

THE ASSOCIATION BETWEEN TECHNOLOGY TYPE AND DIFFUSION PATTERN UNDER DUOPOLISTIC COMPETITION

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Abstract: Many firms consider adopting new technologies as a means for enhancing competitive advantages. Therefore, the subject of technology diffusion has been studied by many researchers from different disciplines in order to explore the diffusion profiles throughout the industry or the country. The argument has frequently been made that the pattern of diffusion associated with most new technologies will typically have certain characteristics. In general, the diffusion pattern within an industry will depend on the competitive arena and technology characteristics. Based on a duopolistic game-theoretic model, this paper tries to explore the association between technology type and diffusion pattern. The results show that the cost-reducing technologies are adopted sequentially within a duopoly. On the other hand, strategic technologies diffuse over time or in a swarm. Although both technologies might be adopted sequentially, the rate for strategic technologies is faster than that for cost-reducing technologies.

Keywords: Game of timing, technology diffusion, Nash equilibrium.

1. INTRODUCTION

New technologies have been considered as a means of improving competitive competences by firms and countries around the world. To fully exploit specific technology, governments or research institutes would concern about the diffusion process of technologies within an economic system. In the last decade, researchers from many disciplines try to address related issues about technology diffusion. Mukoyama [14] pointed out that not much attention has been paid to the economics of diffusion, although we have witnessed a large development in economics of technologies. Diffusion is as important as an innovative technology: no new technologies have an economic impact until they became widespread in the economy.

Technology diffusion is achieved through user adoption, which is the acceptance into use and the continued use of new technologies. Rogers [19] defined technology diffusion as a process by which a technology is diffused over time among members of a social system. Loch and Huberman [13] stated that the acceptance and spread of new technology in a market or user community is commonly referred to as diffusion. It is an important topic of research in several disciplines, such as marketing, strategy, organizational behavior, economics, and the history of technology.

Diffusion rate is a key characteristic of technology diffusion. It is referred to as a relative speed with which a technology is adopted by members in an economic system. Diffusion of new technologies in general is far from easy. Many factors affect such diffusion. Identifying these factors and understanding their interactions are important for us to predict the diffusion rate of any technology. The argument has frequently been made that the pattern of diffusion associated with most new technologies will typically have certain characteristics. Gatignon and Robertson [7] might be the first article which emphasized that competition has a major impact on the diffusion process, although a lot of research had neglected this area. They suggested a set of propositions specifically related to the adoption of innovations by organizations. In their subsequent articles, Robertson and Gatignon [18] further put their particular stress on the issue of how competitive factors affect diffusion patterns, both at the level of the supplier industry and within the potential adopter industry. An empirical test of the effects of competition on the adoption of technological innovations by organizations was also conducted by them in a few years later (Gatignon and Robertson [8]).

In view of time and resource, implementing new technologies strongly impacts many facets of corporate operation. Therefore, the timing of when to adopt a new technology belongs to a strategic context. Canada and Sullivan [3] suggested that decision makers should incorporate market intelligence (size and share), revenue and cost into their planning models for technology investments. To our best knowledge, some evaluation models did not articulate the generating process about payoffs in detail, and hence such models confine their applications to static environment (Reinganum [16-17], Fudenberg and Tirole [6]). Fortunately, Tombak had presented a continuous-time non-cooperative game model with more detailed payoff functions in 1990. Modified from Tombak's [20] work into a continuous-time model, here we analyze a different focus, that is, the association between technology type and diffusion pattern.

In a short, this article based on a dynamic model, that specifies the economics of adoptions within the adopter industry, tried to study the diffusion pattern of two specific technology type, cost-reducing technologies and strategic technologies, under duopolistic

competition. Just as its name, cost-reducing technologies can lower operating cost and hence improve business efficiency. On the other side, firms usually implement strategic technologies for long-term business value, such as key manufacturing capabilities, potential R&D prospects, and sustainable core competences.

The rest of this paper is organized as follows. Next section briefly describes a duopolistic model. Section 3 proves the existence of Nash equilibrium in a technology adoption game. Interpretations about diffusion pattern are articulated clearly subsequently. The last section ends with concluding remarks.

2. A DUOPOLISTIC MODEL

Suppose that non-identical incumbent firms A and B engaged in a duopoly both produce a homogeneous and substitute product. Let

P : unit selling price for the product.

$D(t)$: demand function for the homogenous and substitute product.

C_{AO}, C_{BO} : unit production cost for firms A and B using old technologies, respectively.

C_{AN}, C_{BN} : unit production cost for firms A and B using new technologies, respectively

I_0 : initial investment costs of new technology, which may include all relevant costs of adjustment.

Because the products produced by both incumbents are homogeneous, we specify a single selling price, P , and a dynamic demand function, $D(t)$, for the family of substitute products. Each of them wants to decide when to adopt some kind of new technology, accounting not only for the costs and benefits of technology itself, but also for the effects of competitor's adoption upon pre-adoption and post-adoption profits. Due to their strategic interdependence, the decision to adopt new technologies is modeled as a non-cooperative continuous time game. Let t_A and t_B represent the times at which firms A and B adopt new technologies, respectively, and let the state of the game $S(t)$, be as follows.

$$S(t) = \begin{cases} 1, & 0 \leq t \leq \min\{t_A, t_B\} \\ 2, & t_A \leq t \leq t_B \\ 3, & t_B \leq t \leq t_A \\ 4, & \max\{t_A, t_B\} \leq t \leq \infty \end{cases} \quad (1)$$

When $S(t) = 4$ (or $S(t) = 1$), firms A and B both have (not) adopted new technology at time t . When $S(t) = 2$ (or $S(t) = 3$), firm A (or B) have adopted new technology, however, firm B (or A) still employs the existing technology.

To model the market shares of both firms, we first review several useful market share models. Generally speaking, there are three alternative models of market share: linear model, multiplicative model, and attraction model (Lilien, Kolter, and Moothy [12]). The latter two models belong to the non-linear category. After changing the non-linear models into linear models, the numbers of parameters which need to be estimated in all formulations are equal (Brodie and de Kluyver [2], Ghosh, Neslin, and Shoemaker [9], Leeflang and Reuyl [11]). In this paper, the multinomial logit model which belongs

to the attraction category had been used to describe the market shares of both firms. These market shares are defined as follows:

$$M_A(t) = \begin{cases} \frac{1}{2} & , S(t) = 1 \text{ or } 4 \\ \frac{1}{1 + e^{-\beta|x(t)-y|}} & , S(t) = 2 \\ \frac{e^{-\beta|x(t)-y|}}{1 + e^{-\beta|x(t)-y|}} & , S(t) = 3 \end{cases} \quad (2)$$

and

$$M_B(t) = \begin{cases} \frac{1}{2} & , S(t) = 1 \text{ or } 4 \\ \frac{1}{1 + e^{-\beta|x(t)-y|}} & , S(t) = 3 \\ \frac{e^{-\beta|x(t)-y|}}{1 + e^{-\beta|x(t)-y|}} & , S(t) = 2 \end{cases} \quad (3)$$

where

$M_i(t)$: market share of firm i at time t

$x(t)$: consumers' ideal (or bliss) point of the product attribute

y : product attribute produced by existing technology.

β : weight representing the importance of the product attribute under consideration.

The product attribute (y), which is a specification of the product or a belief of consumers' perception, determines consumers' attitudes towards the product. For example, an important attribute for a car might be miles per gallon (mpg). Holding the other attributes unchanged, everyone will agree that a car giving 40 mpg is better than a car giving 20 mpg. Hence, the ideal point reflects the most favorite attribute any affordable consumer will pursue, and describes the most preferred position in the map of consumers' perception. Intuitively, the distance between the product attribute and consumers' ideal point influences the market share of the product. It is also assumed that the product attribute produced by new technology will be consistent with consumers' ideal point.

To make the preference decline smoothly away from the consumers' ideal point, which Cooper and Nakanishi [4] called it the standard ideal point model, the weight β must be positive. Furthermore, the path of the consumers' ideal point is assumed to drift linearly and increasingly over time. That is $x(t) = at + y, a > 0$. For instance, the ideal point of pharmaceutical potency is expected to increase as the level of technology and science advances.

Prior to presenting subsequent analysis, the following assumptions are made.

Assumption 1: $P > C_{AO}, P > C_{AN}, P > C_{BO}, P > C_{BN}, I_0 > 0$

Assumption 2: (1) $C_{AN} < C_{AO}, C_{BN} < C_{BO}$; (2) $C_{AN} > C_{AO}, C_{BN} > C_{BO}$

Assumption 1 states that both firms make positive profits no matter which technology they adopt. The last condition in Assumption 1 specifies the capital costs of new technologies must be positive. Assumption 2 (1) reflects the well-known fact that cost-reducing technologies could lower the unit production cost. However, Assumption 2(2) is suitable for strategic technologies. Naik and Chakravarty [15] had mentioned that strategic values, e.g. key manufacturing capabilities, potential R&D prospects, and sustainable core competences, could justify the adoption of strategic technologies.

At the beginning of the game, each firm must pre-commit itself to the action of adopting a new technology. Based on the above discussion and let r be the annual discounting rate, the payoff function of firm A is given below.

$$NPV^A(t_A, t_B) = \begin{cases} F^A(t_A, t_B), t_A \leq t_B \\ F^B(t_A, t_B), t_A \geq t_B \end{cases} \quad (4)$$

where

$$F^A(t_A, t_B) = \int_0^{t_A} \frac{1}{2} D(t)(P - C_{AO})e^{-rt} dt + \int_{t_A}^{t_B} \frac{1}{1 + e^{-\beta at}} D(t)(P - C_{AN})e^{-rt} dt + \int_{t_B}^{\infty} \frac{1}{2} D(t)(P - C_{AN})e^{-rt} dt - I_0 e^{-rt_A} \quad (4a)$$

and

$$F^B(t_A, t_B) = \int_0^{t_B} \frac{1}{2} D(t)(P - C_{AO})e^{-rt} dt + \int_{t_B}^{t_A} \frac{e^{-\beta at}}{1 + e^{-\beta at}} D(t)(P - C_{AO})e^{-rt} dt + \int_{t_A}^{\infty} \frac{1}{2} D(t)(P - C_{AN})e^{-rt} dt - I_0 e^{-rt_B} \quad (4b)$$

Similarly, the payoff function of firm B is

$$NPV^B(t_A, t_B) = \begin{cases} G^A(t_A, t_B), t_A \leq t_B \\ G^B(t_A, t_B), t_A \geq t_B \end{cases} \quad (5)$$

where

$$G^A(t_A, t_B) = \int_0^{t_A} \frac{1}{2} D(t)(P - C_{BO})e^{-rt} dt + \int_{t_A}^{t_B} \frac{e^{-\beta at}}{1 + e^{-\beta at}} D(t)(P - C_{BO})e^{-rt} dt + \int_{t_B}^{\infty} \frac{1}{2} D(t)(P - C_{BN})e^{-rt} dt - I_0 e^{-rt_B} \quad (5a)$$

and

$$G^B(t_A, t_B) = \int_0^{t_B} \frac{1}{2} D(t)(P - C_{BO})e^{-rt} dt + \int_{t_B}^{t_A} \frac{1}{1 + e^{-\beta at}} D(t)(P - C_{BN})e^{-rt} dt + \int_{t_A}^{\infty} \frac{1}{2} D(t)(P - C_{BN})e^{-rt} dt - I_0 e^{-rt_B} \quad (5b)$$

Note that when the unit production cost of firms A and B are equal (i.e. $C_{AO} = C_{BO}$ and $C_{AN} = C_{BN}$), it results in a pair of identical incumbents engaged in a game of duopoly.

3. ANALYSIS OF NASH EQUILIBRIA

The strategy space for a timing game of adopting new technology is over $[0, \infty)$. Each firm intends to search for the maximum of its own pay-off function defined on its strategy space. When firm A preempts firm B, the pay-off functions for both firms are reduced to $F^A(t_A, t_B)$ and $G^A(t_A, t_B)$, respectively. Therefore, the first order condition, $\partial F^A(\bar{t}_A, t_B) / \partial t_A = 0$, for firm A is

$$\left[\frac{1}{2} D(\bar{t}_A)(P - C_{AO}) + I_O r \right] (1 + e^{-\beta a \bar{t}_A}) - D(\bar{t}_A)(P - C_{AN}) = 0, \quad (6)$$

where \bar{t}_A denotes the optimal leading time of firm A. The first order condition, $\partial G^A(t_A, \bar{t}_B) / \partial t_B = 0$ for firm B is

$$\left[D(\bar{t}_B)(P - C_{BO}) + I_O r - \frac{1}{2} D(\bar{t}_B)(P - C_{BN}) \right] \cdot e^{-\beta a \bar{t}_B} + \left[I_O r - \frac{1}{2} D(\bar{t}_B)(P - C_{BN}) \right] = 0 \quad (7)$$

where \bar{t}_B denotes the optimal following time of firm B. Obviously, the optimal timing for each firm does not depend on the timing of the other. Since $\bar{t}_A \leq \bar{t}_B$, we call \bar{t}_A and \bar{t}_B as the optimal leading time for firm A and the optimal following time for firm B, respectively.

Similarly, when firm B preempts firm A, let \bar{t}_B and \bar{t}_A denote the optimal leading and following time for firms B and A, respectively. The corresponding first order conditions when firm B pre-empting firm A can be deduced by symmetry. Without loss of generality, we will only deal with the case of firm A pre-empting B.

To show the existence of Nash equilibrium, we first present the following definition (Friedman [5]).

Definition 1: A timing pair (t_A^N, t_B^N) is a Nash equilibrium if no firm has an incentive to deviate from the chosen time given that the other firm does not deviate. Formally, (t_A^N, t_B^N) is a Nash equilibrium if

$$(1) NPV^A(t_A^N, t_B^N) \geq NPV^A(t_A, t_B^N), \quad \forall t_A \in [0, \infty); \text{ and}$$

$$(2) NPV^B(t_A^N, t_B^N) \geq NPV^B(t_A^N, t_B), \quad \forall t_B \in [0, \infty)$$

The Nash equilibrium is a main solution concept for all kinds of non-cooperative games. For ease of reference, let us define the term symmetric Nash equilibrium and asymmetric Nash equilibrium refer to both firms adopt technologies simultaneously or sequentially, respectively. Following Assumptions 1 and 2, one can prove the following theorem.

Theorem 1.

- (1) The optimal leading and following times of firm A for the cost-reducing technologies, \bar{t}_A and $\bar{\bar{t}}_A$, satisfy the inequality $\bar{t}_A \leq \bar{\bar{t}}_A$.
- (2) The optimal leading and following times of firm B for the cost-reducing technologies, \bar{t}_B and $\bar{\bar{t}}_B$, satisfy the inequality $\bar{t}_B \leq \bar{\bar{t}}_B$.

Proof: (1) The optimal leading time of firm A for the cost reducing technologies, \bar{t}_A , is the root of equations (6) for $t_A \in [0, \infty)$. Similarly, the optimal following time of firm A for the cost-reducing technologies, $\bar{\bar{t}}_A$, is the root of equation $f^B(t_A) = 0$ for $t_A \in [0, \infty)$, where $f^B(t_A)$ is defined as the left-hand side of equation (7) after replacing the “B”s by “A”s. Let

$$h(t_A) = f^B(t_A) - f^A(t_A) = \frac{1}{2}D(t)(C_{AO} - C_{AN})(1 - e^{-\beta at_A})$$

Under Assumption 2(1), $h(t_A) \geq 0$ over $[0, \infty)$. Moreover, $f^A(t_A)$ and $f^B(t_A)$ are decreasing over $[0, \infty)$. Therefore, $\bar{t}_A \leq \bar{\bar{t}}_A$.

(2) The proof of (2) is similar to part (1).

From Theorem 1, it is easily shown that the set of four optimal times $\{\bar{t}_A, \bar{\bar{t}}_A, \bar{t}_B, \bar{\bar{t}}_B\}$ is a partially ordered set (POSET) under the order relation \leq . Hasse diagram of the POSET is shown in Figure 1. After applying the topological sorting process to constructing all linear orders (known as lexicographic orders) \prec of the POSET, we obtain the Hasse diagrams in Figure 2 (Kolman and Busby [10]). Tips to sorting the POSET is to enter the elements sequentially and keep the partial order preserved. Figures 2(a)–(d) show two asymmetric Nash equilibria, $(\bar{t}_A, \bar{\bar{t}}_B)$ and $(\bar{\bar{t}}_A, \bar{t}_B)$. After deleting infeasible chronological equilibria, Figures 2(e) and (f) both indicate an asymmetric Nash equilibrium, $(\bar{t}_A, \bar{\bar{t}}_B)$ or $(\bar{\bar{t}}_A, \bar{t}_B)$. It is worth to note that there are always two Nash equilibria in a game of two identical incumbents. Because \bar{t}_A is equal to \bar{t}_B and $\bar{\bar{t}}_A$ is equal to $\bar{\bar{t}}_B$, one equilibrium can be obtained by interchanging the optimal times in another equilibrium.

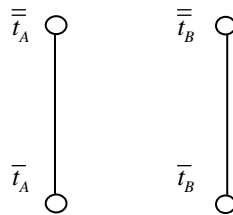


Figure 1: Hasse diagram of the POSET $\{\bar{t}_A, \bar{\bar{t}}_A, \bar{t}_B, \bar{\bar{t}}_B\}$ for cost-reducing technologies

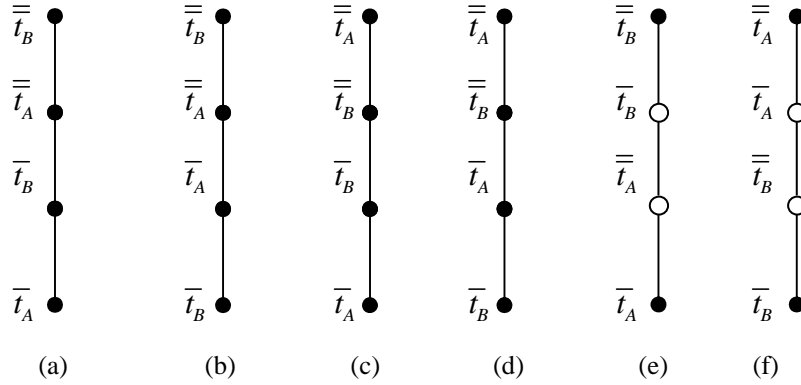


Figure 2: Hasse diagram of all possible linear orders of the POSET $\{t_A^-, t_A^-, t_B^-, t_B^-\}$ for cost-reducing technologies

We next consider the equilibrium for the timing game of adoption in strategic technologies which are not a kind of cost-reducing technology. These technologies obey Assumption 2(2) and are named strategic technologies as before. The violation of Assumption 2(1) reverses the inequalities in Theorem 1 (or the partial ordering in Figure 1). Anyone can follow the logic in Theorem 1 to prove the following theorem.

Theorem 2.

- (1) The optimal leading and following times of firm A for the strategic technologies, t_A^- and t_A^- , satisfy the inequality $t_A^- \geq t_A^-$.
- (2) The optimal leading and following times of firm B for the strategic technologies, t_B^- and t_B^- , satisfy the inequality $t_B^- \geq t_B^-$.

The Hasse diagrams of all possible linear orders of the POSET for strategic technologies are shown in Figure 3. Figures 3(a)-(d) each exhibits a symmetric Nash equilibrium occurring in time intervals $[t_B^-, t_A^-]$, $[t_A^-, t_B^-]$, $[t_B^-, t_B^-]$, and $[t_A^-, t_A^-]$, respectively. That is, both firms will simultaneously adopt strategic technologies over four possible closed time intervals. The last two figures, Figures 3(e) and (f), each exhibits an asymmetric Nash equilibrium (t_A^-, t_B^-) and (t_A^-, t_B^-) , respectively. That is, one will be a leader in the game of timing, and the other will follow suit later. Obviously, the time lag between leader and follower for strategic technologies is narrower than that of cost-reducing technologies. In case of Figure 3(c), the leading and following payoff functions of both firms are shown in Figure 4. Considering the furthestmost left-end time interval, because their leading payoff functions, $NPV^A(t_A^-, 0)$ and $NPV^B(0, t_B^-)$, are increasing, hence each firm would like to be a follower by postponing their adoption to t_A^- and t_B^- , respectively. By the same token, $[t_A^-, t_B^-]$, $[t_B^-, t_A^-]$, and $[t_A^-, \infty]$ all can not be a time

interval of symmetric Nash equilibrium. However, for any time between \bar{t}_B and \bar{t}_B , neither incumbent would wish to lead the pack, since both leading payoff functions are increasing. Similarly, neither incumbent would wish to be a follower, since their following payoff functions are decreasing. Finally, the following theorem concludes these results.

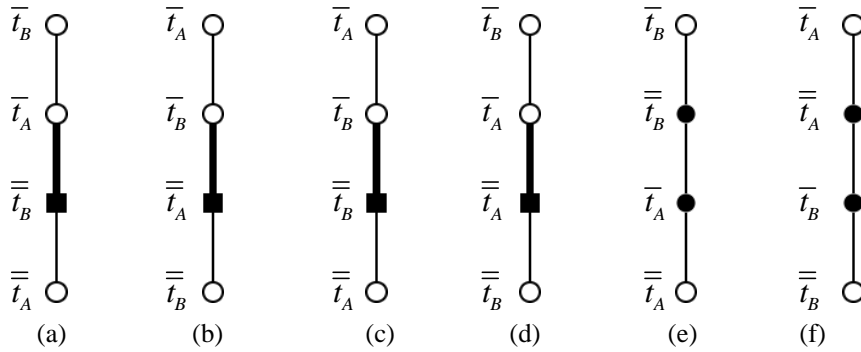


Figure 3: Hasse diagrams of all possible linear order of the POSET $\{\bar{t}_A, \bar{t}_A, \bar{t}_B, \bar{t}_B\}$ for strategic technologies

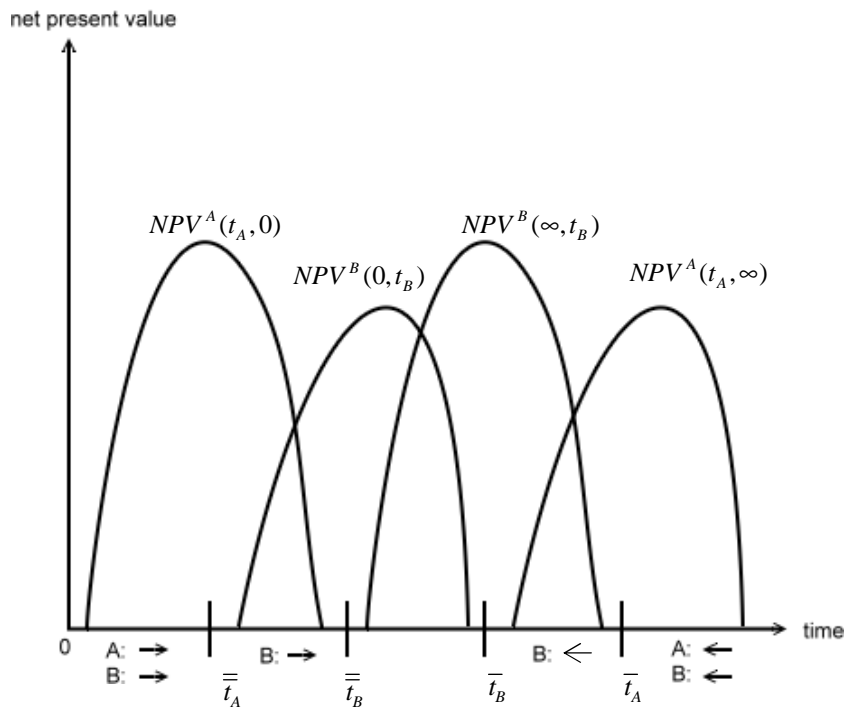


Figure 4: Leading and following payoffs for strategic technologies in case of Figure 3(c)

Theorem 3.

- (1) *For non-identical duopolists who are interested in cost-reducing technologies, there are at least one and no more than two asymmetric Nash equilibria. That is, cost-reducing technologies diffuse over time within a duopoly.*
- (2) *For non-identical duopolists who are interested in strategic technologies, both firms may adopt strategic technologies simultaneously or sequentially. However, even in the case of asymmetric equilibrium, the timing of adoption for strategic technologies are more concentrated than those for cost-reducing technologies.*

Next we tried to explain the findings in Theorem 3 from two perspectives. First, strategic technologies often bring radical changes in many aspects, while cost-reducing technologies normally provide incremental improvement for specific process. Abernathy and Utterback [1] pointed out that industries often go through cycles of incremental innovations, punctuated by short periods of radical change. This coincides with the asymmetric and symmetric equilibriums for cost-reducing technologies and strategic technologies in Theorem 3, respectively. Second, the firms within a duopoly tend to adopt strategic technologies in a swarm. The logic is that industry participants under duopoly conditions pay close attention to each other's competitive moves, especially when there is any competitor tries to pursue long-term business value by adopting strategic technologies.

4. CONCLUSIONS

To be competitive and survival, it is imperative for firms to adopt new technology. Global competition forces governments or research institutes to study the pattern of technology diffusion. Under a simple but reasonable circumstance, this paper show that at least one and no more than two sequential Nash equilibriums for cost-reducing technologies exist, implying a discrete adoption of cost-reducing technologies over time line. Nash equilibrium for strategic technologies, however, may be sequential or simultaneous. Even in the case of sequential adoption, the diffusion rate for strategic technologies is steeper than that for cost-reducing technologies.

It is clear that some research remains to be undertaken in the future. Using other solution concepts, such as Stackelberg or bargaining theory, to analyze the diffusion pattern can help decision makers make wiser choice. In addition, the demand function might have many other types in real world. Another extension of this research is to set the analysis in an oligopolistic environment. A more sophisticated competitive environment makes such analysis more intractable. However, to fully exploit the competitive structure, studying the oligopolistic case is inevitable.

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