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ORIGINAL RESEARCH

Investment with network externality under uncertainty

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Abstract The purpose of this paper is to develop a real option model with a stochastic network size to simultaneously consider firm's investment and household's consumption behaviors in an equilibrium framework. First, the consumer's waiting-to-buy effect is crucial in determining trigger network size of firm's investment. Second, increasing network externality has an ambiguous effect on trigger network size of firm's investment. Third, using NPV rule not only underestimates trigger network size but, also possibly results in the misleading relationship between network externality and trigger network size.

Keywords Real Option Investment · Network Externality · Consumer's Waiting-to-Buy Effect

JEL Classification G12 · O31 · O34

1 Introduction

Network externality has been defined as a change in the benefit, or surplus, that an agent derives from a good when the number of other agents consuming the same kind of good changes. This means that utility function is associated with the number of other households

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which have bought the product. Shy (1996) and Economides (1996) set up utility function by adding network size into the model to explicitly investigate a network-externality product. However, many studies take the network size as an exogenous variable. For example, Bulow (1986), and Waldman (1993) spilt the time span into two periods and assume that the network size in the first period is equivalent to the newborn populations in the second period, and no any death happens in these two periods. Katz and Shapiro (1985) assume that consumer has perfect foresight about the network size. However, in reality, the network size is not necessary to be time-invariant. Thus, to fit the real world closer, a model with random network size to deal with firm's and consumer's dynamic decisions is proposed.

Using the real option approach to analyze a firm's investment decision is now standard in economics and finance (Mcdonald and Siegel 1985; Dixit and Pindyck 1994; Hasett and Metcalf 1999; Grenadier and Weiss 1997, 2005; Lambrecht and Perraudin 2003; Duan, Lin and Lee 2003; Tsai 2005). However, there are two crucial issues which have not been discussed. One is the character of industry. For example, some industries might be associated with network-externality.[1] The other is the fact that consumers probably wait to buy.

There are three reasons for why a household's consumption decision of the product with network externality can be modeled by the real option approach.[2] First, after a consumer buying the product there is no refunding without any discount, i.e., irreversibility. Second, the utilities (payoff) gained by a consumer is random due to the stochastic network size. Third, a consumer has the right to choose the optimal time to buy the product, i.e., she can wait.[3]

This paper contributes to the literature by developing a real option model with a stochastic network size to incorporate investment decisions of the firm and consumption decisions of the household simultaneously under an equilibrium framework. We show that the trigger network size of firm's investment is determined by: (1) the supply-side effect of the firm's waiting-to-invest decision, (2) the demand-side effect of the consumer's waiting-to-buy decision, and (3) convex effect due to convexity of the profit function with respect to the network size. The consumer's waiting-to-buy effect also significantly affects the trigger network size especially when the volatility is high. In addition, the relationship between the network externality and the trigger network size is ambiguous, and volatility plays an important role in determining the relationship. Moreover, using NPV rule not only underestimates trigger network size but also possibly results in the misleading relationship between network externality and trigger network size.

2 Uncertain network size of investment with entries and exits

We first introduce a dynamic model describing an uncertain network size with entries and exits. At any time t, the growth rate of entries and exits are affected by l and m types of independently random disturbances. Thus, within a specified time period, the incremental number of entries and exists are:

[1] Lee et al. (2009) investigate the valuation of information technology investments by real options analysis. However, the feature of network-externality is not incorporated.

[2] In the following sections, we refer to *the product* as the one with network externality.

[3] Many studies applying real option method to analyze the network-externality issues do not take consumer's waiting-to-buy decision into account (Benaroch and Kauffman 1999; Balasubramanian et al. 2000; Courchane et al. 2002; Hori and Mizuno 2006).

$$dN_1 = \mu_1 N dt + \sum_{i=1}^{l} \upsilon_{1i} N, \tag{1}$$

$$dN_2 = \mu_2 N dt + \sum_{j=1}^{m} \upsilon_{2j} N, \tag{2}$$

where N_1 and N_2 are the number of entries and exists, μ_1 and μ_2 are the average growth rate of entries and exists, $\mu_1 \geq 0$ and, $\mu_2 \geq 0$. N is the network size, and υ_{1i}, υ_{2j} are mutually independent random variables with zero mean and variance σ_{2i}^2 and σ_{2j}^2 such that $dN_1 \geq 0$ and $dN_2 \geq 0$. $\mu_1 dt$ ($\mu_2 dt$) can be interpreted as the average probability that a person enters (exits) within dt.

The change in current network size is the difference between the incremental number of entries and exits:

$$dN = \mu N dt + \left[\sum_{i=1}^{l} \upsilon_{1i} - \sum_{j=1}^{m} \upsilon_{2j} \right] N, \tag{3}$$

where $N = (N_1 - N_2)$, $\mu = (\mu_1 - \mu_2)$, and μ is the average growth rate of the network size. If l and m are very large then, according to the central limit theorem, it is assumed that:

$$\sum_{i=1}^{l} \upsilon_{1i} - \sum_{j=1}^{m} \upsilon_{2j} = \sigma dz, \tag{4}$$

where σ is the volatility of the network size and dz is the increment of a standard Wiener process. Therefore, from (3) and (4) we have:.[4]

$$dN = \mu N dt + \sigma N dz. \tag{5}$$

3 Decisions of consumer and monopolist

3.1 Consumer's buying decision

Suppose that the risk neutral consumers are homogeneous. The product cannot be resold and the deprecation of the product is assumed to be zero for simplicity. The value of the product for a consumer is $\alpha dt + \theta(N - 1)dt$, where θ denotes the network externality and $0 < \theta \leq \alpha$. Therefore, the expected present value of consuming the product which is discounted by the risk-free rate r is:

$$\begin{aligned} & E\left[\int_0^\infty \mu_2 e^{-\mu_2 T} \int_0^T (\alpha - \theta) e^{-rt} dt dT + \int_0^\infty \mu_2 e^{-\mu_2 T} \int_0^T \theta N(t) e^{-rt} dt dT \right] \\ & = \frac{\theta N}{(r + \mu_2 - \mu)} + \frac{(\alpha - \theta)}{(r + \mu_2)} \\ & = \left[\frac{(\alpha - \theta)}{(r + \mu_2)} + \frac{\theta}{(r + \mu_2 - \mu)} \right] + \frac{\theta}{(r + \mu_2 - \mu)} (N - 1). \end{aligned} \tag{6}$$

[4] For simplicity and analytical tractability, the jump model, such as the model proposed by Wu (2003), is not considered in this paper.

For the convenience of analyzing the issues in this paper, we rewrite (6) as $a + \gamma(N - 1)$, where

$$a = \frac{(\alpha - \theta)}{(r + \mu_2)} + \frac{\theta}{(r + \mu_2 - \mu)}, \tag{7}$$

$$\gamma = \frac{\theta}{(r + \mu_2 - \mu)}. \tag{8}$$

Given the monopoly price P, the consumer will wait to buy until the network size reaches a certain level of critical network size ($N^*_{C\gamma}$). The value of purchasing the product is $f(N)$:

$$f(N) = \begin{cases} K(N) & \text{if } N \leq N^*_{C\gamma} \\ a + \gamma(N - 1) - P & \text{if } N > N^*_{C\gamma}, \end{cases} \tag{9}$$

where $K(N)$ is the waiting value of the representative consumer. The Bellman equation is:

$$rKdt = E(dK). \tag{10}$$

We now expand dK using Ito's Lemma considering the possibility of exiting,

$$E(dK) = \mu N K'(N)dt + \frac{1}{2}\sigma^2 N^2 K''(N)dt - \mu_2 K(N)dt. \tag{11}$$

Therefore, $K(N)$ follows the following differential equation derived according to dynamic programming,

$$\frac{1}{2}\sigma^2 N^2 K''(N) + \mu N K'(N) - (r + \mu_2) K(N) = 0. \tag{12}$$

The value of $K(N)$ has the functional form of AN^{β}, where A is a constant to be determined and

$$\beta = -\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right) + \sqrt{\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2(r + \mu_2)}{\sigma^2}}. \tag{13}$$

Proposition 1 *Let $N^*_{C\gamma}$ denote the critical network size at which it is optimal for the homogeneous consumer to buy the product given the monopoly price P. Then the critical network size $N^*_{C\gamma}$ can be expressed as*:

$$N^*_{C\gamma} = \left(\frac{\beta}{\beta - 1}\right)\left(\frac{P - a + \gamma}{\gamma}\right). \tag{14}$$

Proof According to the well-known continuity and smooth pasting conditions,

$$K(N^*_{C\gamma}) = a + \gamma\left(N^*_{C\gamma} - 1\right) - P, \tag{15}$$

$$K'(N^*_{C\gamma}) = \gamma. \tag{16}$$

We can derive the critical network size at which it is optimal for the consumer to buy the product given the monopoly price P as follows:

$$N^*_{C\gamma} = \left(\frac{\beta}{\beta - 1}\right)\left(\frac{P - a + \gamma}{\gamma}\right). \tag{17}$$

The expected individual consumer surplus is $a + \gamma(N^*_{C\gamma} - 1) - P$ which is equal to $\frac{1}{\beta-1}(P - a + \gamma)$. According to the continuity condition, the expected individual consumer surplus is just equal to the waiting value of the optimal buying decision and it is not equal to zero since the network size is uncertain.

In other words, given the monopoly price P, the consumer will wait to buy the product until the network size reaches $N^*_{C\gamma}$. To induce the consumer to buy, monopolist cannot set up a price to exploit the entire consumer surplus. In fact, the expected consumer surplus is just equal to the waiting value of the optimal buying decision. Also, (17) tells that $N^*_{C\gamma}$ is an increasing function of P, suggesting that the higher price will reduce the net value of buying the product and therefore delay consumer's buying decision. In the next section, we analyze the investment decision of monopolist based on the buying decision of consumer analyzed above and investigate the relationship between the network externality versus the trigger network size of investment.

3.2 Firm's investment decision

Suppose that the firm is a risk neutral monopolist and it invests with a sunk cost I. For simplicity, the variable cost is assumed to be zero. After rearranging (14), we have $P = a - \gamma + \frac{\gamma N(\beta-1)}{\beta}$. The instant profit $R(N)$ at time t is:

$$R(N) = PN = (a-\gamma)N + \gamma\left(\frac{\beta-1}{\beta}\right)N^2. \tag{18}$$

To ensure the convergence of the expected present value of the future profit, it is assumed that $\sigma^2 + 2\mu - \mu_2 - r < 0$.[5] The expected present value of the future profit $H(N)$ is:

$$\begin{aligned} H(N) &= E\int_0^\infty \mu_2 e^{-\mu_2 T}\int_0^T Pe^{-rt}dN_1(t)dT \\ &= -(a-\gamma)\left(\frac{\mu_1}{\mu-\mu_2-r}\right)N - \gamma\left(\frac{\beta-1}{\beta}\right)\left(\frac{\mu_1}{2\mu-\mu_2+\sigma^2-r}\right)N^2. \end{aligned} \tag{19}$$

Therefore, the total expected present value of the profit $G(N)$ is

$$\begin{aligned} G(N) &= R(N) + H(N) \\ &= -(a-\gamma)\left(\frac{2\mu_2+r}{\mu-\mu_2-r}\right)N + \gamma\left(\frac{\beta-1}{\beta}\right)\left(\frac{2\mu-\mu_1-\mu_2+\sigma^2-r}{2\mu-\mu_2+\sigma^2-r}\right)N^2. \end{aligned} \tag{20}$$

Proposition 2 *Let N^*_γ denote the trigger network size at which it is optimal for monopolist to invest given the buying decisions of consumer. Then the trigger network size of investment N^*_γ can be expressed as*:

$$N^*_\gamma = -\frac{D}{2C} + \sqrt{\left(\frac{D}{2C}\right)^2 - \left(\frac{E}{C}\right)} \tag{21}$$

where

[5] Because the discount rate is equal to the risk free rate r plus the hazard rate μ_2 and according to Ito's lemma, $dN^2 = 2NdN + (dN)^2 = (2\mu + \sigma^2)N^2dt + 2\sigma N^2dz$, the assumption $\sigma^2 + 2\mu - \mu_2 - r < 0$ can ensure the convergence of the expected present value of the future profit $H(N)$.

$$C = \gamma \left(\frac{\beta - 1}{\beta}\right)\left(\frac{\beta - 2}{\beta}\right)\left(\frac{2\mu - \mu_1 - \mu_2 + \sigma^2 - r}{2\,\mu - \mu_2 + \sigma^2 - r}\right) > 0, \tag{22}$$

$$D = -(a - \gamma)\left(\frac{\beta - 1}{\beta}\right)\left(\frac{2\mu_2 + r}{\mu - \mu_2 - r}\right) > 0, \tag{23}$$

and[6]

$$E = -I < 0. \tag{24}$$

Proof Similar to the analysis in Sect. 3.1, using the continuity and smooth pasting conditions, the trigger network size of investment N_γ^* should satisfy the following equation:

$$V_\gamma(N) = C\,N^2 + D\,N + E = 0. \tag{25}$$

Therefore, the trigger network size of investment $N_\gamma^* > 0$ for monopolist is:

$$N_\gamma^* = -\frac{D}{2\,C} + \sqrt{\left(\frac{D}{2\,C}\right)^2 - \left(\frac{E}{C}\right)}. \tag{26}$$

4 The determinants of firm's investment

First, for the sake of simplicity, we assume that $\gamma = a$, i.e., $\theta = \alpha$, to show how important the consumer's waiting-to-buy effect is towards determining the trigger network size. According to (20), the total expected present value of the profit $G(N)$ is:

$$G(N) = a\left(\frac{\beta - 1}{\beta}\right)\left(\frac{2\mu - \mu_1 - \mu_2 + \sigma^2 - r}{2\,\mu - \mu_2 + \sigma^2 - r}\right)N^2. \tag{27}$$

$G(N)$ is a function of volatility and it can be broken down into two effects. The term $\frac{2\mu - \mu_1 - \mu_2 + \sigma^2 - r}{2\,\mu - \mu_2 + \sigma^2 - r}$ in (27) is *the convex effect* due to convexity of the profit function with respect to the network size. Convex effect has a negative impact on the trigger network size. Second, decreasing in the term $\frac{\beta - 1}{\beta}$ of (27) represents increasing *the consumer's waiting-to-buy effect* which leads to an increase in trigger network size. As a result, increasing volatility raises firm's waiting-to-invest effect, convex effect, and consumer's waiting-to-buy effect.[7]

In Table 1, we show the importance of consumer's waiting-to-buy effect in determining the trigger network size and compare the results of the cases with/without considering consumer's waiting-to-buy effect.[8] It is found that the difference ratio, which is measured by the difference in trigger network sizes between these two cases and scaledby the trigger network size with consumer's waiting-to-buy effect, can be as large as 26% when the

[6] By the assumption $\sigma^2 + 2\mu - \mu_2 - r < 0$, it is straightforward to find $C > 0$. On the other hand, if $\mu < 0$, $\mu - \mu_2 - r < 0$. If $\mu \geq 0$, $\mu - \mu_2 - r < 0$ since $\mu - \mu_2 - r < -(\sigma^2 + \mu) < 0$ by the assumption $\sigma^2 + 2\mu - \mu_2 - r < 0$. Therefore, $D > 0$.

[7] It is straightforward to show that $\frac{\partial}{\partial \sigma^2}\left(\frac{2\mu - \mu_1 - \mu_2 + \sigma^2 - r}{2\mu - \mu_2 + \sigma^2 - r}\right) = \frac{\mu_1}{(2\mu - \mu_2 + \sigma^2 - r)^2} > 0$ and $\frac{\partial}{\partial \sigma^2}\left(\frac{\beta - 1}{\beta}\right) = \frac{1}{\beta^2}\frac{\partial \beta}{\partial \sigma^2} < 0$.

[8] For the case without consumer's waiting effect, $G(N) = a\left(\frac{2\mu - \mu_1 - \mu_2 + \sigma^2 - r}{2\,\mu - \mu_2 + \sigma^2 - r}\right)N^2$.

Table 1 The relationship between trigger network size and volatility

Volatility	Trigger network size WITHOUT consumer's waiting-to-buy effect	Trigger network size WITH consumer's waiting-to-buy effect	Difference ratio
0.04	9,529	9,896	0.04
0.08	10,341	11,153	0.07
0.16	12,427	14,447	0.14
0.20	13,828	16,686	0.17
0.28	18,089	23,498	0.23
0.32	21,780	29,339	0.26

Parameters are $a = 10$, $\mu_1 = \mu_2 = 0.04$, $r = 0.1$, and $I = 1{,}000{,}000$. The difference ratio is measured by the difference of the trigger values between these two cases divided by the trigger value of the case with consumer's waiting-to-buy effect

volatility is equal to 32%.[9] Namely, if consumer's waiting-to-buy effect is ignored, the trigger network size will be underestimated by 26%. Therefore, it is obvious that the consumer's waiting-to-buy effect is not negligible in determining the trigger network size especially when the volatility is high.

On the other hand, since the trigger network size N_γ^* satisfies (25), we have:

$$\frac{\partial N_\gamma^*}{\partial \theta} = \frac{-\left(\frac{\partial C}{\partial \theta} N_\gamma^{*2} + \frac{\partial D}{\partial \theta} N_\gamma^*\right)}{(D + 2N_\gamma^* C)}. \tag{28}$$

Note that, because $\partial C/\partial\theta > 0$ and $\partial D/\partial\theta < 0$ by (8), (22), and (23), the sign of $\partial N_\gamma^* / \partial\theta$ is undetermined. That is, the relationship between the network externality and the trigger network size of firm's investment is ambiguous. The following two cases are used to show the ambiguous relationship.

Suppose that the average growth rates μ, μ_1, and μ_2 are assumed to approach to zero. In the first case, if volatility approaches to risk-free rate ($\sigma^2 \to r$), this implies $\beta \to 2$. According to (21), (22), (23), and (24), the trigger network size (N_γ^*) will converge to $2I/(a{-}\gamma)$. By (7), the increase in the network externality (θ) will decrease (a - γ) and therefore raise N_γ^*. As a result, the positive relationship between the network externality and the firm's trigger network size of investment is shown.

In a contrasting second case, we assume that when volatility (σ^2) approaches to zero, the network externality (θ) converges to α, and $\mu \leq 0$, thus β will approach infinity. Furthermore, according to (21), (22), (23), and (24), $N_\gamma^* \to \sqrt{I/\gamma}$. By (8), the increase in the network externality (θ) will lead to an increase in γ and therefore lowers N_γ^*. Thus, the negative relationship between the network externality and the firm's trigger network size of investment is obtained. Figure 1 gives examples to show these two different results.

The reason that the relation between the network externality and the trigger network size of firm's investment is ambiguous is that the increasing network externality will increase both the firm's waiting-to-invest value and value of investment. When the volatility is high, the former effect is more likely to dominate the latter. Therefore, increasing network externality leads to an increase in the trigger network size of investment. On the other hand, when the volatility is low, the later effect is more possible to dominate the

9 As the volatility is approaching to $\sqrt{r - 2\mu + \mu_2}$, i.e., $\beta \to 2$. Under this situation, $G(N)$ of the case without consumer's waiting effect is almost twice as large as that of the case with consumer's waiting effect. Moreover, under this situation, the difference ratio is the largest.

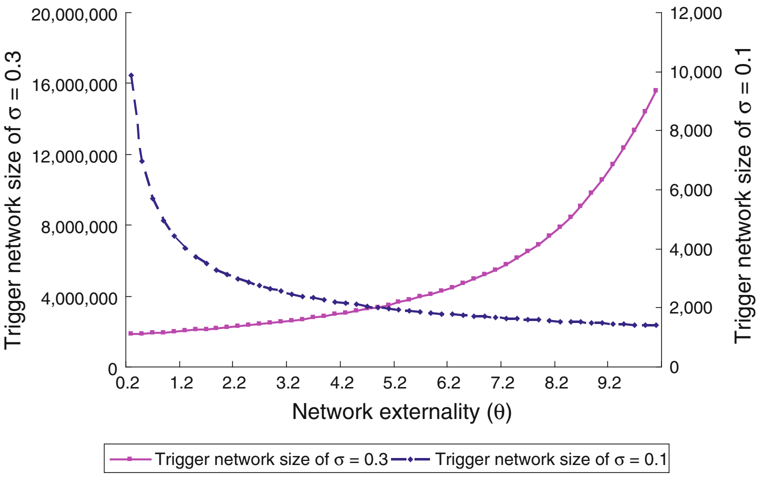

Fig. 1 The relationship between trigger network size and network externality for cases with different volatilities. *Note*: This figure depicts the relationship between the network externality (θ) and trigger network size for models with $\sigma = 0.3$ and $\sigma = 0.1$, respectively. Parameters are $\alpha = 10$, $\mu_1 = \mu_2 = 0.000000001$, $r = 0.09$, and $I = 100{,}000{,}000$

former, suggesting that increasing network externality results in a decrease in the trigger network size of investment.[10]

Particularly, the relationship between the network externality and the trigger network size is always negative when the NPV rule is applied.[11] Figure 2 is an example showing that using the NPV rule to determine the trigger network size not only underestimates it, but also reaches a misleading relationship between the network externality and the trigger network size.

5 Conclusions and further extensions

We contribute to the literature in three respects. First, we show that the consumer's waiting-to-buy effect is important in determining the trigger network size of investment. Second, increasing network externality has an ambiguous effect on the trigger network size. Using the NPV rule not only underestimates the trigger network size but also gives a misleading relationship between the network externality and the trigger network size.

[10] In an unreported result, we show that the model with risk averse is qualitatively similar to that with risk neutral. The conclusion in this paper is not affected by the assumption of consumers risk preference. We would like to thank an anonymous referee for this suggestion.

[11] In this case, consumer and monopolist both use the NPV rule to make their decisions. Therefore, the increase in the network externality raises the consumer's utilities gained by buying the product with network externality so that monopolist can charge a higher price. The total expected present value of the profit is denoted by *GNPV*, and *GNPV* is an increasing function of the number of consumers N and network externality θ. Using $GNPV\text{-}I = 0$, we can find the trigger network size of investment for the NPV rule. It is also found that $\partial N^*_{npv} \Big/ \partial\theta = -\frac{\partial(GNPV)}{\partial\theta} \Big/ \frac{\partial(GNPV)}{\partial N}$, where N^*_{npv} here is the trigger network size of investment for the NPV rule. Thus we have $\partial N^*_{npv} \Big/ \partial\theta < 0$. As a result, the relationship between the network externality and trigger network size of investment is always negative when the NPV rule is used.

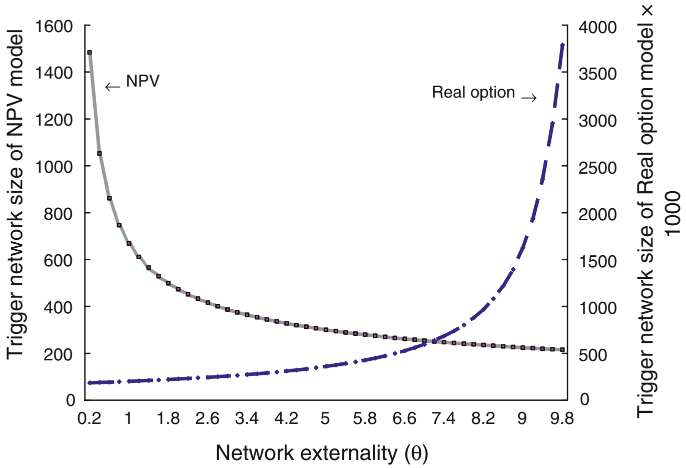

Fig. 2 The relationship between trigger network size and network externality: Real option model V.S. NPV rule. *Note*: The relationship between the network externality and trigger network size for our model from Equation (21) and the NPV rule derived by the equation $GNPV\text{-}I = 0$ where *GNPV* is defined in footnote 7. Parameters are $\alpha = 10$, $\mu_1 = \mu_2 = 0.000000001$, $\sigma = 0.3$, $r = 0.09$, and $I = 100{,}000{,}000$

Finally, we apply the real option theory to simultaneously consider the demand side and supply side so that many issues related to network externality can be analyzed under an equilibrium approach. For example, the model can be extended by incorporating the possibility of upgrading the product with network externality. Then a compound option is used to choose the optimal stopping time of upgrading the product with network externality. In addition, the monopolist might impose the price discrimination between the old users, who can choose to pay extra fee to upgrade the product he already purchased, and the new users, who buy the new upgraded product. The degree of upgrading and the compatibility of the first-generation product and the second-generation product can be designed to be endogenously determined. On the other hand, we can introduce the hysteresis model of investment with the stochastic variable cost of production as Martzoukos (2001) into the model so that we can analyze the investment decision and exit decision. Finally, we can consider two firms and incorporate game theory into the model so that we can investigate the effect of competiveness on the decisions of consumers and the firms. The issues related to network externality discussed above are left for further research.

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