0)$), both have a dominant strategy to stay out, resulting in MNE $\hat{\epsilon}(x, s) = \begin{pmatrix}0\\0\end{pmatrix}$. If demand is sufficient to accommodate only one firm ($\bar{x}\,(0) \leq x < \bar{x}\,(1)$), there is no dominant strategy: if one decides to stay out, its rival should enter, but if one firm enters, its rival should stay out. In this case, there are two pure-strategy MNE $\hat{\epsilon}(x, s) = \left\{\begin{pmatrix}1\\0\end{pmatrix}, \begin{pmatrix}0\\1\end{pmatrix}\right\}$, offering asymmetric payoffs. A third MNE in mixed strategies also exists. The above arising at intermediate demand gives rise to a *coordination problem*. Because the option value term $[(\frac{x}{d})^{\gamma_A} w_i^A(d, \epsilon)]$ in Equation (12) is positive, we cannot readily rank the threshold d vs. the boundaries $\bar{x}(0)$ and $\bar{x}(1)$: a firm may enter and not produce for a while if it expects more favorable market development in the future.

If there is asymmetry among the two firms, we need to consider the ranking of x vs. four roots (rather than two). If heterogeneity is so pronounced that the most efficient firm can sustain a duopoly, while its rival cannot, then multiplicity of equilibria at intermediate demand does not arise. The sole MNE is the one where the most efficient firm enters, while the rival stays out.

More generally, in an asymmetric oligopoly, let s_{-i} be the vector of rivals with successful prototypes that are not firm i. Consider $\epsilon_{-i} \preceq s_{-i}$ and let $\bar{x}_i(\epsilon_{-i})$ denote the root of $x \mapsto V_i(x, \begin{pmatrix}1\\\epsilon_{-i}\end{pmatrix})$, which is unique. Assuming $s_i = 1$, firm i's best response $\mathcal{R}_i(x, \epsilon_{-i})$ is

$$\mathcal{R}_i(x,\epsilon_{-i}) = \begin{cases} 1 \text{ (''Enter'')}, & x \geq \bar{x}_i(\epsilon_{-i}), \\ 0 \text{ (''Stay out'')}, & x < \bar{x}_i(\epsilon_{-i}). \end{cases} \tag{14}$$

Given asymmetry, the identity of potential rivals matters [the function W_i in Equation (12) depends on the vector ε]. Among the set of $N(s)$ successful firms, let $j_l(s)$ be the (index of the) firm ranked lth in increasing quadratic cost c_l. [We drop the dependence on vector s when no confusion arises.] Determining all demand thresholds $\bar{x}_{j_l}(\epsilon_{-j_l})$ can be a daunting task. First, one needs to determine for each successful firm (N firms in total) the threshold above which it will enter for all possible industry structures: monopoly, duopoly, etc. Second, firm j_l's demand threshold for a given industry structure is not unique, but depends on rival identities/indexes. In brief, for each firm j_l, we need to determine the demand threshold corresponding to any permutation in s_{-j_l}, resulting in $N \times 2^{N-1}$ demand thresholds in total. Determining all these demand thresholds is of essence because, as per the reaction functions in (14), each firm j_l's incentive to enter the market depends on whether the demand state x is below or above such thresholds. Because asymmetry relates to the parameters c_i, f_i and I_i, there is no obvious ranking of demand thresholds for a given success scenario s. Above the demand level $\bar{x}^n_{j_l}$ firm j_l can produce profitably alongside the n most cost-efficient firms. If demand is very low ($[0, \bar{x}^0_{j_1}]$) or very large ($[\bar{x}^{N-1}_{j_N}, \infty)$) the MNE is unique. A coordination problem may arise in the intermediate demand regions $[\bar{x}^{l-1}_{j_l}, \bar{x}^l_{j_{l+1}}]$ if, e.g., two firms j_1 and j_2 can enter profitably in a monopoly but not in a duopoly—in which case either market entry is a Nash equilibrium. [In the Appendix S1 we determine all pure-strategy MNE entry decisions for simple industry structures.]

Equilibrium Selection. As discussed, the MNE is not necessarily unique. To overcome this obstacle, we refine our solution concept by employing Schelling's (1960) "focal-point argument." Here we consider the MNE that achieves the largest producer surplus as being "focal" among all possible MNE (following an argument in Fudenberg and Tirole 1991, section 1.2.4). Common sense suggests that if incumbents and start-ups hold a disruptive technology, the former are more likely to enter the market in case of a coordination problem as they would not want to be displaced by newcomers. An alternative solution approach would be to leave market-entry decisions to chance with firms using mixed strategies. This approach, however, does not actually solve the coordination problem. It rather identifies yet another Nash equilibrium in an augmented strategy space and is at odds with fundamental principles in managerial decision-making (Cachon and Netessine 2006).

Proposition 3 below characterizes the focal MNE entry decisions. Leveraging on the MNE in Proposition 3, we compute N demand thresholds (namely $\bar{x}^0_{j_1}, \bar{x}^1_{j_2}, \bar{x}^2_{j_3}, \ldots, \bar{x}^{N-1}_{j_N}$): firms $j_1, \ldots, j_l$ enter profitably in an industry structure with exactly l firms if $x \in (\bar{x}^{l-1}_{j_l}, \bar{x}^l_{j_{l+1}})$. A market entrant does not necessarily produce immediately (if $x < d$) but may wait for a while before commercializing its technology.

PROPOSITION 3. *In state $(x, s) \in \mathbb{R}_+ \times \mathcal{S}$ the MNE entry decisions that achieve the largest producer surplus are*

$$\tilde{\epsilon}(x,s) = \begin{cases} (0), & x \in \left[0, \bar{x}^0_{j_1}\right), \\ \begin{pmatrix} [1]_{j=j_1,\ldots,j_l} \\ [0]_{j\neq j_1,\ldots,j_l} \end{pmatrix}, & x \in \left[\bar{x}^{l-1}_{j_l}, \bar{x}^l_{j_{l+1}}\right),\ l = 1,\ldots,N-1, \\ s, & x \in \left[\bar{x}^{N-1}_{j_N}, \infty\right). \end{cases} \tag{15}$$

We here recall the definition of V_i in Equation (13) and the characterization of the MNE that maximizes producer surplus $\tilde{\epsilon}(x, s)$ in Equation (15). Let $\tilde{V}_i(x, s) := V_i(x, \tilde{\epsilon}(x, s))$ denote firm i's equilibrium payoff in state (x, s) at time T.

5. Development Stage

We discussed how the game unfolds for $t \geq T$. We next consider the development stage $(0, T)$ to determine firms' efforts at developing a prototype. We proceed in several steps. We first determine the value of each firm's shared option to enter the market under given prototype success probabilities $\Lambda = \Lambda(\lambda, D) = (\Lambda_i(\lambda_i, D))_i$. Subsequently, we introduce an iterative scheme to characterize the equilibrium development efforts $\hat{D} = (\hat{D}_i)_i$ of all m firms.

5.1. Incentives to Develop Prototype

Firm i's prototype success S_i follows a Bernoulli trial with probability $\Lambda_i(\lambda_i, D)$. The number of successful firms, $|S| = N$, which thus follows a Poisson-binomial distribution, is of limited use because any permutation in vector s leads to a distinct value $V_i(x, \tilde{\epsilon}(x, s))$. We thus need to consider the probability, $\mathbb{P}_\Lambda(S = s)$, of each draw of $s \in \{0, 1\}^m$ [2^m possibilities in total], rather than the aggregate metrics $\mathbb{P}_\Lambda(|S| = N)$ [$m + 1$ in total]. Because prototype successes and the market demand are assumed independent, the present value of firm i's shared option to enter the market is

$$U_i(x, \Lambda) := \sum_{s\in\mathcal{S}} \mathbb{P}_\Lambda(S = s) \times u_i(x, s), \tag{16}$$

where

$$u_i(x, s) := e^{-rT}\ \mathbb{E}_x\ \tilde{V}_i(X_T, s). \tag{17}$$

We next obtain an expression for $u_i(x, s)$ that generalizes the BSM European option formula to a multi-stage oligopoly setting. Here, the realization of random demand X_T entails strategic interactions among heterogeneous firms, leading to the MNE $\tilde{\epsilon}(X_T, s)$ in Proposition 3. Also the payoff $\tilde{V}_i(\cdot, s)$ is a (piecewise) "polynomial" function [because of $W_i(\cdot, \epsilon)$ in Equation (12)], while it is (piecewise) affine in the standard BSM model. Lemma 1 helps decompose $u_i(\cdot, s)$ in Equation (17). To proceed, define the terms

$$Q(\gamma) = r - \gamma\mu - \frac{1}{2}\gamma(\gamma - 1)\sigma^2, \quad \gamma \in \mathbb{R}, \tag{18}$$

$$\mathsf{N}^z_\gamma := N\left(\frac{\ln(x/z) + \left[\mu + (\gamma - \frac{1}{2})\sigma^2\right]T}{\sigma\sqrt{T}}\right), \tag{19}$$

where $N(\cdot)$ stands for the standard cumulative normal distribution function.

LEMMA 1. *For $T \geq 0$,*

$$\mathbb{E}_x\left[e^{-rT} X_T^{\gamma}\, \mathbb{1}_{\{X_T \geq z\}}\right] = x^{\gamma} e^{-Q(\gamma)T} \mathsf{N}_{\gamma}^{z}, \quad \gamma \in \mathbb{R}. \tag{20}$$

The term $x^{\gamma}e^{-Q(\gamma)T}$ on the right-hand side (RHS) of Equation (20) is the present value of a forward contract paying an amount X_T^{γ} at future time T. The factor N_{γ}^{z} on the RHS of Equation (20) indicates the contingency of receiving X_T^{γ} only if X_T exceeds threshold z. The "state price" of receiving 1 if X_T exceeds threshold z at T obtains as special case by setting $\gamma = 0$ in Equation (20). The BSM formula for a European call option with payoff $x \mapsto (x - z)^{+}$ where z is the option's strike price readily obtains as special case by setting $\gamma = 1$ and $\gamma = 0$ in Equation (20).[4] In contrast to the "power" payoff function of Lemma 1, we consider below a polynomial function corresponding to firm i's payoff involving various demand regions and thresholds. For Proposition 4, we recall the expressions for $\Theta_i(\epsilon)$ and $w_i^{A/B}$ in Equations (6) and (8), respectively, and introduce the functions

$$\upsilon_i(x,\epsilon) := \Bigg[\bar{w}_i(x,\epsilon) - e^{-rT}\left(I_i + \frac{f_i}{r}\right) + \left(\frac{x}{d}\right)^{\gamma_A} w_i^{A}(d,\epsilon) \times\left(1 - \mathsf{N}_{\gamma_A}^{d}\right) + \left(\frac{x}{d}\right)^{\gamma_B} w_i^{B}(d,\epsilon)\mathsf{N}_{\gamma_B}^{d}\Bigg]\mathbb{1}_{\{\epsilon_i = 1\}} \tag{21}$$

$$\bar{w}_i(x,\epsilon) := \Theta_i(\epsilon)\left\{x^2 \frac{e^{-(r-2\mu-\sigma^2)T}\mathsf{N}_2^{d}}{r-2\mu-\sigma^2} - 2xd\frac{e^{-(r-\mu)T}\mathsf{N}_1^{d}}{r-\mu} + d^2\frac{e^{-rT}\mathsf{N}_0^{d}}{r}\right\}. \tag{22}$$

PROPOSITION 4. (SHARED REAL OPTION VALUE). *The function u_i in Equation* (17) *admits the functional representation*

$$u_i(x,s) = \sum_{l=1}^{N-1} \upsilon_i\left(x, \begin{pmatrix}[1]_{j=j_1,\ldots,j_l}\\ [0]_{j\neq j_1,\ldots,j_l}\end{pmatrix}\right)\left[\mathsf{N}_0^{\bar{x}_{j_l}^{l-1}} - \mathsf{N}_0^{\bar{x}_{j_{l+1}}^{l}}\right] + \upsilon_i\left(x, \begin{pmatrix}[1]_{j=j_1,\ldots,j_N}\\ [0]_{j\neq j_1,\ldots,j_N}\end{pmatrix}\right)\mathsf{N}_0^{\bar{x}_{j_N}^{N-1}}, \tag{23}$$

where N and $j_1, \ldots, j_N$ are deterministic functions of state s and N_{γ}^{z} is given in Equation (19).

To interpret (23), consider its components. Here, we face two parallel demand partitions. First, firm value W_i in (2) admits different analytic expressions depending on future demand X_T being above or below threshold d. Second, following Proposition 3, we consider different equilibrium outcomes depending on the demand regions $[\bar{x}_{j_l}^{l-1}, \bar{x}_{j_{l+1}}^{l})$ in which future demand X_T falls. The expression for $u_i(x, s)$ in Equation (23) considers the second demand partitioning, while $\upsilon_i(x, \epsilon)$ in Equation (21) embeds the first. Expression (23) decomposes the option value $u_i(x, s)$ into several mutually exclusive components, $\upsilon_i\left(x, \begin{pmatrix}[1]_{j=j_1,\ldots,j_l}\\ [0]_{j\neq j_1,\ldots,j_l}\end{pmatrix}\right)$, weighting each using $\mathsf{N}_0^{\bar{x}_{j_l}^{l-1}} - \mathsf{N}_0^{\bar{x}_{j_{l+1}}^{l}}$ [and $\mathsf{N}_0^{\bar{x}_{j_N}^{N-1}}$ for $l = N$]. The term $\upsilon_i\left(x, \begin{pmatrix}[1]_{j=j_1,\ldots,j_l}\\ [0]_{j\neq j_1,\ldots,j_l}\end{pmatrix}\right)$ gives firm i's option value when it invests as one of l successful firms. Certain adjustments are noted: the relevant demand state for $\upsilon_i(x, \epsilon)$ is known at time T, which involves discounting and accounting for the probability distribution of X_T, with term N_{γ}^{d}, $\gamma = 0, 1, 2, \gamma_A, \gamma_B$ reflecting whether the demand realization falls above or below threshold d.

5.2. Equilibrium Development Efforts

Proposition 4 provided an explicit expression for the value of firm i's development opportunity $U_i(x, \Lambda)$ as given in Equation (16). We address next the equilibrium development efforts. Firm i's objective is to maximize the value of its development opportunity, net of development costs D_i, that is, to maximize

$$J_i(x,\lambda,D) := U_i(x,\Lambda(\lambda,D)) - D_i. \tag{24}$$

We note by $\Delta_i(x, \lambda, D_{-i}) \in \mathbb{R}_+$ the solution to the optimization problem

$$\Delta_i(x,\lambda,D_{-i}) := \arg\sup_{D_i \geq 0} J_i\left(x,\lambda,\begin{pmatrix}D_i\\ D_{-i}\end{pmatrix}\right). \tag{25}$$

Provided a unique solution exists for each tuple (x, λ, D_{-i}), we define firm i's reaction function $D_{-i} \mapsto \Delta_i(x, \lambda, D_{-i})$ and introduce $\Delta(x, \lambda, D) = (\Delta_i(x, \lambda, D_{-i}))_i$. A MNE is a solution $\hat{D}(x, \lambda) \in \mathbb{R}_+^m$ to the fixed-point equation

$$\Delta\big(x,\lambda,\hat{D}(x,\lambda)\big) = \hat{D}(x,\lambda). \tag{26}$$

Solving Equation (25) is not straightforward because we cannot readily differentiate the function $D_i \mapsto U_i(x, \Lambda(\lambda, D))$ given by Equation (16). We thus proceed numerically, adopting an iterative scheme akin to Cournot tâtonnement process. We consider x and λ as parameters and fix an initial vector $D^0 = (0)_i$. In each iteration step n for a given vector D^n, we determine firm i's optimal reaction $\Delta_i(x, \lambda, D_{-i}^n)$ to the rivals' strategies D_{-i}^n and then replace D^n by $D^{n+1} = \begin{pmatrix}\Delta_i(x,\lambda,D_{-i}^n)\\ D_{-i}^n\end{pmatrix}$. We consider all firms in sequence and then reiterate the procedure until the scheme converges to the fixed point $\hat{D}(x, \lambda)$ in Equation (26).[5]

6. Numerical Illustrations and Comparative Statics

We next provide numerical analyses to illustrate application of our findings and derive further model insights via comparative statics. In the base case, we contextualize our model in the setting of disruptive innovations in the automotive sector. Although we aim for a realistic choice of parameter values satisfying constraint (9), we do not claim perfect calibration with industry data. Table 1 presents two sets of parameters: set 1 is the *base case* and set 2 is used for robustness. The long-term riskfree interest rate $\rho = 0.03$ is based on the 30-year US Treasury bill rate. The effective interest rate is adjusted to account for the risk of sudden market displacement or "exponential decay" at a rate of $\varrho = 0.01$. This yields an effective discount rate of $r = \rho + \varrho = 0.04$. The base volatility estimate of 20% is in line with the current option-implied volatility of select (listed) automotive OEMs, such as Ford, Honda, and Toyota. In base-case Set 1, we set a risk-neutral drift μ at zero to focus on the effect of uncertainty, but allow for some positive growth μ in Set 2. The production cost parameters are chosen such that the incumbent (firm 1) has an advantage over its rivals (firms 2 and 3) in scaling up production and distribution. These parameter values are varied in comparative statics analyses. We assume symmetry with respect to the fixed costs $f_i = 0$ and $I_i = 250$ to focus on the effect of differentials in development and production.

Table 1 Parameter Values for Numerical Analyses

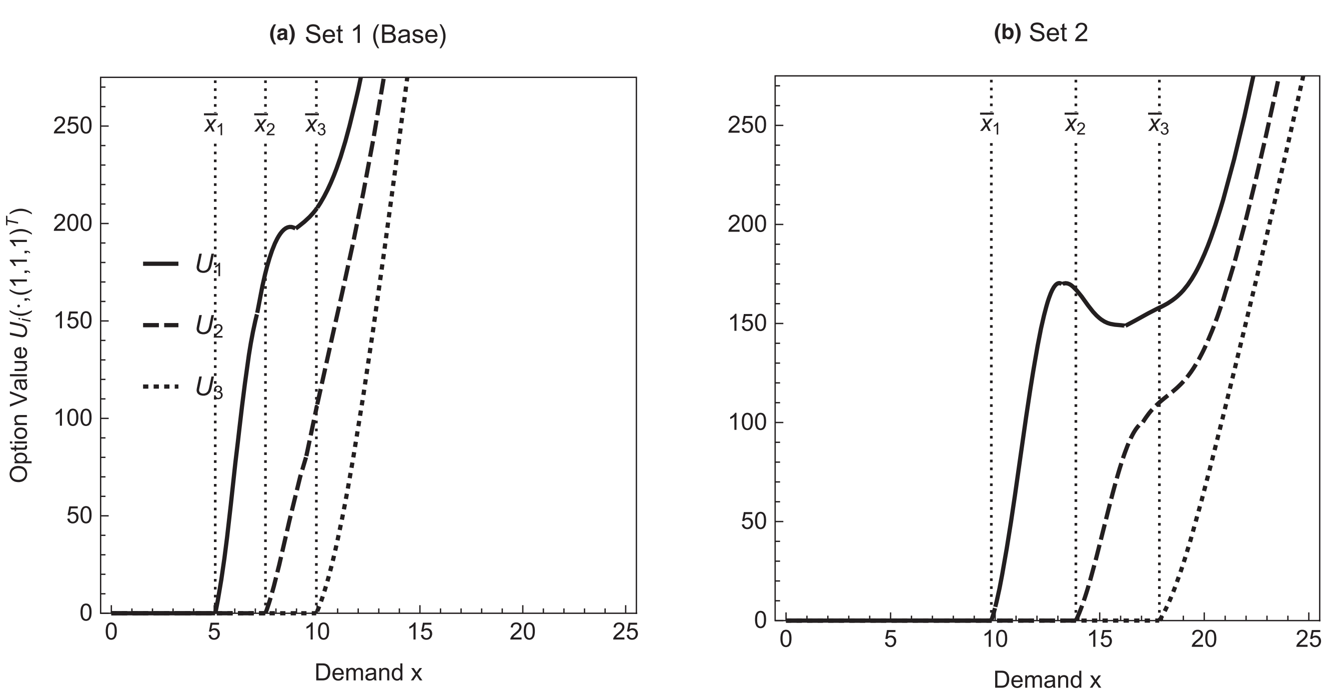
		Set 1 (base case)	Set 2 (robustness)
Demand	Risk-neutral drift	$\mu = 0.00$	$\mu = 0.01$
	Volatility	$\sigma = 0.19$	$\sigma = 0.10$
	Slope	$b = 5$	
Production costs	Fixed	$f_i = 0$	
	Linear	$d = 10$	
	Quadratic	$(c_1, c_2, c_3) = (0.5, 0.75, 1.0)$	
Investment opportunity	Horizon (maturity)	$T = 1$	
	Entry cost	$I_i = 250$	
Discount rate	Riskfree rate	$\rho = 0.03$	
	Exponential decay rate	$\varrho = 0.01$	
	Effective rate	$r = \rho + \varrho = 0.04$	

6.1. "Competitive Waves" from Rival Entries

We focus on firm market-entry decisions by considering $m = 3$ firms with *successful prototypes*. Figure 2 illustrates the (equilibrium) shared investment option values $x \mapsto U_i\left(x, \begin{pmatrix}1\\1\\1\end{pmatrix}\right)$ [as per Proposition 4], for the two parameter sets of Table 1.

Contrary to standard European call options, shared investment option values are not necessarily convex increasing. They rather exhibit "*competitive waves*" of

Figure 2 Values of the Market-Entry Option $x \mapsto U_i\left(x, \begin{pmatrix}1\\1\\1\end{pmatrix}\right)$ for Three Firms for the Two Sets of Table 1



alternating convex and concave segments.[6] The option payoff of firm 1 most benefiting from economies of scale (the "incumbent") is increasing faster at low demand; this is so because if it operates in the market ($\bar{x}_1 \leq X_T \leq \bar{x}_2$), it benefits from demand increases enjoying a monopoly status. In Figure 2a, an inflection is seen for $x \mapsto U_1\left(x, \begin{pmatrix}1\\1\\1\end{pmatrix}\right)$ close to firm 2's entry threshold $\bar{x}_2$; this is so because for $\bar{x}_1 \leq X_T < \bar{x}_2$ only firm 1 operates in the market (as a monopolist), while for $\bar{x}_2 \leq X_T < \bar{x}_3$ firm 2 also enters, resulting in (lower) duopoly profits for firm 1. Another inflection takes place close to demand threshold $\bar{x}_3$ above which firm 3 enters. The value of the least cost-efficient firm (firm 3) does not exhibit the "competitive wave" pattern (and behaves like a standard European call option) because, as a last entrant, firm 3 invests when rivals are already "in." In Figure 2, whether the "tide" of these waves is located before or after threshold $\bar{x}_i$ depends on the relative values of μ and σ (influencing the distribution of X_T) and of r (affecting the discounted value). We next focus on the "base case" (Set 1 in Table 1) to derive insights by comparative statics.

Figure 3 shows variations of the base case (set 1) to stress the impact of demand volatility σ and the horizon until market entry T on firms' entry thresholds and values. The competitive waves are more pronounced in panel d for lower volatility ($\sigma = 0.10$) and/or shorter maturity ($T = 0.25$). In the face of high volatility σ or longer horizon until market entry T, the shifts in value caused by rival entry smooth out: greater cumulative demand volatility ($\sigma\sqrt{T}$) leads to more dispersed future demand X_T and lower predictability of future strategic interactions.

6.2. Illustration of MNE Development Efforts

Above, we assumed all three firms will have a successful prototype, that is, $\Lambda = \begin{pmatrix}1\\1\\1\end{pmatrix}$. However, a firm's chance of prototype success $\Lambda_i(\lambda_i, D)$ and its reward $J_i(x, \lambda, D)$ in Equation (24) actually depend on the development efforts D exerted by all rivals during the development stage. For illustration, we specialize the function Λ_i to

$$\Lambda_i(\lambda_i, D) := 1 - (1 - \lambda_i)\exp(-\psi_i(D_{-i}, \eta)D_i). \quad (27)$$

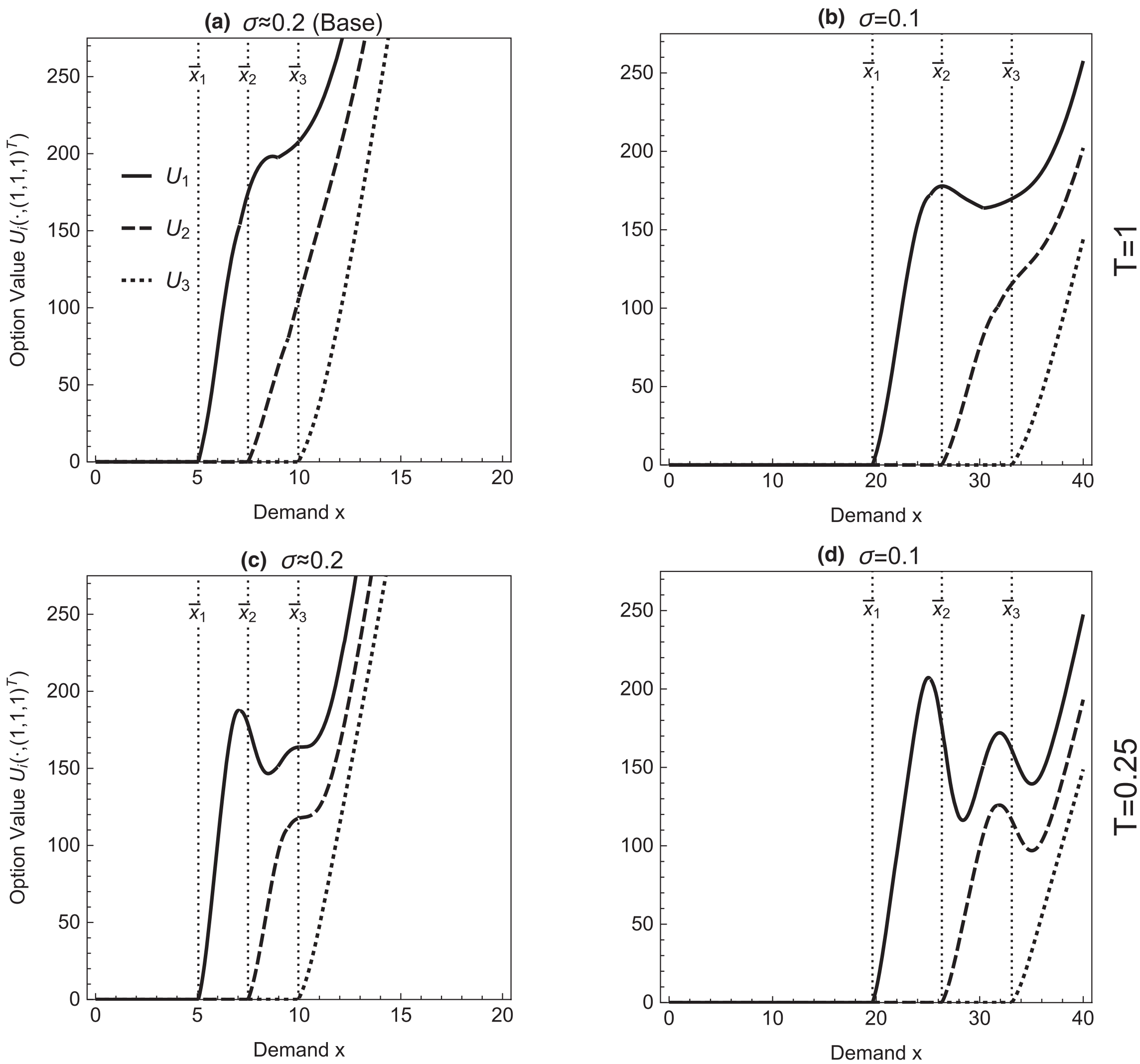
Function $D_i \mapsto \Lambda_i(\lambda_i, D)$ is monotone increasing from λ_i to 1. The rate at which it increases is driven by $\psi_i(D_{-i}, \eta) := a_i(1 + \sum_{j \neq i} D_j)^\eta$ with $a = (a_i)_i \in \mathbb{R}_+^m$ and the parameter η capturing the externality among the firms' development efforts. Firm i is more effective than firm j at developing a prototype ("more innovative") if $a_i > a_j$. With no externalities ($\eta = 0$), there is no interaction between firms' probabilities of success. With positive externalities ($\eta > 0$), a firm becomes more effective at developing a prototype when a rival expends greater development effort; this beneficial effect might arise due to imitation, greater public awareness, network effects (e.g., EV charging infrastructure, navigation platforms) or more intense collective lobbying. If externalities are negative ($\eta < 0$), a firm needs to exert larger effort to attain a given probability of prototype success; this may be the case if firms compete over scarce human resources (e.g., AI specialists).

For illustration, suppose (27) involves a headstart among firms with $\lambda = \begin{pmatrix}0\\0.1\\0.2\end{pmatrix}$. Given the base-case parameters (Set 1 in Table 1), we can now profile the three firms. Firm 1 excels at exploiting economies of scale ($c_1 < c_2 < c_3$) but has limited innovation capability—much like an established *incumbent* trapped in the classic "productivity dilemma" (Abernathy 1978). On the other end, firm 3 has a headstart ($\lambda_3 > \lambda_2 > \lambda_1$) and is more effective at developing the prototype further ($a_3 > a_2 > a_1$), yet it is less capable to ramp up production and distribute. Firm 2 fares better than firm 3 in terms of production efficiency but less so than incumbent firm 1. Firm 2 is also more effective at developing a prototype than established firm 1 but less effective than firm 3.

6.2.1. Reaction Functions and Externality Effects in a Duopoly.

Illustrating reaction functions is easier in two-player games, so in this section we focus on a duopoly involving an incumbent (firm 1) and an innovator (here, firm 2). Figure 4 depicts their reaction functions for situations characterized by distinct degrees of externalities. The *externalities are assumed negligible* ($\eta = 0$) in panel a. Here, one firm's efforts to develop a prototype reduce the other firm's chances to wield market power in the future as both would operate at large demand X_T if they hold a viable prototype; development efforts are thus strategic substitutes (reaction functions are downward-sloping). The equilibrium development efforts $\hat{D}(x, \lambda)$ in Figure 4 correspond to the coordinates of the (bold) points at which the reaction functions intersect (e.g., point A for $x = 10$). Whether a greater effort is expended by the incumbent or the innovator (as can be seen from the 45-degree line in Figure 4) depends on the current market outlook (current demand state x). If the market is a niche (low demand $x = 10$), the innovator would expend greater effort [$\hat{D}_2(10, \lambda) > \hat{D}_1(10, \lambda)$ at point A]: the innovator expends development effort at a cost advantage while the incumbent reduces its effort in

Figure 3 Comparative Statics on Market-Entry Option Values $x \mapsto U_i\left(x, \begin{pmatrix}1\\1\\1\end{pmatrix}\right)$ in a Triopoly with Respect to Demand Volatility σ and the Market-Entry Time (maturity) T

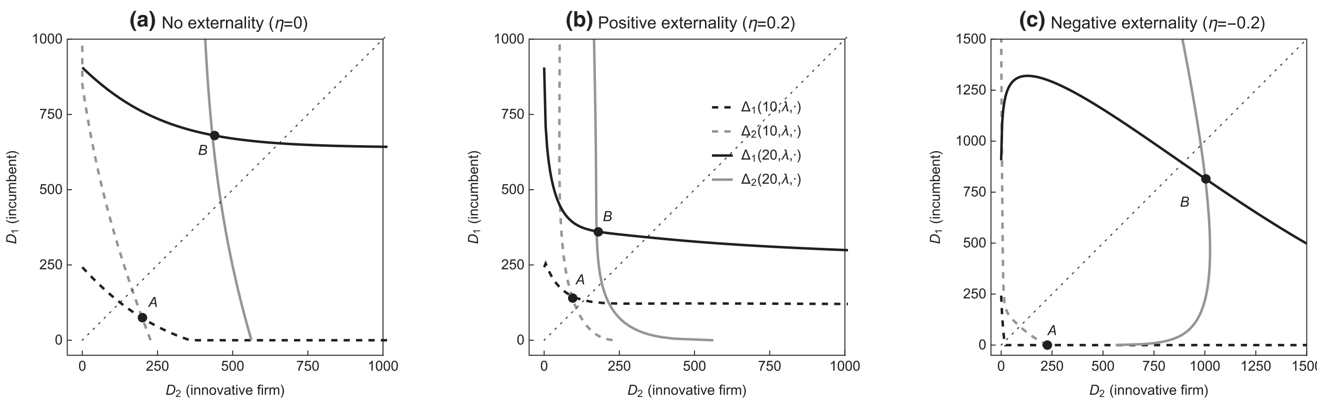


reaction (given strategic substitutability). If the market is sufficiently large to accommodate both (e.g., if $x = 20$), the incumbent (firm 1) puts greater effort to develop a prototype [$\hat{D}_2(20, \lambda) < \hat{D}_1(20, \lambda)$ at point B] despite being less efficient in development; it does so to improve its chances to subsequently benefit from economies of scale.

Externalities can also affect the equilibrium development efforts $\hat{D}(x, \lambda)$ in Equation (26). *Positive externalities*—shown for $\eta = 0.2$ in Figure 4b—enhance the incumbent's effectiveness at developing its own prototype, so the incumbent needs to expend less effort (vs. panel a) to achieve a given probability of success. The innovator also exerts less effort because it does not want the incumbent to free-ride (given strategic substitutability). Consequently, the NE points A and B shift to the bottom left corner (vs. panel a). In panel b, for both demand states ($x = 10$ and 20), the incumbent expends the greater effort in NE.

In the case of *negative externalities*—illustrated for $\eta = -0.2$ in Figure 4c—each firm's development effort reduces the efficiency of the other's. Whether development efforts are strategic substitutes or complements here depends on the demand state x. At low initial demand ($x = 10$), the reaction functions are monotone decreasing, representing strategic substitutability, while at high demand ($x = 20$) a firm's reaction function is first monotone increasing (up to a certain level), exhibiting strategic complementarity, and then decreasing, exhibiting strategic substitutability. When the market is likely to accommodate only one rival ($x = 10$), engaging in a costly development race is not rational for either firm; this leads to strategic substitutability. But when the market can

Figure 4 Reaction Functions $D_{-i} \mapsto \Delta_i(x, \lambda, D_{-i})$ in a Duopoly for Different Demand States x and Externality Effects η



accommodate more firms (x = 20), each firm is willing to go the extra mile to counteract the reduced efficiency induced by negative externalities as both firms vie for a more lucrative market.[7] The innovator (firm 2) has better prospects in the development race because it does not need to expend as much effort to overcome this inefficiency.

6.2.2. Impact of Demand Characteristics on Equilibrium Development Efforts. Our previous discussion related to the strategic interactions for given demand x = 10 or 20. We now illustrate further the effect of demand changes on the equilibrium development efforts.

Innovator vs. Incumbent in Duopoly. Figure 5 depicts duopoly firms' NE development efforts $\hat{D}_i(x, \lambda)$ across a range of demand states x. A firm will not put any effort to develop a prototype (with $\hat{D}_i(x, \lambda) = 0$) if demand is low ($x \leq x_i^\star$). If a firm puts an effort ($x \geq x_i^\star$), then its effort $\hat{D}_i(x, \lambda)$ increases with demand x. Upon market entry, the payoff $x \mapsto W_i\left(x, \begin{pmatrix} 1 \\ \epsilon_{-i} \end{pmatrix}\right)$ grows at a higher rate for the incumbent (firm 1) than for the innovator (2) due to the incumbent's more efficient production $[\Theta_1(\epsilon) \geq \Theta_2(\epsilon)]$. As the innovator (firm 2) has an advantage in development $[a_2 > a_1]$ and the incumbent (firm 1) in production, there exists a threshold $x_A \geq x_1^\star$ below (resp. above) which the innovator (resp., the incumbent) expends the greater effort.

If the market is likely to accommodate only one firm, the innovator develops the technology at a lower cost, while the incumbent refrains. If the market prospects improve, the incumbent expends more effort to enhance its chances of success, despite its disadvantage in development (with $a_1 < a_2$), while the innovator backs down (given strategic substitutability) for negligible or positive externalities. If externalities are negative (η = −0.2 as in panel c), the incumbent's decision to develop a prototype above $x_1^\star$ is an adverse development, which the innovator must counter to be successful; this results in an up jump in the innovator's efforts $\hat{D}_2(\cdot, \lambda)$ to the right of $x_1^\star$.[8]

Middle Firm in Triopoly. Figure 6 provides comparative statics on equilibrium development efforts in a triopoly. Here, firm 3 is the *innovator* and firm 2 is a *middle firm*, excelling neither in development nor production but faring well overall. At low demand $x < x_A$, the innovator (firm 3) exerts the greatest development effort, while for large demand $x \geq x_C$ the incumbent (firm 1) does so. In the intermediate demand region $x_A \leq x < x_C$, the middle firm (2) puts the greatest effort as it would benefit more from economies of scale at market entry than the innovator [as $\Theta_2(\epsilon) > \Theta_3(\epsilon)$] while being more effective at developing a viable prototype than the incumbent [as $a_2 > a_3$]. In a subset of this demand region—namely $[x_B, x_C)$—the incumbent exerts a greater effort than the innovator. The region $[x_A, x_C)$ expands if the middle firm is better at developing a prototype (from $a_2 = 0.0045$ in the left panel to 0.012 in the right panel), resembling an innovative firm (3). By contrast, if the middle firm becomes less efficient at ramping up production (from $c_2 = 0.75$ in panels a and b to 0.95 in panels c and d), like the innovator (firm 3), the range of demand $[x_A, x_C)$ for which the middle firm exerts the greatest effort would shrink somewhat.

Figure 7 illustrates the equilibrium development efforts depending on demand volatility σ for a given demand state (x = 20 or 30). For a given demand level x, there is a cut-off volatility level $\sigma_i^\star(x)$ below which firm i would not invest in development activities. This cut-off $\sigma_i^\star(x)$ decreases in demand x (panel b vs. panel a) because better demand prospects x do not necessitate volatility to be as large for the market to be attractive. The development effort of the incumbent (firm 1) takes off at a higher volatility than the innovator's ($\sigma_1^\star > \sigma_3^\star$), but it is steeper. The incumbent is less efficient in development, yet it benefits more from

Figure 5 Comparative Statics on Equilibrium Development Efforts $x \mapsto \hat{D}_i(x, \lambda)$ in a Duopoly with Respect to Externality Effects η at Different Levels of Demand x

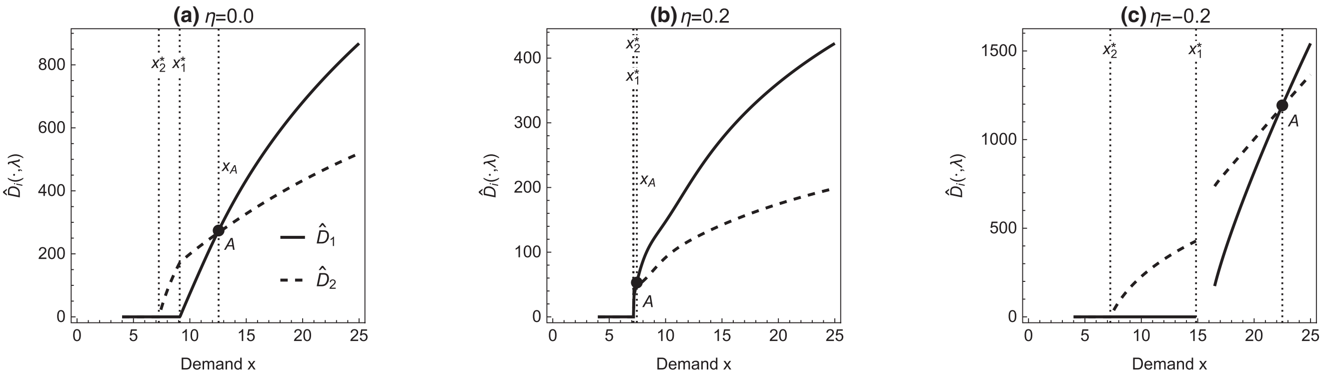


Figure 6 Comparative Statics on Equilibrium Development Efforts $x \mapsto \hat{D}_i(x, \lambda)$ in a Triopoly with Respect to the "Middle" Firm's Development Efficiency Parameter a_2. We Assume No Externalities ($\eta = 0$)

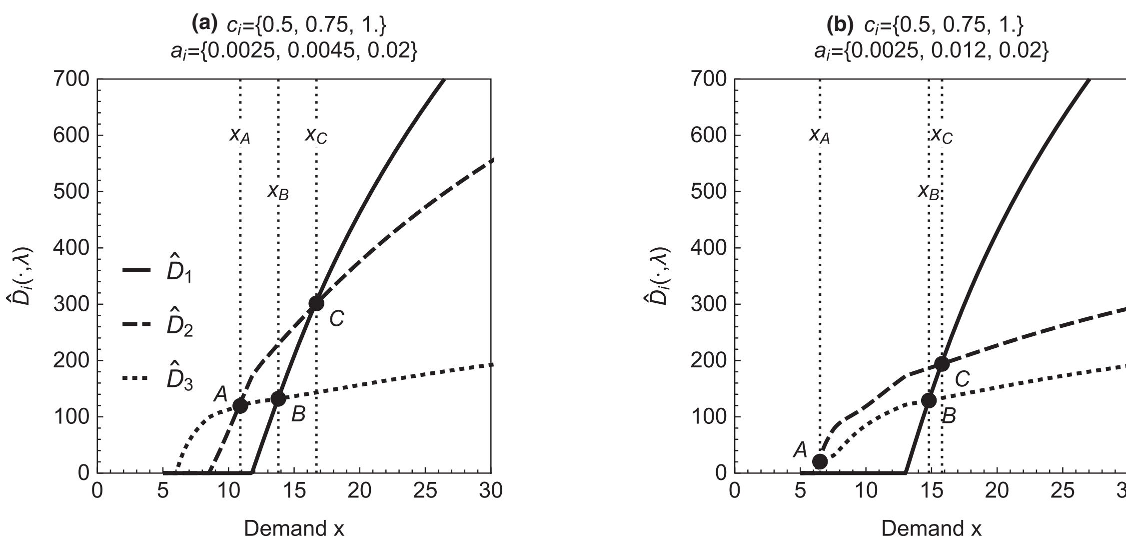


Figure 7 Comparative Statics on Equilibrium Development Efforts $\hat{D}_i$ with Respect to Demand Volatility σ at Different Levels of Demand x. We Assume No Externalities ($\eta = 0$)

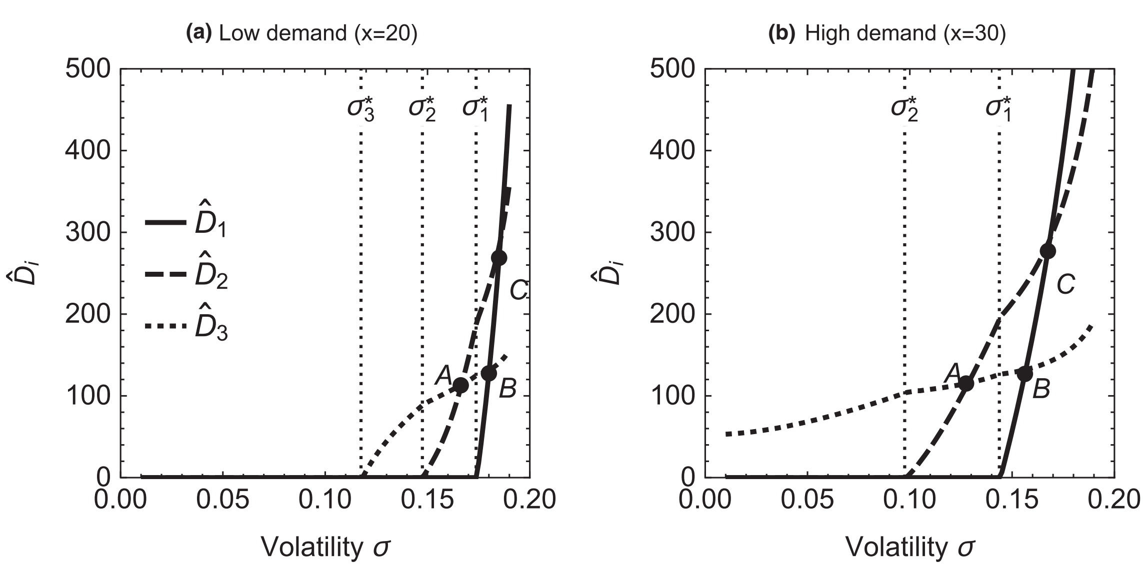
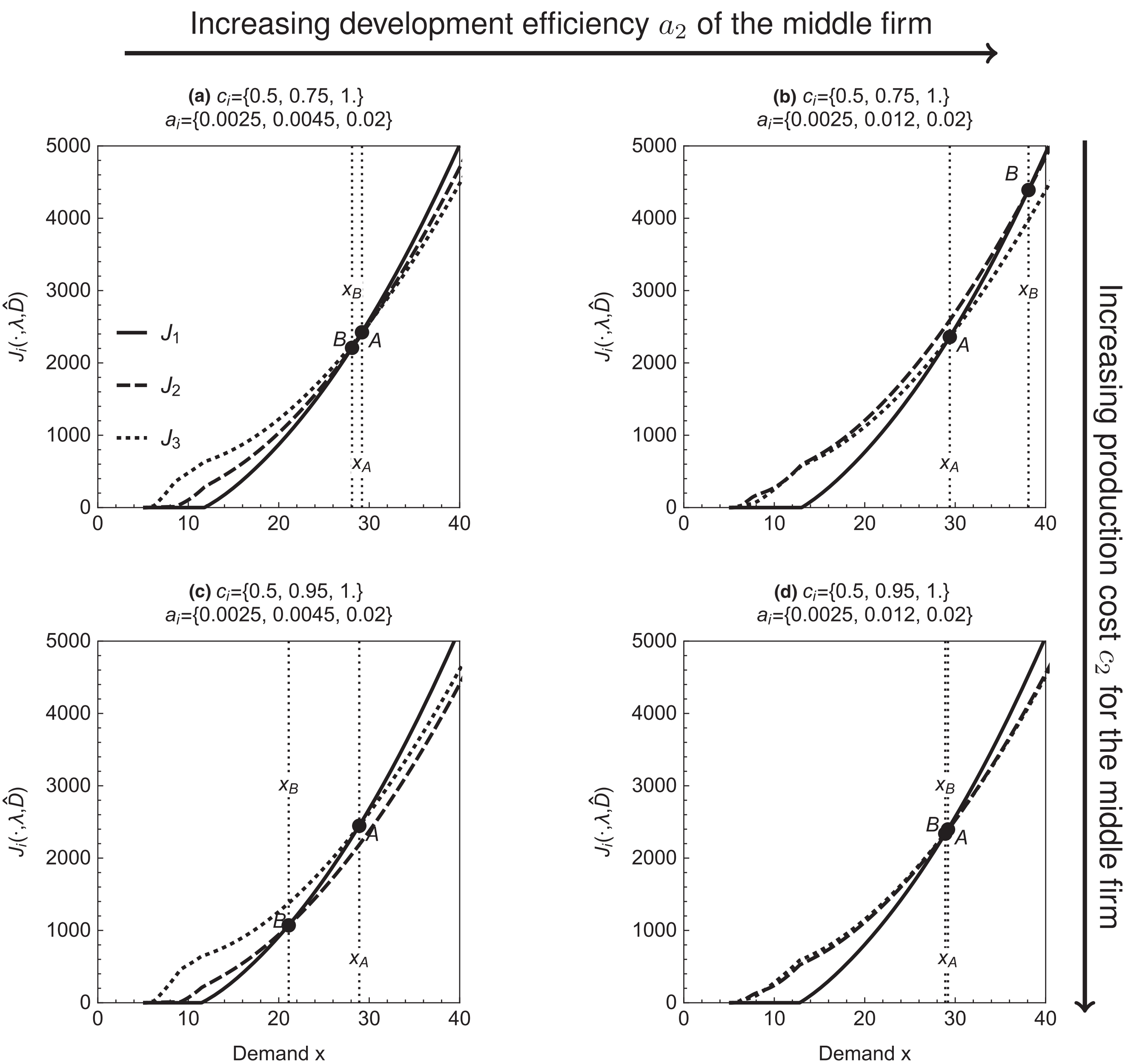


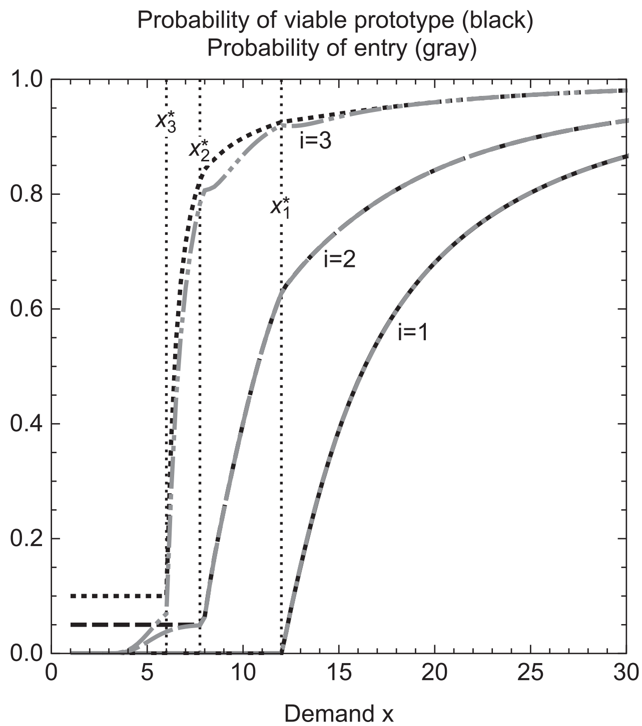
Figure 8 Comparative Statics for Equilibrium Firm Values $x \mapsto J_i(x, \lambda, \hat{D}(x, \lambda))$ with Respect to the Middle Firm's Cost Parameters c_2 and a_2 in a Triopoly. We Assume No Externalities (η = 0)



demand volatility because its market-entry and output expansion options become more valuable. This tension helps explain why the incumbent only starts investing in development activities if the market is more uncertain, but then it exerts a greater development effort, while the innovator backs down (given strategic substitutability). This logic applies to the middle firm as well.

Figure 8 depicts the impact of changes to the middle firm's profile (parameters a_2 and c_2) on equilibrium firm values $x \mapsto J_i(x, \lambda, \hat{D}(x, \lambda))$. The incumbent's value $J_1(x, \lambda, \hat{D}(x, \lambda))$ crosses the innovator's $J_3(x, \lambda, \hat{D}(x, \lambda))$ at point A, while the middle firm's value $J_2(x, \lambda, \hat{D}(x, \lambda))$ crosses the incumbent's $J_1(x, \lambda, \hat{D}(x, \lambda))$ at B. The relative ranking of coordinates x_A and x_B depends on the degree of heterogeneity with respect to a_i and c_i. In panel a, the innovator's value exceeds that of its rivals if the market remains a niche ($x < x_A$), but is lowest as production efficiency gives more edge to the incumbent ($x \geq x_A$). In panel b, where the middle firm becomes more efficient in development, it is worth more than the innovator in the region $(0, x_B)$, which is a subset of $(0, x_A)$. In panel c, where the middle firm's production efficiency c_2 declines, the region $[x_B, x_A)$ where the incumbent

Figure 9 Probabilities of Prototype Development Success $x \mapsto \Lambda(\lambda, \hat{D}_i(x, \lambda))$ and of Market Entry $x \mapsto \mathbb{P}_\Lambda(\tilde{\epsilon}_i(x, s) = 1)$ in a Triopoly. We Assume No Externalities ($\eta = 0$)



(1) is worth more than middle firm 2, widens; in panel d, the disadvantage of one firm relative to the others fades.

6.2.3. Likelihood of Successful Prototype Development and Market Entry. Equilibrium development efforts $\hat{D}_i(x, \lambda)$ influence the prototype success probabilities $\Lambda(\lambda, \hat{D}(x, \lambda))$ via Equation (27) and eventually firms' likelihood of market entry. Given the coordination game resolution in Proposition 3, one can derive predictions about industry structure in the face of technological and market uncertainty. Figure 9 illustrates (for the base case) the probabilities of prototype development success (black line) and of market entry (gray). Because prototype success is a prerequisite for market entry, the gray curves are bounded above by the black curves. For low demand ($x \leq x_2^\star$), the middle firm and the innovator benefit from a headstart in development, yet are not likely to enter given low market prospects. When the middle firm decides to exert an effort (at the right of $x_2^\star$) the innovator (firm 3) is less likely to enter. In Figure 9, the two curves for firms 1 and 2 are hardly distinguishable beyond $x_2^\star$ because these firms only invest in development if their prospects for successful market-entry are tangible, whereas the innovator can afford to be more speculative given its greater capability in development.

7. Conclusion

We derived the value of a firm's shared compound option to develop a prototype, enter the market and produce flexibly alongside several heterogeneous rivals. Our result generalizes the BSM formula allowing for firm-specific development success probabilities, heterogeneous market-entry and production costs and for differential capabilities to develop a technology or exploit economies of scale in production. We then use our model to derive insights on oligopoly firms' equilibrium development efforts.

We solve the coordination problem that arises when two or more firms successfully developed viable prototypes while demand is not yet sufficient to accommodate them all. In configurations involving multiple Nash equilibria in entry decisions, we favor the equilibrium where incumbents with viable prototypes enter at the expense of start-up entrants. We derived the demand thresholds above which rival firms with a viable prototype will enter. We determined an explicit expression generalizing the BSM formula for the value of a firm's shared option to enter the market taking account of firms' probabilities of prototype success and developed an iterative scheme to determine the equilibrium development efforts. We also provided numerical illustrations and comparative statics.

Our analysis has led to several interesting findings. It may be optimal for a firm to enter a niche market and stay put for a while if long-term growth prospects prevail over short-term considerations. In contrast to standard call options, the shared option value in oligopoly is not convex or monotone increasing in the state of demand, but it rather exhibits "competitive waves" due to rival entries. These waves are more pronounced when demand volatility or the time remaining until the window of opportunity closes is small. If initial demand is low, an innovator invests more in development, whereas an incumbent invests more if demand is large. Positive externalities reduce the disadvantage of an incumbent in development, making it more prone to innovate. Negative externalities generally favor a start-up innovator as it can counter the negative impact of the incumbent's development efforts more effectively. A middle firm which excels neither in innovation nor in production may put a greater effort than either rival if demand is in the intermediate region because it can more effectively develop a viable prototype than the incumbent while it can benefit more from demand surges by expanding output at a lower cost than the innovator. Demand volatility, by virtue of enhancing the value of firms' market-entry and production flexibility options, gives a greater incentive for firms to invest in development. As a result, the threshold above which firms exert development efforts is lower and more development activities take place.

Our article contributes to extant literature on disruptive innovation by analyzing the impact of heterogeneous cost profiles on industry equilibria. Our model is quite general and allows to accommodate many rival firms and firm heterogeneity. In our numerical illustrations, we focused primarily on heterogeneity with respect to development effectiveness (a_i) and diseconomies of scale (c_i), but analyzing the effect of differences in head-start (λ_i), entry costs (I_i) and fixed operating expenses (f_i) is also feasible given our model. Our framework has certain limitations, which present opportunities for future research. We have left out explicit considerations of capacity constraints. Treating capacity choices as endogenous (as in Bensoussan and Chevalier-Roignant 2019) would add further complexity but promises to yield additional insights. Future research might also consider firms that precommit to a strategic stance, e.g., to commercialize the prototype (if successful) "no matter what" or to accelerate market entry. Relaxing these might yield further insights on preemptive behavior in oligopoly. The information structure in our setup is also restrictive as it rests on the assumption that parameter values and states are public knowledge. Parameters are also assumed to remain fixed. Certain information (and parameter values) may remain private or evolve, while others may be public knowledge. In a world where the media are keen to report on new technological developments, firms are likely to revise their information set on market characteristics and rival cost profiles. Firms may also have blurred beliefs about certain parameter values and states at earlier stages and update them over time (with potential time delays). Control-theoretic methods relying on filtering theory can help deal with "partially observed systems" (see, e.g, Bensoussan 2004, Bensoussan et al. 2007).

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Notes

[1]The "window of opportunity" for a firm to commercialize a product innovation begins when a dominant product design or category emerges (Christensen et al. 1998, Suarez et al. 2015) and ends once process optimization takes over (Klepper 2002). Our above assumption may seem somewhat extreme (as the start and end of this narrow "window" presumably coincide) but it reasonably captures settings—such as our industry examples—where the "window" is short-lived. Owing to this closing "window of opportunity," the product is homogeneous across firms from time T onwards. VR headsets are already homogeneous products. While the market for the "car of the future" may admit several segments, experts expect convergence of key components (electric drive train, camera system, LIDAR lasers).

[2]The affine-cost case ($c_i = 0$ for all i) is well-known (see, e.g., Kulatilaka and Perotti 1998, Tirole 1988): it yields $\Theta_i(\epsilon) = [b(\sum_j \epsilon_j + 1)^2]^{-1}$.

[3]In Equations (10) and (11) the subscript "A/B" should read "A" or "B:" the choice of A vs. B in $\gamma_{A/B}$ determines whether it should be a "+" or a "−" on the RHS of Equation (10).

[4]One can retrieve the Cournot duopoly results in Kulatilaka and Perotti (1998, p. 1026) by setting $\gamma = 0, 1, 2$ and $r = 0$ in Equation (18), obtaining $\frac{1}{9}\mathbb{E}_x[(x - d)^+]^2 = \frac{1}{9}[x^2 e^{\sigma^2}\mathsf{N}_2^d - 2xd\mathsf{N}_1^d + d^2\mathsf{N}_0^d]$.

[5]We do not claim existence and uniqueness of MNE in general. In our numerical analyses, we did not face issues of nonexistence or nonuniqueness, except for the particular case described in note 7.

[6]The existence of such competitive waves is *somewhat* reminiscent of shared investment option value findings in the duopoly model of Dixit and Pindyck (1994, chapter 9). In both cases, the entry of a rival causes an inflection at a threshold value. The underlying premises are quite different, however. In the American-type option setting of Dixit and Pindyck, the option value of a "first mover" exhibits an inflection at the value of the stochastic variable above which a "second mover" enters. Our model relies on the "window of opportunity," ruling out the first vs. second-mover roles. We focus instead on firm real options as European-type options. The above comparison should thus be interpreted with some caution because comparing American and European options may not be as meaningful.

[7]The existence of a pure-strategy NE is not always assured for negative externalities. We drop parameters x and λ in the notations and provide a formal argument in a duopoly for which firm i's reaction function $\Delta_i(\cdot)$ is increasing on $(0, D^\star_{-i})$ and decreasing on $(D^\star_{-i}, \infty)$. In the first iteration, firm 1 responds to firm 2's effort 0 by making an effort $D_1^1 = \Delta_1(0) \geq 0$. If $D_1^1 \in (0, D_1^\star)$, then $D_2^1 = \Delta_2(D_1^1) \geq \Delta_2(D_1^0) \geq 0$. Now if $D_2^1 \in (0, D_2^\star)$, firm 1 makes an effort $D_1^2 = \Delta_1(D_2^1) \geq \Delta_1(0) = D_1^1$. This mechanism goes on beyond $n = 2$. The sequence of best responses $\{(D_1^n, D_2^n)\}_{n \geq 0}$ is at first increasing. Yet, if there exists an integer $n^\star$ such that $D_2^{n^\star} \geq D_2^\star$, firm 1's reaction function $\Delta_1(\cdot)$ is monotone decreasing (strategic substitutes), leading firm 1 to reduce its development effort $D_1^{n^\star+1} \leq D_1^{n^\star}$. In such a situation the sequence $\{(D_1^n, D_2^n)\}_{n \geq 0}$ might not converge as $n \uparrow \infty$, precluding the existence of a pure-strategy NE.

[8]As noted in endnote 7, in this case there is no pure-strategy Nash equilibrium in the right vicinity of $x_1^\star$.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1. Proofs.