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Time-cost substitutability, earlycutting threat, and innovation timing

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HIGHLIGHTS

- We introduce a time-cost substitutable quality development function.
- With higher experimental intensity, an imitator could earlycut the innovator.
- Earlycutting threat reduces new product's quality but advances its launching date.
- Mild earlycutting threat might be socially preferable.

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ABSTRACT

With time-cost substitutability, a potential imitator could threat to "earlycut" the innovator by increasing experimental intensity. The earlycutting threat or uncertainty about the potential imitator's experimental cost advantage usually drives down the new product's quality but advances its launching date.

1. Introduction

Higher quality is usually presumed to be associated with longer time to market, and the tradeoff between early entry with low quality and late entry but with high quality pervades the conventional quality development literature. For example, the entry time is assumed to be proportional to quality (e.g., Dijk, 1996; Dutta et al., 1995; Hoppe and Lehmann-Grube, 2001, 2005; Smirnov and Wait, 2015, example 2). Note that, given the rival's strategy, by increasing the experimental intensity earlier entry with equal or even higher quality is possible. We focus on the first mover's (i.e., the researcher's) innovation timing problem with a potential imitator threating to "earlycut": earlier entry with equal quality.[1] In another word, the researcher's quality development plan is quality-specific, and the imitator could preempt the researcher but only with the quality determined by the researcher. This paper presumes a time-cost substitutable quality development function, and models the first mover's quality-timing decision with complete and incomplete information on the potential imitator's experimental cost advantage respectively. Contribution of our work mainly lies in the combination of the time-cost substitutable quality development function and the earlycutting threat.

2. A time-cost substitutable quality development function

Suppose the researcher plans to develop an advanced product with quality v (with normalized zero production cost). Following the traditional assumption on consumer utility in vertical differentiation literature (see e.g., Chong and Shin, 1992, p. 229), individual consumer's utility is standardly assumed as $u = \theta v - p$ (if

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[1] Earlier entry (i.e., preempting the first mover) with lower or higher quality is also possible. Here we assume an imitator is just an imitator, lack of the extra creativity for quality adding or cutting while imitating. An extension with the imitator owning some creativity might be meaningful.

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buying with price p), or zero (if not buying); where θ, the quality preference parameter, distributes uniformly within [0, 1] as in Boccard and Wauthy (2010, p. 289) or Smirnov and Wait (2015, p. 29). Hence, the quality v could be also read as the highest consumer valuation of the product (i.e., $\max(\theta v) = v$) or the highest price accepted by the market (i.e., zero demand at $p = v$). Technological advance usually is the fruit of experimental trials (Jones, 2005; Lambson and Phillips, 2007). Assume there is a quadric relationship between the required accumulative experimental time and the technological advance (i.e., the new product's quality): $T = \alpha v^2, \alpha > 0$. Regarding T as a time cost, the assumption is in the line with the "commonly used" quadric quality development cost function (Dey et al., 2014, p. 597). Inspired by Lambson and Phillips (2007, p. 50), the research plan executor could decide the number, say n, of experimental trials to be carried out "simultaneously", i.e., the experimental intensity. Approximately, the new product's time to market is $t = \frac{T}{n}$. Assume there is a linear relationship between the experimental cost C and the experimental intensity: $C = \beta n, \beta > 0$. It is mainly because the experimental equipment, space, and other one-shot specific inputs are usually proportional to the experimental intensity. Assume other quality development costs are negligible. As $C = \beta \frac{T}{t} = \frac{\alpha\beta v^2}{t} = \frac{rv^2}{t}$, with $r = \alpha\beta$ as the composite cost parameter, we have a time-cost substitutable quality development function in a Cobb–Douglas production function form as $v = r^{-0.5}C^{0.5}t^{0.5}$; see some possible micro-foundations, especially from the research effort perspective, for the Cobb–Douglas production function in Jones (2005). In conventional vertical differentiation or quality-timing literature, the quality development cost is usually complementary to rather than substitutable to the entry time (e.g., Hoppe and Lehmann-Grube, 2001, 2005), or is commonly predetermined unilaterally by the irreversible quality choice such as the quadric/convex cost-quality relationship exogenously given (e.g., Auer and Sauré, 2017; Brécard, 2010; Dey et al., 2014; Lambertini and Tampieri, 2012; Lambertini and Tedeschi, 2007; Motta, 1993). The time-cost substitutability and the availability of experimental intensity choice release the timing decision from the quality choice, making the quality-timing decision two-dimensional.

3. The model

Suppose some new demand arises at date 0, and the demand period will last 1 time unit. One unit of consumption need emerges uniformly within the demand period, and individual consumers are characterized with unit demand and perfect impatience (i.e., no deferred consumption). Once the researcher decides the new product's quality v (i.e., the specific research plan for a v-quality-level technology) and the new product's time to market t_r at date 0, his quality development cost $\frac{rv^2}{t_r}$, together with his entry decision, is irreversible. On observing the research plan, a potential imitator/earlycutter could imitate it with the same or smaller composite cost parameter, λr, $0 < \lambda \leq 1$ (λ: experimental cost advantage parameter), and decide her earlycutting time t_e, thereby bearing a quality development cost $\frac{\lambda r v^2}{t_e}$. Discount rate is negligible. As demand per unit of time equals to $1 - \frac{p}{v}$, the monopolist would price at $p = \frac{v}{2}$ to maximize the revenue flow $p\left(1 - \frac{p}{v}\right)$ in the monopolistic phase. Individual consumer with $\theta \geq \frac{p}{v} = \frac{1}{2}$ buys; and the monopolist's revenue flow is $\frac{v}{4}$, alike the result such as in Hoppe and Lehmann-Grube (2001, p. 423).

Given the researcher's quality-timing strategy, $\{v, t_r\}$, the potential imitator's payoff is:

$$\pi_e(t_e; v, t_r) = \begin{cases} \frac{v}{4}(t_r - t_e) - \frac{\lambda r v^2}{t_e}, & \text{if earlycutting} \\ 0, & \text{not earlycutting.} \end{cases} \quad (1)$$

During period $[t_r, 1]$, if earlycutting, both firms' revenues are zero due to the Bertrand-like price competition with homogeneous qualities (see e.g., Boccard and Wauthy, 2010, Lemma 1). Solving the first order condition (FOC) of Eq. (1), we have

$$\pi_e^* = \begin{cases} \frac{v}{4}\left(t_r - 4\sqrt{\lambda r v}\right), & t_e^* = 2\sqrt{\lambda r v} \\ 0, & \text{not earlycutting.} \end{cases} \quad (2)$$

So if and only if $t_r > 4\sqrt{\lambda r v}$, the researcher will be earlycut by the imitator (assuming no earlycutting if $\pi_e^* = 0$). Hence, the researcher's payoff is:

$$\pi_r(v, t_r) = \begin{cases} \frac{v}{4}(1 - t_r) - \frac{rv^2}{t_r}, & t_r \leq 4\sqrt{\lambda r v} \\ -\frac{rv^2}{t_r}, & t_r > 4\sqrt{\lambda r v}, \quad \text{being earlycut.} \end{cases} \quad (3)$$

As $t_r = 2\sqrt{rv}$ maximizes $\frac{v}{4}(1 - t_r) - \frac{rv^2}{t_r}$(given v), the researcher's monopolistic payoff is:

$$\pi_r = \begin{cases} \frac{v}{4}\left(1 - 4\sqrt{rv}\right), & \frac{1}{4} \leq \lambda, \quad t_r(v) = 2\sqrt{rv} \\ \frac{v}{4}\left(1 - 4\sqrt{\lambda r v}\right) - \frac{rv^2}{4\sqrt{\lambda r v}}, & \lambda < \frac{1}{4}, \\ \quad t_r(v) = 4\sqrt{\lambda r v}. \end{cases} \quad (4)$$

Solving the FOC of Eq. (4), we have:

$$\{v*, t_r^*, \pi_r^*\} = \begin{cases} \left\{\frac{1}{36r}, \frac{1}{3}, \frac{1}{432r}\right\}, & \frac{1}{4} \leq \lambda \text{ (no threat)} \\ \left\{\frac{16\lambda}{36r(4\lambda+1)^2}, \frac{8\lambda}{3(4\lambda+1)}, \frac{16\lambda}{432r(4\lambda+1)^2}\right\}, \\ \lambda < \frac{1}{4}. \end{cases} \quad (5)$$

Hence, we have Proposition 1:

Proposition 1. *If $\frac{1}{4} \leq \lambda$, the researcher always launches the new product at date $t_r = \frac{1}{3}$. If $\lambda < \frac{1}{4}$, the researcher plays the earlycutting deterring strategy, and increasing earlycutting threat drives down the new product's quality but advances its launching date.*

Along with increasing earlycutting threat, though enjoying lower-quality product, more consumers get benefited from the earlier entry. Denote the consumer surplus as S_c, then:

$$S_c = \left(1 - t_r^*\right)\int_{\frac{1}{2}}^{1}\left(\theta v * - \frac{v*}{2}\right)d\theta = \left(1 - t_r^*\right)\frac{v*}{8}. \quad (6)$$

S_c is continuous in λ and constant for $\lambda \geq \frac{1}{4}$. While $\lambda < \frac{1}{4}$, we have the consumer surplus under λ-earlycutting threat:

$$S_c^\lambda = \frac{\lambda(4\lambda+3)}{54r(4\lambda+1)^3}, \quad 0 < \lambda < \frac{1}{4}. \quad (7)$$

Solving the FOC of Eq. (7), we have $\lambda_c^* = \frac{-2+\sqrt{7}}{4} \approx 0.1614$, that maximizes S_c^λ, and S_c^λ strictly increases for $\lambda \in \left(0, \lambda_c^*\right]$ but strictly decreases for $\lambda \in \left[\lambda_c^*, \frac{1}{4}\right)$. So λ_c^* also maximizes S_c. Denote the social surplus as S_s, continuous in λ and constant for $\lambda \geq \frac{1}{4}$. Then, similarly:

$$S_s^\lambda = S_c^\lambda + \pi_r^* = \frac{\lambda(12\lambda+5)}{54r(4\lambda+1)^3}, \quad 0 < \lambda < \frac{1}{4}. \quad (8)$$

Solving the FOC of Eq. (8), we have $\lambda_s^* = \frac{\sqrt{19}-2}{12} \approx 0.1966$, that maximizes S_s^λ as well as S_s, and S_s^λ strictly increases for $\lambda \in (0, \lambda_s^*]$ but strictly decreases for $\lambda \in [\lambda_s^*, \frac{1}{4})$. Hence, we have Proposition 2:

Proposition 2. *A moderate earlycutting threat (i.e., $\lambda = \lambda_c^*$) benefits consumers most, while a milder earlycutting threat (i.e., $\lambda = \lambda_s^* > \lambda_c^*$) is socially optimal.*

4. Quality-timing under uncertainty

As a mild earlycutting threat is socially optimal since it significantly shortens the new product's time to market and meanwhile does not lower the new product's quality too much, the researcher should not expect a rational policymaker to enforce a perfect intellectual property protection system that eliminates all the earlycutting threat. What is more, the researcher's mistake might be also socially preferable. If the researcher misjudges $\lambda < \frac{1}{4}$ to be $\lambda \geq \frac{1}{4}$, the social surplus turns out to be:

$$\underbrace{\frac{1}{144r}\left(\frac{1}{3}-\frac{\sqrt{\lambda}}{3}\right)}_{\text{earlycutter's revenue}} + \underbrace{\frac{1}{288r}\left(\frac{1}{3}-\frac{\sqrt{\lambda}}{3}\right) + \frac{1}{72r}\left(1-\frac{1}{3}\right)}_{\text{consumer surplus}} - \underbrace{\left(\frac{\sqrt{\lambda}}{432r}+\frac{1}{432r}\right)}_{\text{quality development cost}} = \frac{9-5\sqrt{\lambda}}{864r}, \quad \lambda < \frac{1}{4}, \tag{9}$$

which is much greater than the maximum of S_s^λ ($S_s^{\lambda*} \approx 0.0047\frac{1}{r}$). Obviously, the potential imitator has incentive to hide her true experimental cost advantage parameter, λ. Hence, in the real world, the researcher should make quality-timing decision with incomplete information on λ.

Suppose λ uniformly distributes between 0 and 1. The probability of being earlycut is:

$$p_e(v, t_r) = \begin{cases} \dfrac{t_r^2}{16rv}, & \dfrac{t_r^2}{16rv} \leq 1 \\ 1, & 1 < \dfrac{t_r^2}{16rv}. \end{cases} \tag{10}$$

If $1 < \frac{t_r^2}{16rv}$, the researcher is surely to be earlycut by the imitator since $\pi_e^* > 0$. Otherwise, increasing the quality or shortening the entry time could lower the probability of being earlycut. In consideration of the uncertainty, the researcher's expected payoff is:

$$E\pi_r = \begin{cases} \dfrac{v}{4}(1-t_r)\left(1-\dfrac{t_r^2}{16rv}\right) - \dfrac{rv^2}{t_r}, & \dfrac{t_r^2}{16rv} \leq 1 \\ -\dfrac{rv^2}{t_r}, & 1 < \dfrac{t_r^2}{16rv}. \end{cases} \tag{11}$$

If failing to perceive or ignoring the potential earlycutting threat, the researcher would choose his quality-timing strategy as $\left\{\frac{1}{36r}, \frac{1}{3}\right\}$, and the probability of being earlycut turns out to be as significant as $\left(\frac{1}{3}\right)^2 / \left(\frac{16r}{36r}\right) = 0.25 = \Pr\left(\lambda < \frac{1}{4}\right)$, resulting in an expected payoff $E\pi_r^{ignoring} = \frac{1}{864r}$.

As $\frac{\partial E\pi_r}{\partial v} = \begin{cases} \dfrac{t_r(1-t_r)-8rv}{4t_r} \leq \dfrac{1}{4}\left(1-\dfrac{3}{2}t_r\right), & t_r^2 \leq 16rv \\ -\dfrac{2rv}{t_r} < 0, & 16rv < t_r^2 \end{cases}$, so if $\frac{2}{3} < t_r$, increasing quality to lower the probability of being earlycut just incurs more loss since $\frac{t_r(1-t_r)-8rv}{4t_r} < 0$. Hence, we have:

$$v(t_r) = \begin{cases} \dfrac{t_r(1-t_r)}{8r}, & t_r \leq \dfrac{2}{3} \\ 0, & \dfrac{2}{3} < t_r \leq 1. \end{cases} \tag{12}$$

Substituting Eq. (12) into Eq. (11), then:

$$E\pi_r = \begin{cases} \dfrac{t_r(1-2t_r)(1-t_r)}{64r}, & t_r \leq \dfrac{2}{3} \\ 0, & \dfrac{2}{3} < t_r \leq 1. \end{cases} \tag{13}$$

Solving the FOC of Eq. (13), we have the optimal timing under uncertainty $t_r^{**} = \frac{1}{2} - \frac{\sqrt{3}}{6} \approx 0.2113$, that maximizes the researcher's expected payoff. Correspondingly, the researcher chooses the optimal quality $v^{**} = \frac{t_r^{**}(1-t_r^{**})}{8r} = \frac{1}{48r}$ and has an expected payoff $\pi_r^{**} = \frac{\sqrt{3}}{1152r}$, greater than $E\pi_r^{ignoring}$. Interestingly, $\pi_r^{**} - E\pi_r^{ignoring}$ could be vividly read as the cost of ignorance. The expected probability of being earlycut is $p_e = \frac{t_r^{**}}{2(1-t_r^{**})} \approx 0.1340$, much smaller than $\Pr\left(\lambda < \frac{1}{4}\right) = 0.25$. Hence, we have Proposition 3:

Proposition 3. *Misjudging or ignoring the earlycutting threat might be costly to the researcher but be socially preferable. Suppose λ uniformly distributes between 0 and 1, compared with no earlycutting threat, the researcher lowers the new product's quality and advances its launching date, leaving minor chance for the potential imitator.*

5. Conclusion

With time-cost substitutability, by increasing experimental intensity an imitator could threat to earlycut the first mover. If the imitator owns enough experimental cost advantage over the first mover, the first mover has to play the earlycutting deterring strategy, and increasing experimental cost advantage drives down the new product's quality but advances its launching date. A moderate earlycutting threat usually benefits consumers most, and a milder earlycutting threat is socially optimal. Misjudging or ignoring the earlycutting threat might be costly to the researcher but be also socially preferable. With incomplete information on the potential imitator's experimental cost advantage, the first mover would also sacrifice the new product's quality and shorten its time to market in order to lower the probability of being earlycut. Though very simple and considering just one potential imitator, our work might inspire more research on quality-timing with time-cost substitutability and earlycutting threat.

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