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Strategic Investment in Technological Innovations[★]

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Abstract

The aim of this paper is to determine the optimal timing of technology investment of a single firm in a duopoly framework. As time passes different technologies are invented which after some time become available for the firm to adopt. The question here is not only when a firm should invest but also which technology should be adopted. For different scenarios the optimal technology investment decision is determined. Outcomes range from preemption equilibria to equilibria with second mover advantages.

Key words: Investment analysis, Technology investment, Strategic timing, Preemption, Second mover advantage

1 Introduction

One of the main elements that determines economic growth nowadays is the diffusion of new technologies to firms. Research and development alone is not yet sufficient for technical progress since technological innovations yield no benefits until they are employed. In order to design policy instruments that enhance firm investments in new technologies, it is important to investigate in what circumstances firms are willing to adopt new technologies, and to identify the reasons that make the firm refrain from adoption. At the firm level it can be argued that one of the most crucial decisions is that of investing in new or improved equipment and facilities. For instance, Nair (1995) states that: "These decisions are not only important because of the large initial capital costs involved, but also because of its impact on the firm's performance for many years into the future. Reasons for retrospection on the decision would arise if newer technologies appear soon after the purchase, or if the need for capability or adaptability to changes were not foreseen earlier when the decision was made, or they were not incorporated in the model at that time."

The aim of this paper is to determine the optimal technology investment decision of an individual firm, while taking into account the possible occurrence

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of better technologies in the future and competition of other firms. The first paper that deals with the issue of technology investment together with competition on the output market is Reinganum (1981). She considers a duopoly with two identical firms, which both have the possibility to invest in a new technology from which the price falls over time. Despite the fact that the firms are identical, one of them is given the leader role beforehand. This implies that only this firm is allowed to invest first. The other firm is the follower which has the choice to invest at the same time as the leader or to invest later. As shown in Fudenberg and Tirole (1985) for this framework two scenarios can be identified. In one scenario the optimal outcome is joint adoption, i.e. both firms invest at the same time, while in the other scenario the follower invests later despite of the fact that the leader then obtains the largest payoff. Fudenberg and Tirole (1985) also consider the more realistic case of endogenous firm roles meaning that beforehand it is not known which firm will be the leader. In the case of dispersed adoption timings the leader earns the highest payoff so that both firms want to be the leader. This gives an incentive to try to invest earlier than its competitor, i.e. both firms will try to preempt each other. Fudenberg and Tirole show that this leads to a preemption equilibrium with dispersed adoption times and rent equalization. Stenbacka and Tombak (1994) (see also Götz (2000)) extend this research by introducing uncertainty concerning the length of the period between the point of time that the technology is adopted and the time that it is successfully implemented.

One of the features of the models concerning the investment of new technologies mentioned in the previous paragraph is that only one new technology was available. The availability of more consecutive new technologies complicates the technology investment decision considerably, since every time the

firm evaluates an investment in a new technology it has to take into account that at a later point of time a more efficient technology will be invented.

Especially information technology capital has a very high pace of technological improvement. Yorukoglu (1998) states: "Compared with more traditional types of capital, the efficiency of information technology capital has increased much faster over the last few decades. As an example, consider the market for personal computers. IBM introduced its Pentium PCs in the early 1990s at the same price at which it introduced its 286 PCs in the 1980s. Therefore it took less than a decade for the computing technology to improve on the order of 20 times in terms of both speed and memory capacities, without increasing the cost."

In this paper we provide a first step in analyzing the problem of when a firm could adopt an existing technology knowing that a better technology will become available later, while it has to fight for a market share with an identical firm on the output market. Two technologies are considered: an existing one which can be adopted immediately, and a new one which is more efficient and enters the input market at a known future date. Learning is incorporated in the sense that it is less costly to adopt and successfully implement the new technology if it has adopted the current technology before. As such this framework is taken from Grenadier and Weiss (1997). In that paper the future date at which the new technology becomes available is uncertain and only one firm is considered. So, compared to Grenadier and Weiss (1997) we exchange the uncertainty for competition on the output market. In this way we are able to identify the strategic aspects of this problem.

Two scenarios are worked out in detail: one where the new technology is cheap,

and one where the new technology is so expensive that it is not optimal for both firms to produce with the new technology. In the latter case we show that on a particular time interval it is optimal for one firm to invest right away in the current technology while the other firm waits with investment in order to adopt the new technology as soon as it becomes available. Which firm will do better depends on the comparison between the temporary monopoly profits gained by the first investor before the new technology arrives, versus the higher revenue the other firm obtains after the arrival date of the new technology due to the fact that it produces with a more efficient technology. In case the monopoly profits are outweighed by the higher revenue associated with the new technology, second mover advantages arise. To our knowledge, the way second mover advantages are caused here has not occurred in the literature yet. Different second mover advantages have been found by Hendricks (1992) and Dutta et al. (1995). In Hendricks (1992) they are caused by ex ante uncertainty in the profitability of adoption (see also Hoppe (2000)), while in Dutta et al. (1995) the quality of the product improves over time. These second mover advantages may lead to a better understanding of the fact that from empirical studies it could not always be concluded that early entrants perform better than later entrants. Apart from the numerous studies that found persistent market-share advantages to first entrants, there are many examples of pioneering firms that did not survive the competition of later entrants. Dutta et al. (1995) mention the case of EMI, which developed the first CT scanner but lost its market place because it lacked a technological infrastructure and marketing base in the medical field.

By now it is clear that technology investment is a very relevant topic in today's decision making, and in reality firms also have to deal with competi-

tion. Although it is not a large stream, until now the OR literature contains some papers that deal with the technology investment problem in a one-decision-maker-context (e.g. Nair (1995), Rajagopalan (1999), Rajagopalan et al. (1998)) and even in a game (Gaimon (1989) and Chung and Tsou (1998)). Gaimon (1989) considers a framework where a continuous stream of technologies arrive over time. In this paper the focus is on capacity expansion and output pricing rather than on investment timing as in our paper. The latter topic is also the main focus in Chung and Tsou (1998) where a silent Nash equilibrium is derived. In their paper they mentioned the need for perfect equilibria, and this is what is obtained in this paper.

The contents of this paper is as follows. The model is introduced in Section 2. In Section 3 the solution procedure is explained and optimal investment strategies are analyzed in detail for two specific scenarios. Section 4 concludes.

2 Model Formulation

The model is based on Grenadier and Weiss (1997), but here a duopoly with two identical risk-neutral and value maximizing firms is considered, while in Grenadier and Weiss (1997) the analysis is focussed on a single firm. To produce goods the firms need to acquire a certain technology. Initially, at time $t = 0$, they can invest in a current technology, of which the efficiency is denoted by $\theta_1 (> 0)$. At time $t = T (\geq 0)$, a new and more efficient technology becomes available for adoption, with efficiency $\theta_2 (> \theta_1)$. In our analysis time T is assumed to be known beforehand (contrary to Grenadier and Weiss (1997), where T depends on the realization of a Wiener process that governs the state of technological knowledge). When a firm does not produce we denote this

by $\theta_0 = 0$. The firm's profits per unit of time, while it produces with technology θ_i and the other firm with technology θ_j , are equal to $\pi(\theta_i, \theta_j)$, with $i, j \in \{0, 1, 2\}$. We assume that for $j \in \{0, 1, 2\}$:

$$\pi(\theta_0, \theta_j) = 0, \quad (1)$$

and for $i \in \{1, 2\}$ and $j \in \{0, 1, 2\}$:

$$\pi(\theta_i, \theta_j) > 0. \quad (2)$$

If P_{ij} denotes the value of the firm while this firm itself produces with technology θ_i forever and the other firm with technology θ_j forever, it holds that

$$P_{ij} = \int_{s=0}^{\infty} \pi(\theta_i, \theta_j) e^{-rs} ds = \frac{\pi(\theta_i, \theta_j)}{r}, \quad (3)$$

where $r (> 0)$ is the constant discount rate.

If the new technology is not available for adoption yet, i.e. $t < T$, the firm has the possibility to invest in the current technology, where the investment expenditure equals $C_e (> 0)$. Then the firm's payoff is $P_{1j} - C_e$, where $j = 1$ when the other firm is producing with technology θ_1 and $j = 0$ when the other firm refrains from producing.

From time T onwards the firm can choose to adopt the new technology. If the firm has invested in the current technology before, it may replace this technology by the new one. Then the payoff of investing in the new technology is $P_{2i} - P_{1j} - C_u$, where $C_u (> 0)$ stands for the cost of upgrading. Note that in the formulation of the payoff it is taken into account that the other firm can change its technology too at time T .

If the firm adopts the new technology without having invested in the current technology before, the payoff of this investment is $P_{2i} - C_l$, with $C_l > 0$. At the moment the new technology arrives the demand for the current technology will fall so that it makes sense that the acquisition cost of the current technology will fall too. This makes that if the firm did not buy the current technology before, it may become profitable to adopt this technology after time T . The payoff of this transaction is $P_{1i} - C_d$, with $C_d > 0$.

Concerning the levels of the different cost parameters we impose that

$$C_u < C_l < C_e + C_u, \quad (4)$$

$$C_d < C_e. \quad (5)$$

The first inequality in (4) denotes the learning effect in the sense that it is less costly to adopt and successfully implement the new technology if the firm already produces goods. The second inequality assures that no arbitrage is possible, i.e. it is always more costly to immediately start producing with the current technology and replacing it later by the new one, than to refrain from production initially in order to wait for the new technology to arrive.

The value of a particular technology falls over time, because (1) it becomes old-fashioned, (2) the firms that are most eager to buy the technology have already bought it so that technology suppliers have to drop their price in order to find additional buyers, and (3) due to learning by doing the technology supplier can produce the technology in a cheaper way. For these reasons we assume here that technology investments are irreversible.

Next, we specify how the profit streams are related to each other. Note that from (3) it can be obtained that profits per unit of time $\pi(\theta_i, \theta_j)$ are related to each other in the same way as the discounted profit streams P_{ij} . First, it holds that when the firm produces with a given technology the highest profit it can obtain is the monopoly profit, which the firm receives if the other firm does not produce. Second, its profits will be lowest when the other firm is a strong competitor in the sense that it produces in the most efficient manner by using the modern technology. This leads to

$$P_{i0} > P_{i1} > P_{i2} \quad \text{for } i \in \{1, 2\}. \quad (6)$$

Furthermore, by upgrading its technology, thus exchanging the current technology for the new technology, the firm gains most the less competitive the other firm is. Of course, since the new technology is more efficient, the profit stream always increases due to this exchange. Mathematically, this can be expressed as

$$P_{21} - P_{11} > P_{22} - P_{12} > 0. \quad (7)$$

If the other firm produces more efficiently the home firm has a lower market share and thus produces less products. Therefore, adopting a more efficient technology leads to an efficiency gain for producing less products so that the revenue increase due to this technology investment is lower than when the other firm produces with the current technology.

Finally, in order to limit the number of possible cases, we focus on the scenarios where for each technology investment the discounted future profit stream exceeds the immediate expenditure. Due to (4), (5) and (6) it can be concluded

that this is assured by

$$P_{12} > C_e \quad \text{and} \quad P_{22} > C_l. \quad (8)$$

3 Solution Procedure

3.1 Pure strategies

Since for every technology investment the discounted future profit stream exceeds the immediate cost expenditure (cf. (8)), it is optimal for each firm to invest at least once. This implies that, given that we are at time $t = 0$, each firm has four pure strategies (cf. Grenadier and Weiss (1997)). Note that due to discounting a firm will either invest at time $t = 0$ or at time $t = T$ in a pure strategy. However, as will be shown later, when allowing for mixed strategies strategic interactions can enforce firms to undertake an investment at a time that is different from the times $t = 0$ and $t = T$.

The first pure strategy is called the *Compulsive strategy*. Here the firm invests right away in the current technology, and replaces this current technology by the new one as soon as the latter becomes available. The payoff of the Compulsive strategy equals

$$P_{1j} - C_e + e^{-rT} (P_{2i} - P_{1j} - C_u). \quad (9)$$

In (9), as well as below in (10), (11) and (12), the other firm produces with technology θ_j before time T and with technology θ_i after time T . Of course, if j or i equals 0 it is meant that the other firm does not produce at all.

The second pure strategy is the *Buy and Hold strategy* by which it is meant that the firm invests right away in the current strategy and keeps on producing with it forever. The firm's payoff then equals

$$P_{1j} - C_e + e^{-rT} (P_{1i} - P_{1j}). \quad (10)$$

The third pure strategy is the *Leapfrog strategy*. Then the firm waits for the new technology to arrive and adopts it then. The payoff of this strategy is

$$e^{-rT} (P_{2i} - C_l). \quad (11)$$

The fourth pure strategy is to wait for the new technology to arrive, and at that moment invest in the current technology, which then can be bought against a cheaper price. The payoff of this so-called *Laggard strategy* then equals

$$e^{-rT} (P_{1i} - C_d). \quad (12)$$

3.2 Equilibrium strategies

The equilibrium strategies of both firms depend on the scenarios in which they have to operate. It holds that in some scenarios upgrading is optimal, implying that the payoff of the Compulsive strategy exceeds the payoff of the Buy and Hold strategy, while in other ones it is not. Another factor that distinguishes the different scenarios are the payoffs of the Leapfrog and the Laggard strategies: the Leapfrog payoff can exceed the Laggard payoff but it can be the other way round too. Here it also has to be taken into account that the ranking of the payoffs depends on what the other firm is doing:

Table 1

Possible scenarios and their specifications.

Scenario	Specifications
1	$P_{22} - P_{12} < P_{21} - P_{11} \leq C_l - C_d, C_u$
2	$P_{22} - P_{12} \leq C_l - C_d < P_{21} - P_{11} \leq C_u$
3	$P_{22} - P_{12} \leq C_u < P_{21} - P_{11} \leq C_l - C_d$
4	$P_{22} - P_{12} \leq C_l - C_d, C_u < P_{21} - P_{11}$
5	$C_l - C_d < P_{22} - P_{12} < P_{21} - P_{11} \leq C_u$
6	$C_l - C_d < P_{22} - P_{12} \leq C_u < P_{21} - P_{11}$
7	$C_u < P_{22} - P_{12} < P_{21} - P_{11} \leq C_l - C_d$
8	$C_u < P_{22} - P_{12} \leq C_l - C_d < P_{21} - P_{11}$
9	$C_l - C_d, C_u < P_{22} - P_{12} < P_{21} - P_{11}$

producing with the current technology or with the new one. On the other hand, all scenarios have in common that when the firm exchanges the current technology for the new technology, it gains more when the other firm produces with the current technology instead of the new technology (cf. (7)).

In Table 1 all possible scenarios are listed. In total there are nine scenarios, each giving a different solution. It would lead to using up too much space and unnecessary repetitions if in the sequel we would study all these solutions. Instead we describe two of these solutions in detail in the next subsections. In order to still cover many different aspects of optimal technology investments we choose rather opposite scenarios. In the first case it is relatively cheap to

acquire the new technology, while in the second case the new technology is expensive and the learning effect is negligible.

In both subsections we start out by analyzing the case of exogenous firm roles, i.e., despite the fact that both firms are identical one of them is given the leader role beforehand. This implies that only this firm is allowed to invest first. The other firm is the follower, which can choose between investing at the same time as the leader resulting in joint adoption, or investing later. The resulting solution is taken as a starting point to consider the more realistic case of endogenous firm roles, meaning that beforehand it is not known which firm will be the leader.

3.3 *Equilibrium strategies if the new technology is cheap*

The scenario we have in mind here is number 9 in Table 1, from which it can be obtained that it must hold that

$$P_{21} - P_{11} > P_{22} - P_{12} > \max(C_u, C_l - C_d). \quad (13)$$

Due to (9) and (10) we can conclude that under (13) Compulsive dominates Buy and Hold, while (11) and (12) imply that Leapfrog dominates Laggard.

3.3.1 *Exogenous firm roles*

Despite of the fact that both firms are identical one of them gets the leader role beforehand so that the other firm is the follower. Straightforward calculations lead to the equilibrium strategies that are presented in Table 2. Concerning the notation, $T_{xy,z}$ means that: (i) if the second technology arrives exactly

at this point of time a firm is indifferent between strategy x and y , given that the other firm performs strategy z , and (ii) when the second technology arrives before (after) time $T_{xy,z}$ the firm prefers strategy x (y), given that the other firm uses strategy z . Here the names of the strategies are abbreviated (C : Compulsive, Le : Leapfrog, La : Laggard, and B : Buy and Hold). So, if for instance the arrival date of the second technology $T \in [0, T_{LeC,Le}]$, according to Table 2 both firms should follow a Leapfrog strategy. With equations (9) and (11) we derived that

$$T_{LeC,Le} = \frac{1}{r} \log \left(\frac{P_{10} - C_l + C_u}{P_{10} - C_e} \right), \quad (14)$$

$$T_{LeC,C} = \frac{1}{r} \log \left(\frac{P_{11} - C_l + C_u}{P_{11} - C_e} \right). \quad (15)$$

Equations (4) and (6) imply that

$$0 < T_{LeC,Le} < T_{LeC,C}. \quad (16)$$

Table 2

Equilibrium strategies in scenario 9 as function of T , the arrival time of the second technology, when the firm roles are assigned exogenously.

T interval	Leader	Follower
$[0, T_{LeC,Le}]$	Leapfrog	Leapfrog
$(T_{LeC,Le}, T_{LeC,C}]$	Compulsive	Leapfrog
$(T_{LeC,C}, \infty)$	Compulsive	Compulsive

Since in scenario 9 the new technology is attractive, only those strategies occur under which this technology will be bought: Compulsive and Leapfrog. On the first interval $[0, T_{LeC,Le}]$ the arrival of the new technology is that near that for both firms it is optimal to wait with investment until the new technology

becomes available. This explains the occurrence of the Leapfrog strategy on this interval.

On the time interval $(T_{LeC,Le}, T_{LeC,C}]$ T is a bit further away, which implies that, given that the leader announces a Compulsive strategy, the follower will prefer Leapfrog, i.e. refrain from immediate investment in order to wait for the new technology to arrive. The explanation is that the time interval in which the current technology will be used is too short to make investing in the current technology profitable. Also the learning effect, i.e. implementing the new technology is cheaper when the firm has already production experience due to using the current technology, cannot make up for this (cf. (4)). But, given that the follower will not adopt the current technology so that it will not produce before time T , by investing in the current technology the leader can become a monopolist until the time that the new technology arrives.

When the point of time at which the new technology appears on the market lies relatively far in the future, it is optimal for both firms to apply the Compulsive strategy, i.e. buy the current technology immediately and upgrade at time T . This explains why for both firms the Compulsive strategy is optimal when the arrival date of the second technology lies somewhere in the interval $(T_{LeC,C}, \infty)$.

3.3.2 *Endogenous firm roles*

Since firms are identical there seems to be no reason why one of these firms should be given the leader role beforehand. This makes the outcome of the exogenous firm roles case hard to accept. However, here we use this outcome to generate the equilibria of the case where it is not known beforehand which

firm will invest first. The fact that firms are identical and rational also implies that it is reasonable to impose that firms behave in the same manner, since no reason of why they should act differently can be given. Therefore we restrict ourselves to symmetric strategies.

Denote the value of the leader and the follower as function of T , the arrival time of the second technology, by $L(T)$ and $F(T)$, respectively. When both firms apply the leader's strategy, their payoff equals $M(T)$. From Table 2 and equations (9) and (11) it follows that

$$L(T) = \begin{cases} e^{-rT} (P_{22} - C_l) & \text{if } T \in [0, T_{LeC, Le}], \\ P_{10} - C_e & \\ +e^{-rT} (P_{22} - P_{10} - C_u) & \text{if } T \in (T_{LeC, Le}, T_{LeC, C}], \\ P_{11} - C_e & \\ +e^{-rT} (P_{22} - P_{11} - C_u) & \text{if } T \in (T_{LeC, C}, \infty), \end{cases} \quad (17)$$

$$F(T) = \begin{cases} e^{-rT} (P_{22} - C_l) & \text{if } T \in [0, T_{LeC, C}], \\ P_{11} - C_e + e^{-rT} (P_{22} - P_{11} - C_u) & \text{if } T \in (T_{LeC, C}, \infty), \end{cases} \quad (18)$$

$$M(T) = \begin{cases} e^{-rT} (P_{22} - C_l) & \text{if } T \in [0, T_{LeC, Le}], \\ P_{11} - C_e + e^{-rT} (P_{22} - P_{11} - C_u) & \text{if } T \in (T_{LeC, Le}, \infty). \end{cases} \quad (19)$$

In Figure 1 the payoffs are plotted. This figure should be read as a feedback diagram.

Fig. 1. Payoffs in scenario 9 as function of T , the arrival time of the second technology, when the firm roles are endogenously determined.

Looking at Figure 1 we see that, apart from the interval $(T_{LeC,Le}, T_{LeC,C}]$, in the case of exogenous firm roles the firms choose for the same strategy, meaning that they invest at the same time in the same technology. Hence, there is no difference in the behavior of leader and follower so that we end up with the same equilibria as in the case of endogenous firm roles.

So, determining the equilibria on the interval $(T_{LeC,Le}, T_{LeC,C}]$ is the thing left to do. From Figure 1 we obtain that the firm that invests first gets the highest payoff, since $L(T) > F(T)$ for $T \in (T_{LeC,Le}, T_{LeC,C}]$. In case both firms invest at the same time, they both get $M(T)$.

Let us determine the optimal strategy of both firms if the second technology arrives at a point of time $T_0 \in (T_{LeC,Le}, T_{LeC,C}]$. It is attractive to be the first investor, but when both firms apply the strategy "invest right away at time

$t = 0$ ", with probability one they end up with a compulsive payoff associated with the $M(T_0)$ payoff in Figure 1. Therefore, we have to look for a mixed strategy. To do so, let us define $V(T)$ as the value of the firm in the game where the second technology arrives at time T , $p(T)$ is the probability that the firm invests at time $t = 0$ in that game, while $q(T)$ is the probability that the other firm invests at time $t = 0$. $p(T)$ and $q(T)$ are the control variables of both firms that need to be optimally determined. Then, while suppressing the time arguments, the value of the firm is given by

$$V = p(1 - q)L + (1 - p)qF + pqM + (1 - p)(1 - q)V. \quad (20)$$

This equation reflects that with probability $p(1 - q)$ the firm invests first so that it obtains the payoff L , with probability $(1 - p)q$ the other firm invests first so that the firm gets the payoff F , with probability pq the firms invest at the same time leading to a payoff being equal to M , while with probability $(1 - p)(1 - q)$ nothing has happened so that we are back in the original situation. Then the game is instantaneously replayed, and this process ends when one of the firms has invested. Rewriting (20) gives the following expression for the value of the firm

$$V = \frac{p(1 - q)L + (1 - p)qF + pqM}{1 - (1 - p)(1 - q)}. \quad (21)$$

To find the optimal value for p we differentiate (21) with respect to p and put this expression equal to zero. After imposing symmetrical strategies, i.e.

$p = q$, we derive that¹

$$p = q = \frac{L - F}{L - M}. \quad (22)$$

It is easily verified that the second order condition for optimality is satisfied. From Figure 1 we learn that $M \leq F < L$, so that we are sure that the probability p lies between zero and one. Fudenberg and Tirole (1985) show that the strategies formed by (22) are a perfect equilibrium, while the expected value of the firm equals F . The last result can be checked by substitution of (22) into (21). From (22) we further obtain that, given the difference $L - M$, the firm is more eager to invest when the difference between the payoffs associated with investing first and second, respectively, is large, which makes sense.

Of course, both firms do not want to invest at the same time, because it leaves them with the lowest possible payoff $M(T)$. From (21) and (22) it can be derived that the probability of occurrence of such a mistake is

$$\frac{p(T)}{2 - p(T)}, \quad (23)$$

which naturally increases with $p(T)$. Due to the fact that $p(T)$ is strictly positive, the probability of making a mistake is strictly greater than zero. In a similar way it can be obtained that the probability of a firm being the first investor equals

$$\frac{1 - p(T)}{2 - p(T)}. \quad (24)$$

Due to symmetry this is also the probability of ending up being follower. Since

¹ A similar value for p was found in Fudenberg and Tirole (1985) and Simon (1987).

The latter paper applied a timing game to solve a so-called gunfighter problem.

the probability of simultaneous adoption increases with $p(T)$, it follows that the probability of being the first investor decreases with $p(T)$, which is at first sight a strange result. But it is not that strange, because if one firm increases its probability to invest, the other firm does the same. This results in a higher probability of making a mistake, which leaves less room for the equal probabilities of being the first investor.

Substitution of the Compulsive and the Leapfrog payoffs, which are given by (9) and (11), respectively, into (22) results in the following expression for $p(T)$ for $T \in (T_{LeC,Le}, T_{LeC,C}]$:

$$p(T) = \frac{P_{10} - C_e + e^{-rT}(-P_{10} + C_l - C_u)}{(P_{10} - P_{11})(1 - e^{-rT})}. \quad (25)$$

To compare different situations concerning the arrival time of the new technology, differentiate (25) with respect to T , and eventually obtain $\frac{\partial p(T)}{\partial T} > 0$. The implication is that if we consider two games, one where the second technology arrives at time T_1 and the other one where the second technology arrives at time T_2 , where T_1 and T_2 are related such that $T_{LeC,Le} < T_1 < T_2 < T_{LeC,C}$, then the probability of making the simultaneous adoption mistake in the game where the second technology arrives at time T_1 is smaller than in the game where the second technology arrives at time T_2 . To understand this result, consider Figure 1: (1) the difference between the payoff from being the leader and the payoff of the follower increases, so that the relative profitability of winning the investment race rises, and (2) the difference between the follower payoff and the payoff that results from simultaneous investment decreases so that firms more and more prefer to win the investment race rather than to make the joint adoption mistake.

Furthermore from (25) and the fact that the probability of the joint adoption mistake increases with $p(T)$, the following ceteris paribus results can be derived: the joint adoption mistake is more likely to occur for lower values of C_e or C_u , and for higher values of P_{10} , P_{11} , C_l , or r .

3.4 *Equilibrium strategies if learning is negligible and the new technology is expensive*

In this subsection scenario 2 of Table 1 is analyzed. From that table we obtain that in this scenario it holds that

$$P_{21} - C_u - P_{11} \leq 0, \tag{26}$$

$$P_{21} - C_l > P_{11} - C_d, \tag{27}$$

$$P_{22} - C_l \leq P_{12} - C_d. \tag{28}$$

In Table 1 we see that the cost of upgrading is large in this scenario. This means that, even in case the firm is already active on this market by producing with the current technology, the learning effect is that low that it is still costly to buy and implement the new technology. From (26) it can be concluded that, given that the other firm produces with the current technology, it is not profitable to upgrade so that the Compulsive strategy will not be optimal. The same holds when the other firm produces with the new technology, because then exchanging the current technology for the new one is even less profitable.

Taking into account the payoffs of the Leapfrog and the Laggard strategy (cf. (11) and (12)), we can derive from (27) and (28) that the Leapfrog strategy is more profitable than the Laggard strategy if the other firm produces with the current technology, while it is the other way round when the other firm produces with the new technology. Since we already concluded that upgrading

is never optimal, it follows that in this scenario demand on the output market is too small for two firms producing with the more expensive new technology.

3.4.1 Exogenous firm roles

Again we first consider the case where one firm is the leader and the other firm the follower. The equilibrium strategies are presented in Table 3. Time $T_{B,Le}$ is defined such that at that time the payoffs of Buy and Hold and Leapfrog are equal². With equations (10), (11), and (12) we derive that

$$T_{LaB,Le} = \frac{1}{r} \log \left(\frac{P_{10} - C_d}{P_{10} - C_e} \right), \quad (29)$$

$$T_{B,Le} = \frac{1}{r} \log \left(\frac{P_{21} - C_l - P_{12} + P_{10}}{P_{10} - C_e} \right), \quad (30)$$

$$T_{LeB,B} = \frac{1}{r} \log \left(\frac{P_{21} - C_l}{P_{11} - C_e} \right). \quad (31)$$

From equations (5) and (27) it follows that

$$0 < T_{LaB,Le} < T_{B,Le}. \quad (32)$$

Further, we derived that

$$T_{B,Le} < T_{LeB,B}, \quad (33)$$

² The reason for choosing the notation $T_{B,Le}$ here is that any other notation does not fit with our notation introduced earlier. The reason is that the other firm does not play a fixed strategy. At $T_{B,Le}$ it holds that payoffs are equal in case the firm plays Leapfrog while the other plays Buy and Hold, and when the firm plays Buy and Hold and the other firm Leapfrogs.

if and only if the following equation holds

$$\frac{P_{11} - C_e}{P_{21} - C_l} < \frac{P_{10} - P_{11}}{P_{10} - P_{12}}. \quad (34)$$

The economic interpretation of this inequality becomes clear later in this section when we consider the case where $T_{LaB,Le} < T < T_{LeB,B}$.

Table 3

Equilibrium strategies in scenario 2 as function of T , the arrival time of the second technology, when the firm roles are assigned exogenously.

T interval	Leader	Follower
$[0, T_{LaB,Le}]$	Leapfrog	Laggard
$(T_{LaB,Le}, T_{B,Le}]$	Leapfrog	Laggard
$(T_{B,Le}, T_{LeB,B}]$	Buy and Hold	Leapfrog
$(T_{LeB,B}, \infty)$	Buy and Hold	Buy and Hold

Since in this scenario the cost of upgrading is too high for a replacement of the current technology by the new technology to be profitable, the Compulsive strategy will never be applied. On the interval $[0, T_{LaB,Le}]$ the arrival time of the new technology is that close that for both firms it is not optimal to invest immediately. One firm will adopt the new technology as soon as it arrives. The other firm waits until time T to acquire the current technology, since from this time onwards the acquisition cost of the current technology is lower (cf. (5)). Note that, given the fact that one firm plays Leapfrog, expression (28) implies that for the other firm the Laggard strategy is most profitable. The reason is that the demand for output is too low for the two firms to produce both with the new expensive technology.

On the time interval $(T_{LaB,Le}, T_{LeB,B}]$ T is a bit further away, which implies that, given that the leader follows a Buy and Hold strategy, the follower will prefer Leapfrog. The earnings that arise from producing with the current technology on the time interval before time T are not large enough for the follower to justify the immediate acquisition of the current technology. Note that, given that the leader applies a Buy and Hold strategy, for the follower the Leapfrog payoff is higher than the Laggard payoff (cf. (27)). The fact that the follower plays Leapfrog implies that until the new technology arrives the leader is the only producer on the market. This monopoly position increases revenue before time T , compared to the situation where both firms apply Buy and Hold. On the other hand, after time T the Buy and Hold strategy will generate less revenue, because then the other firm captures a larger share of the market since it produces more efficiently with the new technology. Hence, two opposite effects are working on the Buy and Hold payoff once the follower switches to Leapfrog. In Table 3 and in Figure 2 (presented later on) the monopoly effect is assumed to dominate, which explains the downward jump of the Buy and Hold (leader) payoff right at $T_{LeB,B}$. But the reverse can also be true. After straightforward calculations it can be concluded that the jump is indeed downward in case (34) holds. We see that in any case at the beginning of the interval $(T_{LaB,Le}, T_{LeB,B}]$ the Buy and Hold payoff is less than the Leapfrog payoff so that the first investor earns less than the follower. Recall that $T_{B,Le}$ is the point of time at which the payoffs of Buy and Hold and Leapfrog are equal (see Figure 2, note that $T_{B,Le}$ does not exist in case (34) does not hold). Then, on the interval $(T_{LaB,Le}, T_{B,Le}]$ (or $(T_{LaB,Le}, T_{LeB,B}]$ if (34) does not hold) the leader refrains from investment and applies a Leapfrog strategy. The follower is not allowed to invest earlier than the leader, so he has to choose between Leapfrog and Laggard. The follower's choice will be Laggard, since this leaves

him with the highest payoff (cf. (28)). In case equation (34) holds we have to consider the interval $(T_{B,Le}, T_{LeB,B}]$. For the leader it is optimal to apply the Buy and Hold strategy and the follower responds by using the Leapfrog strategy.

When the point of time T at which the new technology appears on the market is relatively far away, it is optimal for both firms to start producing with the current technology. Therefore, both firms apply the Buy and Hold strategy if the arrival time of the second technology belongs to the interval $(T_{LeB,B}, \infty)$.

3.4.2 Endogenous firm roles

Here it is not specified beforehand which firm will be the first investor, so that both firms can be leader or follower. As said before this seems the proper way to analyze a duopoly with identical firms. Since firms are identical, we restrict ourselves to symmetric strategies. From Table 3 and equations (10), (11) and (12) it follows that (with one modification which will be explained right after (37))

$$L(T) = \begin{cases} e^{-rT} (P_{21} - C_l) & \text{if } T \in [0, T_{LaB,Le}], \\ P_{10} - C_e + e^{-rT} (P_{12} - P_{10}) & \text{if } T \in (T_{LaB,Le}, T_{LeB,B}], \\ P_{11} - C_e & \text{if } T \in (T_{LeB,B}, \infty), \end{cases} \quad (35)$$

$$F(T) = \begin{cases} e^{-rT} (P_{12} - C_d) & \text{if } T \in [0, T_{LaB,Le}], \\ e^{-rT} (P_{21} - C_l) & \text{if } T \in (T_{LaB,Le}, T_{LeB,B}], \\ P_{11} - C_e & \text{if } T \in (T_{LeB,B}, \infty), \end{cases} \quad (36)$$

$$M(T) = \begin{cases} e^{-rT} (P_{22} - C_l) & \text{if } T \in [0, T_{LaB,Le}] , \\ P_{11} - C_e & \text{if } T \in (T_{LaB,Le}, \infty) . \end{cases} \quad (37)$$

Note that now the leader plays the Buy and Hold strategy in the games where the second technology arrives somewhere in the interval $(T_{LaB,Le}, T_{B,Le}]$, because a firm can only become leader by investing as first. The expected value of waiting equals the Laggard payoff which is less than the payoff resulting from the Buy and Hold strategy. Therefore one firm will invest in the current technology. In Figure 2 the payoffs are plotted.

Fig. 2. Payoffs in scenario 2 as function of T , the arrival time of the second technology, when the firm roles are endogenously determined.

From Figure 2 it is obtained that only for the interval $(T_{LeB,B}, \infty)$ the strategies of both firms are identical, implying that the equilibrium for games where $T \in (T_{LeB,B}, \infty)$ is the same for the exogenous and the endogenous firm roles

case.

To solve the whole problem we divide the remaining time interval into three subintervals and treat the three cases in order of timing. For the games with arrival date of the second technology in the interval $[0, T_{LaB,Le}]$ the optimal strategies are Leapfrog and Laggard, i.e. no investment takes place before time T . The firms wait until the arrival of the new technology after which the following game will be played. Without loss of generality we set $T = 0$ for the moment. Since the highest payoff can be obtained by a Leapfrog strategy (provided that the other firm plays Laggard), it is attractive to be the first investor in the new technology. However, when both firms apply the strategy invest right away in the new technology at time T , with probability one they end up with the payoff $M(0)$, which is less than what could be obtained by investing in the current technology, $F(0)$. Hence, it seems that a mixed strategy is called for in this preemption game. It is important to realize that we only need to take into account positive probabilities for investment in the new technology. The reason for considering an investment in the current technology would be that the firm does not want to end up in a situation where they both have invested in the new technology. However, the probability of reaching this situation only depends on the probability of investing in the new technology. Hence, investing in the current technology will only occur after an investment in the new technology by the other firm. In the appendix a mathematical proof is given. The equilibrium strategy is given by the function (see the previous subsection for details)

$$p(0) = q(0) = \frac{L(0) - F(0)}{L(0) - M(0)} = \frac{P_{21} - C_l - (P_{12} - C_d)}{P_{21} - P_{22}}. \quad (38)$$

The worst thing that can happen is that both firms invest in the new technology at the same time, leaving them with a low payoff $M(0) = P_{22} - C_l$. Analogous to the previous subsection, the probability that this happens is given by equation (23). The expected value of the firm resulting from the optimal mixed strategy described by equation (38) equals the payoff associated with the Laggard strategy (cf. Fudenberg and Tirole (1985) where it is proved that the expected payoff in a preemption game equals the follower payoff). Therefore, the value of the firm is also equal to the Laggard payoff if $T \in (0, T_{LaB,Le}]$, and from equation (36) it can be concluded that this value decreases in T .

It turns out to be convenient to divide the interval $(T_{LaB,Le}, T_{LeB,B}]$ into two parts: $(T_{LaB,Le}, T_{B,Le}]$ and $(T_{B,Le}, T_{LeB,B}]$. Note that $T_{B,Le} \in (T_{LaB,Le}, T_{LeB,B}]$ only in case (34) holds. If (34) does not hold, then during the whole interval $(T_{LaB,Le}, T_{LeB,B}]$ the Buy and Hold payoff falls below the Leapfrog payoff. Let us first consider $(T_{LaB,Le}, T_{B,Le}]$. Here the new technology will become available soon, which implies that the Leapfrog strategy is more profitable than Buy and Hold. Therefore, the payoff of the first investor is lower than the payoff of the follower, so that a second mover advantage arises. Hence, each firm prefers to be the follower, but if it has to be the first investor, it prefers to invest earlier rather than later, because the Buy and Hold payoff falls over time. Thus the game is an attrition game. A possible strategy would be to refrain from investment during this interval, waiting for the other firm to invest. Since with identical firms there is no reason to believe why the other firm would act differently, nothing happens on this interval. This implies that both firms end up with playing the game at time T , which is described above. The expected value of the firm obtained from playing this game equals the

Laggard payoff, and this payoff lies below the payoffs of both Buy and Hold and Leapfrog. In Hendricks et al. (1988) the subgame perfect equilibrium is given for an attrition game with identical players, as it occurs here. Define $G(t)$ as the probability distribution on $[0, T - T_{LaB,Le}]$ ³. In fact, $G(t)$ equals the probability that the firm has invested in the current technology at or before t . According to Hendricks et al. (1988) the mixed investment strategy that lead to a subgame perfect equilibrium is described by

$$G(t) = 1 - \exp \left(- \int_{v=0}^t \frac{dL(T-v)}{F(T-v) - L(T-v)} dv \right), \quad (39)$$

where $t \in [0, T - T_{LaB,Le}]$. Hendricks et al. (1988) show that any mass point can be ruled out implying that the probability that a firm moves exactly at a particular point of time equals zero⁴. Consequently, the probability that the two firms move exactly at the same time is also zero, which explains why M (thus the payoff in case both firms play Buy and Hold) does not affect the mixed investment strategy in (39).

From (39) it is easily obtained that for $T \in (T_{LaB,Le}, T_{B,Le}]$ it holds that

$$\lim_{t \uparrow T - T_{LaB,Le}} G(t) < 1. \quad (40)$$

³ Note that the war of attrition lasts until $T - T_{LaB,Le}$. If no investments occur until this point of time we are in the same situation as when $T \in [0, T_{LaB,Le}]$. We thank one of the anonymous referees for pointing this out to us.

⁴ The implication is that, in the notation of previously described games $p(T)$ equals zero for all relevant T .

Note that, if this were not the case, the symmetric investment strategy is not a Nash equilibrium. The reason is that when

$$\lim_{t \uparrow T - T_{LaB,Le}} G(t) = 1, \quad (41)$$

then one of the firms could do better by refraining from investment during the interval $[0, T - T_{LaB,Le})$, since this firm knows for sure that its competitor will have invested at some time before $T - T_{LaB,Le}$.

Substitution of the relevant formulas for the payoffs into (39) leads to

$$G(t) = 1 - \exp \left(- \int_{v=0}^t \frac{r e^{-r(T-v)} (P_{12} - P_{10})}{C_e - P_{10} + e^{-r(T-v)} (P_{21} - C_l - P_{12} + P_{10})} dv \right). \quad (42)$$

The firm's willingness to invest increases with the relative performance of Buy and Hold compared to Leapfrog. In this light the following ceteris paribus results, that are derived from (42), are easy to understand: G goes up with r , T , P_{10} , C_l , and goes down with C_e and P_{21} .

Finally, we analyze games for which $T \in (T_{B,Le}, T_{LeB,B}]$. Solving this case leads to analogous results as in the previous subsection. In the symmetric equilibrium both firms use the following strategy

$$p(T) = \frac{L(T) - F(T)}{L(T) - M(T)}, \quad (43)$$

where $T \in (T_{B,Le}, T_{LeB,B}]$. Right at the start of the game one of the firms will invest in the current technology. The other firm refrains from investment until time T at which it will adopt the new technology. The probability that both firms invest in the current technology exactly at the same time is again given by equation (23). It is unclear how the arrival time of the second technology influences $p(T)$, since two opposite effects are working here: (1) the difference

in payoffs between leading and following decreases with the arrival time of the second technology, which has a negative effect on $p(T)$, and (2) the difference in payoffs between leading and joint adoption decreases as the arrival time of the second technology increases, which has a positive effect on $p(T)$.

4 Conclusions

This paper treats the technology adoption decision of the firm in a duopoly framework. One of the main difficulties concerning the technology investment decision in practice is that in the future better technologies than now available will be invented. The model in this paper tries to capture this important aspect by considering two technologies: one which is available immediately, and the other one which is more efficient and becomes available at a known point of time in the future. By doing so, work of Reinganum (1981), Fudenberg and Tirole (1985), Hendricks (1992), Stenbacka and Tombak (1994), Götz (2000), and Hoppe (2000) who consider only one technology, is extended. Moreover, learning is incorporated in the way that adoption of the current technology makes it less costly to adopt and implement the new technology.

We focussed on the scenario where for every technology investment it holds that the discounted future profit stream exceeds the immediate expenditure. In case the arrival date of the new technology lies far in the future, the future presence of a new technology does not prevent that investing in the current technology is still optimal. When this date comes nearer it is not optimal anymore for both firms to invest in the current technology right away. Hence, one of the firms has to refrain from investment, which implies that by investing in the current technology the other firm obtains monopoly profits until the

arrival date of the new technology. To capture these monopoly profits a firm must try to invest earlier than its competitor. In this way the preemption equilibria arise that we already know from, e.g., Fudenberg and Tirole (1985), but here no rent equalization occurs as was the case in that paper. A consequence of the absence of rent equalization is that a positive probability arises that both firms invest at the same time, leaving them with a very low payoff.

Another new element in our paper is the occurrence of second mover advantages in technology adoption problems. This happens in scenarios where technology upgrading is not optimal so that firms have to make a choice between investing in the current technology right away and keep on producing with it, or waiting with investment until the new technology arrives. The advantage of the immediate investor is that monopoly profits are gained until the arrival of the new technology, while the investor in the new technology has the advantage of producing with a better technology once it is available. A second mover advantage arises when the advantage of producing with the new technology in the future leads to a higher payoff than the current temporary monopoly profits.

An immediate extension of the model in this paper is to add uncertainty. A distinction can be made between uncertainty concerning the arrival date of new technologies or uncertainty concerning the efficiency of new technologies. For instance, in case of micro-chips the technical parameters and specifications of future designs are known beforehand, but the arrival date is uncertain since the appearance of the technology depends on research and development and the market factors affecting the introduction of the product (see Huisman and Kort (2001) and Nair (1995)).

Another interesting topic of future research is to incorporate asymmetric information in the sense that a firm does not know how profitable a particular innovation is for its opponent. However, as time passes the firm learns about the other firm's profit function from the observed investment behavior of the other firm. Based on this observation it will update its conjecture about the other firm's profit function (see Lambrecht and Perraudin (1999)).

A Proof

Define p_i (q_i) to be the probability that firm 1(2) invests in technology i ($i = 1, 2$). Let us consider the investment decision of firm 1. Concerning the payoffs we introduce the following notation: L is the value of firm 1 if firm 1 invests in the new technology (= technology 2) and firm 2 invests in the current technology (=technology 1), F is the value of firm 1 if firm 1 invests in the current technology, and firm 2 invests in the new technology. M_1 is the value of firm 1 if both firms invest in the current technology, and M_2 is the value of firm 1 if both firms invest in the new technology. It is easily verified that under the conditions given in Section 3.4 it holds that

$$L > M_1 > F > M_2.$$

The value of firm 1 under the strategies (p_1, p_2) and (q_1, q_2) equals

$$\begin{aligned} V(p_1, p_2, q_1, q_2) = & \frac{p_2 q_2 M_2 + p_2 q_1 L + p_2 (1 - q_1 - q_2) L}{1 - (1 - p_1 - p_2) (1 - q_1 - q_2)} \\ & + \frac{p_1 q_2 F + p_1 q_1 M_1 + p_1 (1 - q_1 - q_2) F}{1 - (1 - p_1 - p_2) (1 - q_1 - q_2)} \\ & + \frac{(1 - p_1 - p_2) q_2 F + (1 - p_1 - p_2) q_1 L}{1 - (1 - p_1 - p_2) (1 - q_1 - q_2)}. \end{aligned}$$

After deriving the first order conditions for optimality and considering symmetric strategies it turns out that there is a unique symmetric equilibrium given by:

$$\begin{aligned} p_1 = q_1 &= 0, \\ p_2 = q_2 &= \frac{L - F}{L - M_2}. \end{aligned}$$

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