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Strategic Technology Switching under Risk Aversion and Uncertainty

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Abstract

Firms devising green investment strategies within a deregulated environment must take into account not only economic and technological uncertainty, but also strategic interactions due to competition. Also, further complicating green investment decisions is the fact that firms are likely to exhibit risk aversion, since alternative energy technologies entail risk that cannot be diversified. Therefore, we develop a utility-based, real options framework for pre-emptive and non-pre-emptive competition in order to analyse how economic and technological uncertainty interact with risk aversion to impact the adoption of an existing technology in the light of uncertainty over the arrival of an improved version. We confirm that greater risk aversion delays investment and show that technological uncertainty accelerates the follower's entry, delays the entry of the pre-emptive leader, and, intriguingly, does not affect the non-pre-emptive leader's investment decision. Also, we show how the relative loss in the leader's value due to the follower's entry is affected by economic and technological uncertainty as well as risk aversion, and how the risk of pre-emption under increasing economic uncertainty raises the value of direct investment in the new technology relative to stepwise investment.

Keywords: Competition, sequential investment, technological uncertainty, risk aversion, real options

1. Introduction

In the light of pressing climate change concerns, stringent environmental regulations and the growing demand for energy-efficient technologies have incentivised private firms to switch to green energy technologies and intensify research and development (R&D) activities. However, within a deregulated environment, such capital intensive decisions entail considerable risk, since their efficiency is subject to market forces. Indeed, firms investing in deregulated domains must deal with the likely presence of a rival and the loss in market share it entails, while being exposed to an increasingly volatile economic environment and a greater rate of technological innovation (Lieberman & Montgomery, 1988; Zachary *et al.*, 2015). For example, General Electric (GE), a

company whose traditional business is making equipment for gas-fired power plants, now faces a weaker demand due to the shift towards renewable energy (RE). Therefore, to rebuild its earnings, GE is now not only expanding in the offshore wind market, but is also engaging with R&D of new wind turbines in order to capture market share over its rivals (Financial Times, 2018). Similarly, in the UK, Scottish Power has become the first among the big six major UK energy firms to completely drop fossil fuels in favour of wind power (Independent, 2018).

Apart from RE power plants, other areas where green energy technologies play a critical role in fostering strategic interactions include energy storage and transportation. For example, in the area of electric vehicles, technology pioneer Tesla Motors announced in 2014 that it would make several hundreds of approved patents available to competitors at no cost (The Wall Street Journal, 2014). This is expected to accelerate innovation, increase the market of electric vehicles relative to those based on fossil fuel and promote a more competitive environment, whereby firms may take advantage of other firms' patented technologies. Indeed, some experts claim that "open innovation" might be one of the reasons behind fewer patents being filed in 2014 (Financial Times, 2015). Also, in the area of energy storage, the announcement that Tesla won a tender for the installation of the worlds biggest battery storage system in Australia, motivated a joint venture between Siemens and AES focusing exclusively on battery storage systems (Financial Tribune, 2017). These examples emphasise the relevance of positive spillovers within the energy sector and the increasing likelihood that these may give rise to attrition (Billette de Villemeur *et al.*, 2019).

Additionally, alternative energy technologies typically entail risk that cannot be diversified, and, therefore, firms are likely to exhibit risk aversion. Indeed, the underlying commodities of green energy projects and within the R&D sector of the economy are typically not freely traded, thus preventing risk-neutral valuation as the assumption of hedging via spanning assets breaks down. Therefore, in this article, we aim to address the following open research questions: **i.** How do sequential opportunities to adopt improved technology versions impact the optimal technology adoption strategy under duopolistic competition and risk aversion? **ii.** Is the impact of technological uncertainty on the optimal investment policy under duopolistic competition significantly different compared to the benchmark case of monopoly? **iii.** How do first-mover advantages interact with risk aversion to impact the optimal technology adoption strategy and the associated investment rule? These are critical open research questions that are pertinent to sectors of crucial importance to society and economy, as they underlie complex structural transformations, such as the transition to low-carbon energy systems.

In this paper, we consider a stylised duopolistic competition, where two identical firms compete in the sequential adoption of green energy technologies facing price and technological

uncertainty. Within this context, we analyse the case of non-pre-emptive (proprietary) and pre-emptive (non-proprietary) competition. For example, in the former case, a firm may have its own R&D program, and, thus, proprietary rights over the innovations it develops, whereas in the latter case the innovation process is exogenous to both firms. Additionally, non-pre-emptive competition may also arise when a particular technology receives governmental support, which gives it a competitive advantage over less favoured ones (The Guardian, 2018), while vertical integration may also increase a firm's strategic advantage and reduce the risk of pre-emption (Lazzarini, 2015). Hence, the contribution of our work is threefold. First, we develop a utility-based framework in order to analyse how price and technological uncertainty interact with risk aversion to impact sequential investment decisions under duopolistic competition. Second, we derive analytical results, where possible, for the optimal technology adoption strategy and the associated investment rule of the leader and the follower. Third, we provide managerial insights for sequential investment under rivalry and uncertainty based on analytical and numerical results.

We proceed by discussing some related work in Section 2 and introduce assumptions and notation in Section 3. Section 4 presents the benchmark case of monopoly, which is then extended in Section 5 by considering two firms that adopt each technology that becomes available (compulsive strategy) under non-pre-emptive (Sections 5.1) and pre-emptive duopoly (Section 5.2). In Section 6, we also consider how pre-emption of the existing technology may increase a second-mover's incentive to adopt the new technology directly (leapfrog strategy). Section 7 presents numerical examples for each case, while Section 8 concludes the article and offers directions for further research.

2. Related Work

Although traditional real options models address the problem of optimal investment under uncertainty without considering strategic interactions (McDonald & Siegel, 1985 and 1986; He & Pindyck, 1992; Malchow-Møller & Thorsen, 2005), the game-theoretic real options literature has increased over the last years considerably. Nevertheless, models that analyse the impact of strategic interactions on investment decisions typically ignore either the sequential nature of investment opportunities and the different strategies they entail (Pawlina & Kort, 2006; Siddiqui & Takashima, 2012) or attitudes towards risk (Huisman & Kort, 2015).

Examples of early work in the area of competition include Spatt & Sterbenz (1985), who analyse how the degree of rivalry impacts the learning process and the decision to invest. They find that increasing the number of players hastens investment and that the investment decision resembles the standard net present value (NPV) rule. Also, via a deterministic model

of duopolistic competition, Fudenberg & Tirole (1985) show that a high first-mover advantage results in a pre-emption equilibrium with dispersed adoption timings by increasing a firm's incentive to pre-empt investment by its rival. Extensions of this deterministic framework are presented in Smets (1993), who develops the first continuous-time model of strategic real options allowing for product market competition and stochastic demand, and in Huisman & Kort (1999), who allow for economic uncertainty. The latter find that, in deterministic models, a high first-mover advantage leads to a pre-emption equilibrium, yet, in stochastic models, higher uncertainty may turn a pre-emption into a simultaneous investment equilibrium.

Other examples of traditional game-theoretic real options models include Murto (2004), who analyses the decision to exit a declining market under duopolistic competition. He shows that a unique equilibrium exists when uncertainty is low or the asymmetry between firms is sufficiently high, and that a firm with a cost disadvantage is likely to exit earlier because the rival can credibly commit to stay in the market longer. By developing a two-factor, non-pre-emptive duopoly model, Paxson & Pinto (2005) find that the leader invests in the same threshold as the monopolist, and that increasing the correlation between profits per unit and quantity of units produced raises their aggregate volatility, and, in turn, the investment trigger of both the leader and the follower. Also, a framework for asymmetric competition under uncertainty is presented in Takashima *et al.* (2008), who show how mothballing options facilitate investment and offer a competitive advantage to a thermal over a nuclear power plant.

A generalisation of the pre-emptive duopoly model is presented in Bouis *et al.* (2009), who develop a $n-$firm oligopoly model and show how greater uncertainty has an accordion effect on the firms' investment decision. In the special case involving three firms, they find that if the entry of the third firm is delayed, then the second firm has an incentive to invest earlier so that it can enjoy the duopoly market structure for a longer time. This increases the incentive for the first firm to delay investment, as it faces a shorter period in which it can enjoy monopoly profits. Interestingly, Mason & Weeds (2010) allow for uncertain returns in a dynamic duopoly model and find that the investment trigger of a leader under pre-emptive competition is not only bounded above as uncertainty increases, but also that greater uncertainty may in fact accelerate investment. In the same line of work, Armada *et al.* (2011) assume that competitors arrive according to a Poisson process and Thijssen *et al.* (2012) present an analytical model that deals with the coordination problem in pre-emptive competition. Also, Lavrutich *et al.* (2017) develop a duopolistic pre-emption model in which they show how the presence of a *hidden* competitor, who can appear suddenly and capture part of the market, increases a follower's investment incentive in order to avoid being squeezed out of the market. More recently, a model of imperfect competition under uncertainty is presented in Billette de Villemeur *et al.* (2019),

who study the exercise of strategic growth options by two initially identical firms. The novelty of this work is to characterize the impact of the relative costs of innovation and imitation on the investment strategies of firms and to explore the regulator's choice of optimal intellectual property rights levels. Like in our paper, they analyse how strategic interactions may arise when innovation has positive spillovers for an imitator (follower), however, risk preferences and sequential decision making are not considered.

Although the aforementioned literature offers crucial insights on strategic investment under uncertainty, it is developed under the assumption of risk neutrality. However, the rapid growth of the R&D-based sector of the economy and the associated market incompleteness implies that insights reflecting a risk-neutral setting may not carry over to a risk-averse paradigm. For example, Alvarez & Stenbacka (2004) develop a utility-based framework for optimal regime switching and show that if the decision-maker is risk seeking, then increasing price uncertainty does not necessarily decelerate investment. A similar result is indicated in Henderson (2007), who shows that idiosyncratic risk raises the incentive to accelerate investment and lock in the investment payoff. By contrast, Hugonnier & Morellec (2013) determine the analytical expression for the expected utility of a perpetual stream of cash flows that follows a geometric Brownian motion, and find that greater risk aversion lowers the expected utility of a project and reduces the probability of investment. However, Chronopoulos *et al.* (2011) show that operational flexibility mitigates the impact of risk aversion by increasing the expected utility of a project. Also, Leippold & Stromberg (2017) extend Huisman & Kort (2004) by allowing for market incompleteness and find that undiversifiable risk may accelerate technology adoption.

Further complicating the ambiguous impact of risk aversion on optimal investment under uncertainty is the random arrival of innovations that motivate different technology adoption strategies. Grenadier & Weiss (1997) model sequential investment in technological innovations assuming that a risk-neutral firm may either adopt each technology that becomes available (compulsive), or wait for a new technology to arrive before adopting either the new (leapfrog) or the old technology (laggard), or purchase only an early innovation (buy and hold). They find that a firm may adopt an available technology despite the likely arrival of valuable innovations, whereas decisions on technology adoption are path dependent. Also, Farzin *et al.* (1998) investigate the impact of technological uncertainty on the optimal timing of technology adoption under risk neutrality, yet ignore price uncertainty. The framework of Farzin *et al.* (1998) is revisited by Doraszelski (2001), who shows that, compared to the NPV approach, a firm will defer technology adoption when it takes the option value of waiting into account. Weeds (1999) analyses the decision to invest in a research project and finds that increasing technological uncertainty postpones investment and accelerates abandonment when the profitability of the

project declines. Additionally, Chronopoulos & Siddiqui (2015) find that uncertainty over the arrival of innovations accelerates technology adoption, and Lukas *et al.* (2017) show how optimal capacity is related to a product's life cycle when technological lifetime is uncertain.

Game-theoretic, real options models that account for technological uncertainty include Weeds (2002), who analyses strategic investment in competing research projects and identifies the existence of non-cooperative and cooperative games. The former involves a pre-emptive competition, where firms invest sequentially, and a symmetric outcome in which investment is more delayed than in the case of monopoly. The latter involves sequential investment, yet compared to the non-cooperative game, the investment triggers are higher. Also, compared to the optimal cooperative investment pattern, investment is found to be more delayed when firms act non-cooperatively, as each refrains from investing in fear of starting a patent race. Miltersen & Schwartz (2004) analyse how competition in product development impacts investment in R&D, and find that competition not only increases production and reduces prices, but also shortens the development stage and raises the probability of a successful outcome. Huisman & Kort (2004) study a dynamic duopoly in which firms compete in the adoption of new technologies and find that the likely arrival of a new technology could turn a pre-emption game into one where the second mover gets the highest payoff. Alternatively, a follower may benefit from knowledge spillover as in Femminis & Martini (2011), who find that even for low levels of spillover, the follower invests as soon as she attains the cost benefit.

More pertinent to our work is the non-pre-emptive duopoly model of Siddiqui & Takashima (2012), who analyse the extent to which sequential decision making offsets the impact of competition under risk neutrality. They find that a duopoly firm's value relative to a monopolist's decreases with uncertainty as long as the loss in market share is high, and show that this loss in value decreases if a firm adopts a sequential investment approach. Similarly, we consider a spillover-knowledge duopoly in which firms compete in the sequential adoption of two technologies. However, unlike Siddiqui & Takashima (2012), we also consider the optimal investment strategy of each firm under pre-emptive competition and allow for technological uncertainty, in terms of the arrival of a new, more improved technology version. Additionally, we relax the assumption of risk neutrality, and, thus, we analyse how risk aversion interacts with price and technological uncertainty to affect the technology adoption strategy of each firm.

With respect to the existing technology, we show that the likely arrival of an innovation has a non-monotonic impact on the entry threshold of the follower, delays the entry of the pre-emptive leader, but, intriguingly, does not affect the non-pre-emptive leader's entry threshold. Additionally, we show how the non-pre-emptive leader's investment threshold for the second technology is lower than that of the monopolist. Furthermore, we find that the embedded option

to adopt an improved technology version decreases the leader's relative loss in value due to the presence of a rival. Also, increasing price uncertainty and risk aversion raise the incentive to delay investment, yet have an ambiguous impact on the relative loss in the value of the leader. Finally, we find that pre-emption of the first technology by one firm could make direct adoption of the second one more attractive for the other relative to stepwise investment. Hence, like Kort *et al.* (2010), we show that the value of stepwise investment decreases with greater uncertainty, even though we do not assume that stepwise investment requires an investment cost premium.

3. Assumptions and Notation

We assume that the firms compete in the sequential adoption of two technologies, denoted by $i = 1, 2$, of which the first is available whereas the second has not arrived yet. Technological uncertainty is introduced by assuming that the time of arrival, ν, of the second, improved technology version follows an exponential distribution with parameter λ, i.e. $\nu \sim \exp(\lambda)$. Both technologies have an infinite lifetime and no operating cost, while the investment cost is I_i ($I_1 \leq I_2$). Also, we assume that the electricity price process $\{E_t, t \geq 0\}$ follows a geometric Brownian motion (GBM), as in (1), where μ is the annual growth rate, σ is the annual volatility and dZ_t is the increment of the standard Brownian motion. The subjective discount rate is denoted by $\rho > \mu$ [1], while $r > 0$ is the risk-free rate. While a different stochastic process may be applied, a GBM is often utilised in the real options literature due to the analytical tractability it provides. Additionally, with respect to the energy sector, Pindyck (1999) surveys 127 years of data and finds that although energy prices are mean reverting, their rate of mean reversion is low enough that assuming GBM for investment analysis is unlikely to lead to large errors.

$$dE_t = \mu E_t dt + \sigma E_t dZ_t, \quad E_0 \equiv E > 0 \tag{1}$$

Note that in the case of pre-emptive competition the innovation process is assumed to be exogenous to both firms, which is reflected in the independence between price and technological uncertainty. For ease of exposition we maintain the same assumption under non-pre-emptive competition. The dependence between ν and $\{E_t, t \geq 0\}$ and its implications for duopolistic competition is outside the scope of the paper and is left for future work.

Each firm's risk preferences are described by a hyperbolic absolute risk aversion (HARA) utility function, as indicated in (2), where γ is the risk aversion parameter. Risk aversion occurs for $\gamma < 1$ and a lower γ implies greater risk aversion. However, note that this framework can

[1] The assumption of risk neutrality is common within the context of corporate finance, yet relies on market completeness. Hence, in the area of green investment, this assumption may not be particularly relevant due to lack of hedging instruments. In turn, this motivates the use of an exogenously defined (subjective) discount rate.

accommodate a wide range of utility functions, such as constant absolute risk aversion (CARA) and constant relative risk aversion (CRRA) utility functions. The specific choice of utility function serves the purpose of enabling comparisons with earlier literature (Henderson, 2007; Hugonnier & Morellec, 2013; Chronopoulos *et al.*, 2014 and Chronopoulos & Lumbreras, 2017).

$$U(E) \quad = \quad \frac{E^{\gamma}}{\gamma}, \quad \gamma > 0 \tag{2}$$

We let $b = m, \ell, f$ denote the monopolist, the leader and the follower, respectively, where the leader is the first firm to enter the market under duopolistic competition, and, if $b = \ell$, then $a = p, n$ denotes the non-pre-emptive (**p**roprietary) and pre-emptive (**n**on-proprietary) leader, respectively. The profitability coefficient for each technology is denoted by D_i, where $D_{\underline{i}}$ or $D_{\overline{i}}$ indicates that there is either one $(\underline{i})$ or two $(\overline{i})$ firms in the market, respectively. Hence, D_i is decreasing in the number of active firms and increasing in i. Intuitively, profits are higher for the leader in the absence of a follower, as in Billette de Villemeur *et al.* (2019), i.e:

$$\begin{array}{ccc} D_{\underline{1}} & > & D_{\overline{1}} \\ \wedge & & \wedge \\ D_{\underline{2}} & > & D_{\overline{2}} \end{array} \tag{3}$$

Depending on the number of firms in the industry, a firm's option to invest in technology i while operating technology $i-1$ is denoted by $F^{ab}_{i-1,i}(\cdot)$, and the expected utility from operating technology i inclusive of embedded options is denoted by $\Phi^{ab}_{i}(\cdot)$. Also, the optimal time of investment and the corresponding optimal investment threshold are denoted by $\tau^{ab}_{i-1,i}$ and $\varepsilon^{ab}_{i-1,i}$, respectively. For example, $F^{n\ell}_{0,1}(\cdot)$ is the pre-emptive leader's option to invest in the first technology with a single embedded option to adopt the second one, while $\tau^{n\ell}_{0,1}$ and $\varepsilon^{n\ell}_{0,1}$ are the corresponding optimal time of investment and optimal investment threshold, respectively.

To facilitate the exposition of the results, our work is based on a set of research questions in the form of testable hypotheses that are outlined below and illustrated in Figure 1. The hypotheses are based on the assumption that the new technology produces greater output than the existing one, yet is more capital intensive. In terms of context, a firm may hold an investment opportunity to develop a production facility in two steps. First, it develops the production facility and then it exercises the option to retrofit it with a new technology. For example, oil production facilities have been converted to utilise gas reserves but at a substantial cost in order to implement export facilities and retrofitting (Støre *et al.*, 2018).

– **Hypothesis 1**: *The non-pre-emptive leader cannot adopt the new technology before the follower invests in the existing one, i.e.* $\varepsilon^{p\ell}_{\overline{1},\underline{2}} > \varepsilon^{f}_{0,\overline{1}}$, *because the new technology is more capital intensive (left panel).*

– **Hypothesis 2**: *The loss in the non-pre-emptive leaders' option value due to the follower's entry increases the leader's incentive to accelerate investment in the new technology relative to the case of monopoly, i.e.* $\varepsilon^{p\ell}_{\overline{1},\underline{2}} < \varepsilon^{m}_{1,2}$ *(left panel).*

– **Hypothesis 3**: *Competition induces myopic behaviour. Specifically, sharing the existing technology before the leader adopts the new one* (**Hypothesis 1**) *lowers monopoly profits, thereby mitigating the impact of a higher innovation in terms of accelerating investment.*

– **Hypothesis 4**: *Loss of first-mover advantage may motivate a firm to skip the existing technology and invest in the new one directly. The relative value of this strategy may increase when* **i.** *the output price is high;* **ii.** *major price changes are more likely; or* **iii.** *when risk aversion is low, i.e. when* γ *is high (right panel).*

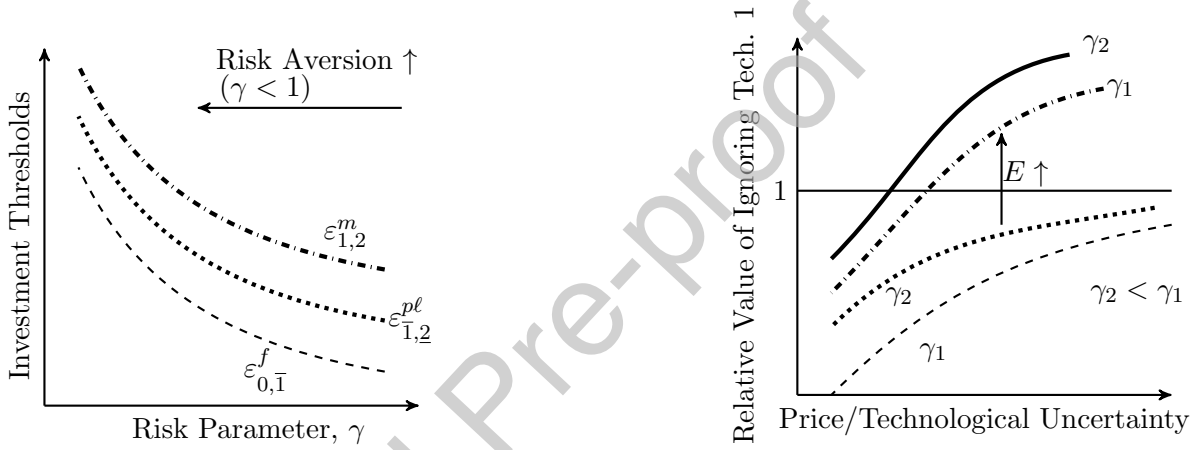

Figure 1: Optimal investment thresholds (left panel) and relative value of skipping the first technology (right panel).

4. Benchmark Case: Single Investment under Monopoly

First, we consider the benchmark case where a monopolist holds a single investment opportunity and faces only price uncertainty. This has already been analysed in Hugonnier & Morellec (2013) and Conejo *et al.* (2016), but we present the analysis here for ease of exposition and to allow for comparisons. In terms of notation, since there is a single firm in the market, we set $b = m$ and we also suppress the first index, a, as it is not relevant in the absence of competition. Also, because the monopolist holds a single investment opportunity, we can relax the notation by ignoring the subscripts indicating investment in the first or the second technology. Thus, the option to invest $F^{ab}_{i-1,i}(\cdot)$ becomes $F^{m}(\cdot)$ and $\tau^{ab}_{i-1,i}$ becomes τ^{m}. Similarly, we set $I_1 \equiv I$ and $D_1 \equiv D$. Because the utility function $U(\cdot)$ is not separable, the key insight is to decompose all the cash flows of the project into disjoint time intervals. Hence, we assume that the monopolist has initially placed the amount of capital required for investment in a certificate of deposit and

earns a risk-free rate, r. Thus, until time τ^m, the monopolist earns the instantaneous utility $U(rI)$. At time τ^m, the monopolist swaps this risk-free cash flow in return for the instantaneous utility $U(ED)$, as shown in Figure 2.

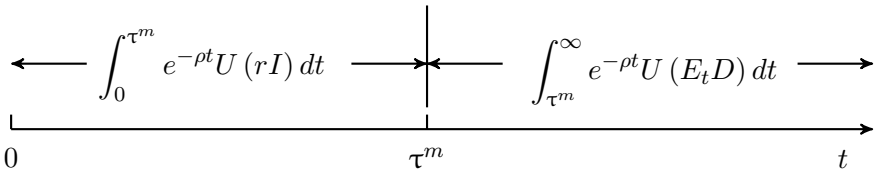

Figure 2: Irreversible investment under monopoly.

The time-zero expected discounted utility of all the cash flows of the project is described in (4), where $\mathbb{E}_E[\cdot]$ denotes the expectation operator conditional on the initial output price, E.

$$\mathbb{E}_E\left[\int_0^{\tau^m} e^{-\rho t}U(rI)\,dt + \int_{\tau^m}^{\infty} e^{-\rho t}U(E_tD)\,dt\right] \tag{4}$$

By decomposing the first integral, we can rewrite (4) as in (5).

$$\int_0^{\infty} e^{-\rho t}U(rI)\,dt + \mathbb{E}_E\left[\int_{\tau^m}^{\infty} e^{-\rho t}\left[U(E_tD) - U(rI)\right]dt\right] \tag{5}$$

Notice that the first term in (5) is deterministic, as it does not depend on the investment threshold. Therefore, the optimisation objective is reflected in the second term and is expressed as an optimal stopping-time problem in (6) using the law of iterated expectations and the strong Markov property of the GBM. The latter states that the values of the process $\{E_t, t \geq 0\}$ after time τ^m are independent of the values of the process before time τ^m and depend only on the value of the process at time τ^m. The objective is to determine the first passage time of the price process through the critical threshold τ^m that is defined as $\tau^m = \inf\{t \geq 0 : E_t \geq \varepsilon^m\}$.

$$F^m(E) = \sup_{\tau^m \in \mathcal{S}} \mathbb{E}_E\left[e^{-\rho\tau^m}\mathbb{E}_{\varepsilon^m}\left[\int_0^{\infty} e^{-\rho t}\left[U(E_tD) - U(rI)\right]dt\right]\right] \tag{6}$$

Thus, (6) is the discounted (to time $t = 0$) expected utility of cash flows from a power plant that becomes active at τ^m and operates forever. Note that the inner conditional expectation's independence from E means that the two expectations may be separated as follows:

$$F^m(E) = \sup_{\tau^m \in \mathcal{S}} \mathbb{E}_E\left[e^{-\rho\tau^m}\right]\mathbb{E}_{\varepsilon^m}\left[\int_0^{\infty} e^{-\rho t}\left[U(E_tD) - U(rI)\right]dt\right] \tag{7}$$

Also, the stochastic discount factor is $\mathbb{E}_E\left[e^{-\rho\tau^m}\right] = \left(\frac{E}{\varepsilon^m}\right)^{\beta_1}$ (Dixit & Pindyck, 1994 p. 315), $\beta_1 > 1, \beta_2 < 0$ are the roots of the quadratic $\frac{1}{2}\sigma^2\beta(\beta-1) + \mu\beta - \rho = 0$ and $\mathcal{S}$ is the set of stopping times generated by the filtration of the process $\{E_t, t \geq 0\}$. Using Theorem 9.18 of Karatzas & Shreve (1999), we can express the expected utility of a perpetual stream of cash flows that follows a GBM as in (8).

$$\mathbb{E}_E\int_0^{\infty} e^{-\rho t}U(E_tD) = \Upsilon U(ED), \quad \text{where} \quad \Upsilon = \frac{\beta_1\beta_2}{\rho(\beta_1-\gamma)(\beta_2-\gamma)} \tag{8}$$

By inserting the expression for the stochastic discount factor, we can now recast the optimal stopping-time problem in (7) as the following unconstrained nonlinear maximization problem:

$$F^m(E) = \max_{\varepsilon^m > E} \left(\frac{E}{\varepsilon^m}\right)^{\beta_1} \Phi^m(\varepsilon^m) \tag{9}$$

where $\Phi^m(E) = \Upsilon U(ED) - \frac{1}{\rho} U(rI)$ is the expected utility of the active project. Solving the unconstrained optimisation problem (9), we obtain the optimal investment threshold that is indicated in (10). Note that, although the investment threshold is commonly expressed in terms of β_1, it is more expedient to use β_2 in our case, due to the relationship $\beta_1\beta_2 = -2\rho / \sigma^2$. Additionally, the second-order sufficiency condition requires the objective function to be concave at ε^m, which is shown in Chronopoulos & Lumbreras (2017). Also, note that the analysis of sequential technology adoption for the monopolist is identical to the follower's (see Section 5.1), except for replacing $D_{\bar{i}}$ by $D_{\underline{i}}$ to indicate the absence of competition.

$$\varepsilon^m = rI\left[\frac{\beta_2 - \gamma}{\beta_2 D^\gamma}\right]^{\frac{1}{\gamma}} \tag{10}$$

From the existing literature (Dixit & Pindyck, 1994; Hugonnier & Morellec, 2013), we know that, in the benchmark case, increasing price uncertainty and risk aversion delay investment by raising the associated opportunity cost and decreasing the expected utility of the active project, respectively. However, the benchmark case does not allow for strategic interactions or sequential investment opportunities that may be subject to technological uncertainty. Consequently, crucial aspects that could impact an investment decision substantially are ignored. For example, uncertainty over the arrival of innovations accelerates investment by raising the incentive to adopt an existing technology (Chronopoulos & Siddiqui, 2015). Furthermore, the presence of a rival may also induce earlier investment due to the risk of pre-emption (Huisman & Kort, 1999). These features introduce opposing forces that are overlooked in the benchmark case and will be addressed in the following sections.

5. Compulsive Strategy

5.1. Non-pre-emptive Duopoly

Follower

We extend Section 4 by assuming that there are two firms in the market competing in the sequential adoption of technological innovations. First, we consider the optimal investment policy of the follower, who makes transitions between states $(i-1, i)$ and i, $i = 1, 2$. Note that the corresponding value functions and critical thresholds for a single firm under sequential investment and risk neutrality can be obtained by replacing $D_{\bar{i}}$ with $D_{\underline{i}}$ and setting $\gamma = 1$ (Chronopoulos & Siddiqui, 2015). Also, since the follower will adopt each technology after the

leader, we can relax the notation by indicating the presence of two firms via $\bar{i}$ only when it is necessary to avoid confusion, i.e. when it is not implied by the superscript. For example, $\varepsilon^f_{0,\bar{1}}$ reduces to $\varepsilon^f_{0,1}$.

As indicated in Figure 3, the follower is initially in state $(0,1)$ and holds the option to invest in the first technology. Upon investing at $\varepsilon^f_{0,1}$, the follower moves to state 1. Subsequently, once an innovation takes place, the follower moves to state $(1,2)$, where she has the option to invest in the second technology. The option is exercised at $\varepsilon^f_{1,2}$ and the follower moves to state 2. We denote a transition due to an innovation (investment) by a dashed (solid) line.

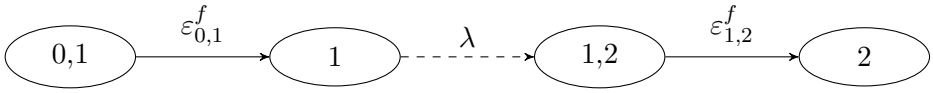

Figure 3: State-transition diagram for the non-pre-emptive follower under a compulsive strategy.

Although we do not consider the choice between the two technologies[2] (Décamps *et al.*, 2006), the feasibility of a compulsive strategy requires a trade-off between the two technologies so that they both present viable investment opportunities for different price ranges, as indicated in Proposition 1. Formally, this trade-off implies that: **i.** there exists an $E^* > 0$ such that $\Phi_1^{pb}(E) > \Phi_2^{pb}(E)$ for $E < E^*$ and $\Phi_1^{pb}(E) < \Phi_2^{pb}(E)$ for $E > E^*$, so that the NPVs of the two technologies intersect at some $E^* > 0$; and **ii.** the NPV at the point of intersection between the expected NPVs of the two technologies needs to be positive. Otherwise, only the new technology presents a viable investment opportunity. Note that the condition presented in Proposition 1 is a more general version of that in Chronopoulos & Siddiqui (2015), as it relaxes the assumption of risk neutrality (all proofs can be found in the appendix).

Proposition 1. *A trade-off between the two technologies exists if the first (second) technology is preferred for low (high) output prices and requires that* $\frac{D_1^\gamma}{I_1^\gamma} > \frac{D_2^\gamma}{I_1^\gamma + I_2^\gamma}$.

Like in Section 4, the amount of capital required for the adoption of each technology is exchanged at investment for the risky cash flows of the project. To illustrate the decomposition of the cash flows under sequential investment and within a utility-based framework, we assume in Figure 4 that the second technology is available. Thus, at time $\tau^f_{0,1}$ the follower borrows that the capital required for investing in the first technology and exchanges it for the risky cash flows it generates. Analogously to (5) and (6), this results in the instantaneous utility $U\left(ED_{\bar{1}}\right) - U\left(rI_1\right)$, which accrues from $\tau^f_{0,1}$ until $\tau^f_{1,2}$. Similarly, at $\tau^f_{1,2}$ the follower exchanges the capital required for investing in the second technology for the risky cash flows it generates.

[2]Apart from a compulsive strategy, it is possible for the follower to wait for both technologies to become available before deciding to invest in either the older (laggard strategy) or the newer version (leapfrog strategy). These strategies have been analysed in Grenadier & Weiss (1997) and Chronopoulos & Siddiqui (2015).

The representation and decomposition of the cash-flows in Figure 4 facilitates the treatment of the investment cost within a utility-based framework, where the utility function is not separable, i.e. $U(rI_1+rI_2) \neq U(rI_1)+U(rI_2)$. In addition, this representation is in line with technological uncertainty and accounts for the case $\lambda = 0$. Hence, the firm does not hold the entire capital required for both investments in a security of deposit from the very beginning, since the arrival of the second technology is uncertain.

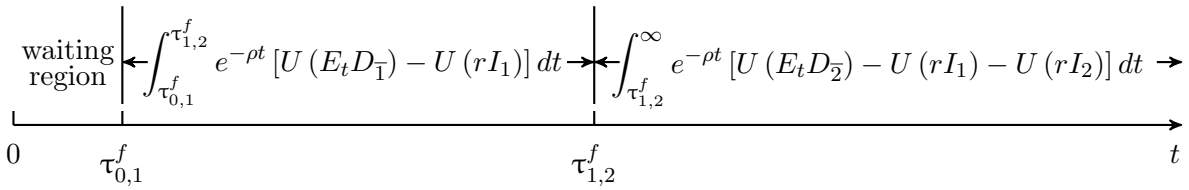

Figure 4: Sequential investment under a compulsive strategy.

The follower's objective is to maximise the time-zero discounted expected utility of all the cash flows of the project. Building on Figure 4, the follower's optimisation objective is described in (11) as an optimal stopping-time problem, where we assume that $\tau^f_{0,1} < \nu < \tau^f_{1,2}$ to indicate that the improved technology version arrives after the first one is adopted. The first (second) integral in (11) indicates the expected utility of the cash flows from operating the first (second) technology.

$$\sup_{\substack{\tau^f_{0,1}\in\mathcal{S} \\ \tau^f_{1,2}>\nu>\tau^f_{0,1}}} \mathbb{E}_E\left[\int_{\tau^f_{0,1}}^{\tau^f_{1,2}} e^{-\rho t}\left[U\left(E_t D_{\overline{1}}\right) - U\left(rI_1\right)\right] dt + \int_{\tau^f_{1,2}}^{\infty} e^{-\rho t}\left[U\left(E_t D_{\overline{2}}\right) - U\left(rI_1\right) - U\left(rI_2\right)\right] dt\right] \tag{11}$$

Following the same approach as in (6) and (7), we decompose the first integral and rewrite (11) as in (12).

$$\begin{aligned}\sup_{\tau^f_{0,1}\in\mathcal{S}} \mathbb{E}_E\left[e^{-\rho\tau^f_{0,1}}\right]\Bigg[\mathbb{E}_{\varepsilon^f_{0,1}}\int_0^{\infty} e^{-\rho t}\left[U\left(E_t D_{\overline{1}}\right) - U\left(rI_1\right)\right] dt + \sup_{\tau^f_{1,2}>\nu>\tau^f_{0,1}} \mathbb{E}_{\varepsilon^f_{0,1}}\left[e^{-\rho\left(\tau^f_{1,2}-\tau^f_{0,1}\right)}\right] \\ \times\mathbb{E}_{\varepsilon^f_{1,2}}\int_0^{\infty} e^{-\rho t}\left[\left(D^{\gamma}_{\overline{2}} - D^{\gamma}_{\overline{1}}\right) U\left(E_t\right) - U\left(rI_2\right)\right] dt\Bigg]\end{aligned} \tag{12}$$

We determine the follower's value function in each state using backward induction. Therefore, we first assume that the follower in state 2, i.e. has already adopted and operates the second technology. The expected utility of the perpetual stream of profits from operating the second technology is described in (13).

$$\Phi^f_2(E) = \mathbb{E}_E\int_0^{\infty} e^{-\rho t}\left[U\left(E_t D_{\overline{2}}\right) - U\left(rI_1\right) - U\left(rI_2\right)\right] dt = \Upsilon U\left(E D_{\overline{2}}\right) - \frac{U\left(rI_1\right) + U\left(rI_2\right)}{\rho} \tag{13}$$

Next, to facilitate the analysis of technological uncertainty, we present the value function and optimal investment threshold of the follower in state $(1,2)$ as the solution to a free-boundary problem. Using the Bellman principle, the follower's value function is described in (14), where

the first term in the top part is the utility of the immediate cash flow from operating the first technology and the second term is the expected utility in the continuation region. The bottom part is the expected utility of the second technology and is already determined in (13).

$$F_{1,2}^{f}(E) = \begin{cases} \left[U\left(ED_{\overline{1}}\right) - U\left(rI_1\right)\right]dt + e^{-\rho dt}\mathbb{E}_E\left[F_{1,2}^{f}(E+dE)\right] & , E < \varepsilon_{1,2}^{f} \\ \Phi_2^f(E) & , E \geq \varepsilon_{1,2}^{f} \end{cases} \tag{14}$$

By expanding the top part on the right-hand side of (14) using Itô's lemma we obtain the ordinary differential equation (ODE) $\left[\mathcal{L} - \rho\right] F_{1,2}^{f}(E) + U\left(ED_{\overline{1}}\right) - U\left(rI_1\right) = 0$, where $\mathcal{L} = \frac{1}{2}\sigma^2 E^2 \frac{d^2}{dE^2} + \mu E \frac{d}{dE}$ is the differential generator. The ODE is solved subject to two boundary conditions, namely the value-matching and smooth-pasting condition, indicated in (A–12) and (A–13), respectively, and, thus, we obtain the analytical expression for the value function of the follower in state $(1,2)$ and the optimal investment policy, as indicated in Proposition 2. The first two terms in the top part of (15) represent the expected utility from operating the first technology and the third term is the option to invest in the second one.

Proposition 2. *The value function of the follower in state* $(1,2)$ *is*

$$F_{1,2}^{f}(E) = \begin{cases} \Upsilon U\left(ED_{\overline{1}}\right) - \frac{U(rI_1)}{\rho} + A_{1,2}^{f}E^{\beta_1} & , E < \varepsilon_{1,2}^{f} \\ \Phi_2^f(E) & , E \geq \varepsilon_{1,2}^{f} \end{cases} \tag{15}$$

where the endogenous constant $A_{1,2}^{f}$ *and optimal investment threshold* $\varepsilon_{1,2}^{f}$ *are indicated in* (16) *and* (17)*, respectively, and are obtained by applying value-matching and smooth-pasting conditions to the two branches of* (15).

$$A_{1,2}^{f} = \left(\frac{1}{\varepsilon_{1,2}^{f}}\right)^{\beta_1}\left[\Upsilon\left(D_{\overline{2}}^{\gamma} - D_{\overline{1}}^{\gamma}\right)U\left(\varepsilon_{1,2}^{f}\right) - U\left(rI_2\right)\right] \tag{16}$$

$$\varepsilon_{1,2}^{f} = rI_2\left[\frac{\beta_2 - \gamma}{\beta_2\left(D_{\overline{2}}^{\gamma} - D_{\overline{1}}^{\gamma}\right)}\right]^{\frac{1}{\gamma}} \tag{17}$$

Alternatively, $A_{1,2}^{f}E^{\beta_1}$ can be expressed as in (18), which corresponds to the inner optimal stopping-time problem of (12).

$$\begin{aligned} A_{1,2}^{f}E^{\beta_1} &= \max_{\varepsilon_{1,2}^{f} > E}\left(\frac{E}{\varepsilon_{1,2}^{f}}\right)^{\beta_1}\mathbb{E}_{\varepsilon_{1,2}^{f}}\int_0^{\infty} e^{-\rho t}\left[\left(D_{\overline{2}}^{\gamma} - D_{\overline{1}}^{\gamma}\right)U\left(E_t\right) - U\left(rI_2\right)\right]dt \\ &= \max_{\varepsilon_{1,2}^{f} > E}\left(\frac{E}{\varepsilon_{1,2}^{f}}\right)^{\beta_1}\left[\Upsilon\left(D_{\overline{2}}^{\gamma} - D_{\overline{1}}^{\gamma}\right)U\left(\varepsilon_{1,2}^{f}\right) - U\left(rI_2\right)\right] \end{aligned} \tag{18}$$

Also, note that $\varepsilon_{1,2}^{f} > \varepsilon_{1,2}^{m}$, since the follower's market share is smaller than the monopolist's, which, in turn, raises the incentive to delay investment relative to the monopolist.

$$\varepsilon_{1,2}^{f} = rI_2\left[\frac{\beta_2 - \gamma}{\beta_2\left(D_{\overline{2}}^{\gamma} - D_{\overline{1}}^{\gamma}\right)}\right]^{\frac{1}{\gamma}} > rI_2\left[\frac{\beta_2 - \gamma}{\beta_2\left(D_{\underline{2}}^{\gamma} - D_{\underline{1}}^{\gamma}\right)}\right]^{\frac{1}{\gamma}} = \varepsilon_{1,2}^{m} > \varepsilon^{m} \tag{19}$$

Next, we step back to state 1, where the follower is operating the first technology and holds an embedded option to invest in the second one, that has yet to become available. The dynamics of the expected utility of the active project are described in (20), where the first term on the right-hand side represents the instantaneous utility of the profits from operating the first technology and the second term is the expected utility of the project in the continuation region. As the second term indicates, with probability λdt the second technology will arrive and the follower will receive the value function $F^f_{1,2}(E)$, whereas, with probability $1-\lambda dt$, no innovation will occur and the follower will continue to hold the value function $\Phi^f_1(E)$.

$$\Phi^f_1(E) = \left[U\left(ED_{\overline{1}}\right) - U\left(rI_1\right)\right]dt + e^{-\rho dt}\mathbb{E}_E\left[\lambda dt F^f_{1,2}(E+dE) + (1-\lambda dt)\,\Phi^f_1(E+dE)\right] \quad (20)$$

By expanding the right-hand side of (20) using Itô's lemma, we obtain (21), where $\mathcal{L} = \frac{1}{2}\sigma^2E^2\frac{d^2}{dE^2} + \mu E\frac{d}{dE}$ denotes the differential generator.

$$\left[\mathcal{L} - (\rho+\lambda)\right]\Phi^f_1(E) + \lambda F^f_{1,2}(E) + U\left(D_{\overline{1}}E\right) - U\left(\rho I_1\right) \;=\; 0 \quad (21)$$

Next, we solve the ordinary differential equation (ODE) (21) for each expression of $F^f_{1,2}(E)$ indicated in (15) and obtain (22). Note that $\Lambda = \frac{\Upsilon}{\lambda\Upsilon+1}$ and $\delta_1 > 0, \delta_2 < 0$ are the roots of the quadratic $\frac{1}{2}\sigma^2\delta(\delta-1) + \mu\delta - (\rho+\lambda) = 0$. The first two terms on the top part represent the expected utility of the revenues and cost, respectively. The third term is the option to invest in the second technology, adjusted via the last term because the second technology is not available yet. The first three terms on the bottom part, represent the expected utility of operating the second technology, and the fourth term represents the likelihood of the price dropping in the waiting region.

$$\Phi^f_1(E) \;=\; \begin{cases} \Upsilon U\left(ED_{\overline{1}}\right) - \frac{U(rI_1)}{\rho} + A^f_{1,2}E^{\beta_1} + A^f_1E^{\delta_1} & , E < \varepsilon^f_{1,2} \\ \Lambda\left[\lambda\Upsilon U\left(ED_{\overline{2}}\right) + U\left(ED_{\overline{1}}\right)\right] - \frac{\lambda U(rI_2)}{(\lambda+\rho)\rho} - \frac{U(rI_1)}{\rho} + B^f_1E^{\delta_2} & , E \geq \varepsilon^f_{1,2} \end{cases} \quad (22)$$

The endogenous constants $A^f_1 > 0$ and $B^f_1 < 0$, are determined analytically by applying value-matching and smooth-pasting conditions to the two branches of (22), and are indicated in (23) and (24), respectively. Note that by setting $\gamma = 1$, we can retrieve the risk-neutral version of A^f_1 and B^f_1 as in Chronopoulos & Siddiqui (2015).

$$A^f_1 = \frac{\varepsilon^{f\,-\delta_1}_{1,2}}{\delta_2-\delta_1}\left[(\delta_2-\gamma)\,\lambda\Lambda\Upsilon U\left(\varepsilon^f_{1,2}\right)\left[D^\gamma_{\overline{2}} - D^\gamma_{\overline{1}}\right] + (\beta_1-\delta_2)\,A^f_{1,2}\varepsilon^{f\,\beta_1}_{1,2} - \frac{\delta_2\lambda U\left(rI_2\right)}{\rho\left(\rho+\lambda\right)}\right] \quad (23)$$

$$B^f_1 = \frac{\varepsilon^{f\,-\delta_2}_{1,2}}{\delta_1-\delta_2}\left[(\gamma-\delta_1)\,\lambda\Lambda\Upsilon U\left(\varepsilon^f_{1,2}\right)\left[D^\gamma_{\overline{2}} - D^\gamma_{\overline{1}}\right] + (\delta_1-\beta_1)\,A^f_{1,2}\varepsilon^{f\,\beta_1}_{1,2} + \frac{\delta_1\lambda U\left(rI_2\right)}{\rho\left(\rho+\lambda\right)}\right] \quad (24)$$

Finally, the follower's value function in state $(0,1)$ is indicated in (25). By applying value-matching and smooth-pasting conditions to the two branches of (25), we can solve for the

optimal investment threshold, $\varepsilon^f_{0,1}$, and the endogenous constant, $A^f_{0,1}$, numerically.

$$F^f_{0,1}(E) = \begin{cases} A^f_{0,1}E^{\beta_1} & , E < \varepsilon^f_{0,1} \\ \Phi^f_1(E) & , E \geq \varepsilon^f_{0,1} \end{cases} \tag{25}$$

Leader

Next, we consider the investment policy of the non-pre-emptive leader. Notice that once the leader invests in the first technology, thus moving from state $(0, \underline{1})$ to state $\underline{1}$, she receives monopoly profits until the follower enters. This may reflect an industry with weak patent protection, where knowledge spillover enables the immediate entry of a rival. Once the follower adopts the first technology, both firms share the market in state $\overline{1}$. Subsequently, the same process is repeated with respect to the second technology, until, finally, the two firms share the market in state $\overline{2}$.

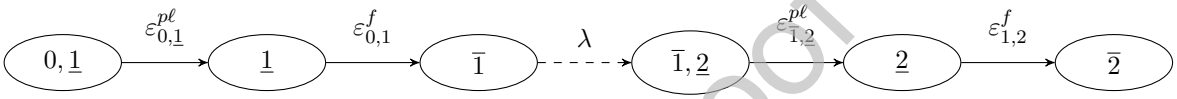

Figure 5: State-transition diagram for the non-pre-emptive leader under a compulsive strategy.

We start with state $\overline{2}$, and, assuming that the follower chooses the optimal investment policy, the value function of the non-pre-emptive leader is the same as the follower's because in state $\overline{2}$ the two firms share the market, i.e. $\Phi^{p\ell}_{\overline{2}}(E) = \Phi^f_2(E)$. However, before the follower has adopted the second technology, i.e. for $\varepsilon^{p\ell}_{\overline{1},\underline{2}} < E < \varepsilon^f_{1,2}$, the non-pre-emptive leader enjoys monopoly profits and the expected utility from operating the second technology is indicated in (26).

$$\begin{aligned} \Phi^{p\ell}_{\underline{2}}(E) = \mathbb{E}_E \Bigg[& \int_0^{\tau^f_{1,2}} \left[U\left(E_t D_{\overline{2}}\right) - U\left(rI_1\right) - U\left(rI_2\right)\right] dt \\ & + \int_{\tau^f_{1,2}}^{\infty} \left[U\left(E_t D_{\underline{2}}\right) - U\left(rI_1\right) - U\left(rI_2\right)\right] dt \Bigg] \end{aligned} \tag{26}$$

By decomposing the first integral in (26), we can express it as in (27)

$$\begin{aligned} \Phi^{p\ell}_{\underline{2}}(E) = \mathbb{E}_E \Bigg[& \int_0^{\infty} \left[U\left(E_t D_{\overline{2}}\right) - U\left(rI_1\right) - U\left(rI_2\right)\right] dt \\ & + \mathbb{E}_E\left[e^{-\rho\tau^f_{1,2}}\right] \mathbb{E}_{\varepsilon^f_{1,2}} \int_0^{\infty} \left[U\left(E_t D_{\underline{2}}\right) - U\left(E_t D_{\overline{2}}\right)\right] dt \Bigg] \end{aligned} \tag{27}$$

and by substituting for the analytical expression of the first integral and for $\mathbb{E}_E\left[e^{-\rho\tau^f_{1,2}}\right]$ we obtain (28). The first two terms on the right-hand side reflect the monopoly profits from operating the second technology and the third term is expected reduction in utility due to the follower's entry.

$$\Phi^{p\ell}_{\underline{2}}(E) = \Upsilon U\left(ED_{\underline{2}}\right) - \frac{U\left(rI_1\right) + U\left(rI_2\right)}{\rho} + \left(\frac{E}{\varepsilon^f_{1,2}}\right)^{\beta_1} \Upsilon U\left(\varepsilon^f_{1,2}\right)\left[D^{\gamma}_{\overline{2}} - D^{\gamma}_{\underline{2}}\right] \tag{28}$$

Next, in state $(\overline{1},\underline{2})$, i.e. before the second technology is adopted, the non-pre-emptive leader's value function is described in (29). The first two terms on the top part reflect the expected utility of the profits from operating the first technology, and the third term is the embedded option to invest in the second one. The bottom part is the expected utility of the active project, which is already determined in (28).

$$F^{p\ell}_{\overline{1},\underline{2}}(E) \;=\; \begin{cases} \Upsilon U\left(ED_{\overline{1}}\right) - \frac{U(rI_1)}{\rho} + A^{p\ell}_{\overline{1},\underline{2}} E^{\beta_1} & , E < \varepsilon^{p\ell}_{\overline{1},\underline{2}} \\ \Phi^{p\ell}_{\underline{2}}(E) & , E \geq \varepsilon^{p\ell}_{\overline{1},\underline{2}} \end{cases} \tag{29}$$

Following the same approach as in Proposition 2, the endogenous constant, $A^{p\ell}_{\overline{1},\underline{2}}$, and the optimal investment threshold, $\varepsilon^{p\ell}_{\overline{1},\underline{2}}$, can be obtained analytically via value-matching and smooth-pasting conditions and are indicated in (30).

$$\varepsilon^{p\ell}_{\overline{1},\underline{2}} = rI_2 \left[\frac{\beta_2 - \gamma}{\beta_2\left(D^{\gamma}_{\underline{2}} - D^{\gamma}_{\overline{1}}\right)}\right]^{\frac{1}{\gamma}} \text{ and } \quad A^{p\ell}_{\overline{1},\underline{2}} = \left(\frac{1}{\varepsilon^{p\ell}_{\overline{1},\underline{2}}}\right)^{\beta_1} \left[\Phi^{p\ell}_{\underline{2}}\left(\varepsilon^{p\ell}_{\overline{1},\underline{2}}\right) - \Upsilon U\left(\varepsilon^{p\ell}_{\overline{1},\underline{2}} D_{\overline{1}}\right) + \frac{U(rI_1)}{\rho}\right] \tag{30}$$

Using Proposition 1, we find that the non-pre-emptive leader will not invest in the second technology before the follower adopts the first one. This happens because the second technology is more costly and can not be adopted when the output price is below the follower's required investment threshold for the first technology. Also, unlike the case where a firm holds a single investment option (Chronopoulos *et al.*, 2014), the leader's required investment threshold in the second technology is lower than the corresponding monopoly threshold. Intuitively, the entry of the follower reduces the leader's monopoly profits with respect to the first technology. In turn, this raises the value of the leader's option to invest in the second technology and lowers the required adoption threshold, thereby extending the corresponding period of monopoly profits. Both results as shown in Proposition 3, thus confirming **Hypothesis 1&2**.

Proposition 3. *The non-pre-emptive leader invests in the second technology earlier than the corresponding monopoly threshold but after the follower invests in the first one, i.e.* $\varepsilon^{f}_{0,1} < \varepsilon^{p\ell}_{\overline{1},\underline{2}} < \varepsilon^{m}_{1,2}$.

In state $\overline{1}$, the leader shares the market with the follower waiting for the arrival of the second technology. Following the same approach as in (20), we derive the ODE that describes the dynamics of the value function of the leader, which is indicated in (31).

$$\left[\mathcal{L} - (\rho + \lambda)\right] \Phi^{p\ell}_{\overline{1}}(E) + \lambda F^{p\ell}_{\overline{1},\underline{2}}(E) + U\left(ED_{\overline{1}}\right) - U\left(rI_1\right) = 0 \tag{31}$$

Like (20), we solve (31) to derive the non-pre-emptive leader's value function in state $\overline{1}$. This is indicated in (32), where $A^{p\ell}_{\overline{1}}$ and $C^{p\ell}_{\overline{1}}$ are determined by value matching and smooth pasting

the two branches, and $B_{\overline{1}}^{p\ell}$ is obtained by value matching (32) with the bottom branch of (22) at $\varepsilon_{1,2}^{f}$. The first two (three) terms in the top (bottom) part of (32) reflect the expected utility of the profits under a low (high) output price. The third term on the top part is the option to invest in the second technology adjusted via the fourth term for technological uncertainty. The fourth term on the bottom part is the reduction in the expected utility of the leader's profits due to the follower's entry adjusted for technological uncertainty via the fifth term. The last term reflects the likelihood of the price dropping in the waiting region.

$$\Phi_{\overline{1}}^{p\ell}(E) = \begin{cases} \Upsilon U\left(ED_{\overline{1}}\right) - \frac{U(rI_1)}{\rho} + A_{\overline{1},\underline{2}}^{p\ell} E^{\beta_1} + A_{\overline{1}}^{p\ell} E^{\delta_1} & , E < \varepsilon_{\overline{1},\underline{2}}^{p\ell} \\ \Lambda\left[\lambda \Upsilon U\left(ED_{\underline{2}}\right) + U\left(ED_{\overline{1}}\right)\right] - \frac{U(rI_1)}{\rho} - \frac{\lambda U(rI_2)}{\rho(\rho+\lambda)} & \\ + A_{\underline{2}}^{p\ell} E^{\beta_1} + B_{\overline{1}}^{p\ell} E^{\delta_1} + C_{\overline{1}}^{p\ell} E^{\delta_2} & , E \geq \varepsilon_{\overline{1},\underline{2}}^{p\ell} \end{cases} \tag{32}$$

The value function of the non-pre-emptive leader in state $\underline{1}$ is indicated in (33) and is determined following the same approach as in (28). The first two terms on the right-hand side reflect the expected utility from operating the first technology and the last term is the expected loss in the non-pre-emptive leader's profits due to the follower's entry.

$$\Phi_{\underline{1}}^{p\ell}(E) = \Upsilon U\left(ED_{\underline{1}}\right) - \frac{U\left(rI_1\right)}{\rho} + \left(\frac{E}{\varepsilon_{0,1}^{f}}\right)^{\beta_1} \left[\Upsilon U\left(\varepsilon_{0,1}^{f}\right)\left[D_{\overline{1}}^{\gamma} - D_{\underline{1}}^{\gamma}\right] + A_{\overline{1},\underline{2}}^{p\ell} \varepsilon_{0,1}^{f\beta_1} + A_{\overline{1}}^{p\ell} \varepsilon_{0,1}^{f\delta_1}\right], \quad E < \varepsilon_{0,1}^{f} \tag{33}$$

In state $(0,\underline{1})$, the non-pre-emptive leader holds the option to invest in the first technology with an embedded option to invest in the second one, that has yet to become available. The expression of $F_{0,\underline{1}}^{p\ell}(E)$ is described in (34), where the top part is the value of the option to invest and the bottom part is the expected utility of the active project inclusive of the embedded option to invest in the second technology. The expressions of $\varepsilon_{0,\underline{1}}^{p\ell}$ and $A_{0,\underline{1}}^{p\ell}$ are indicated in (A–21).

$$F_{0,\underline{1}}^{p\ell}(E) = \begin{cases} A_{0,\underline{1}}^{p\ell} E^{\beta_1} & , E < \varepsilon_{0,\underline{1}}^{p\ell} \\ \Phi_{\underline{1}}^{p\ell}(E) & , E \geq \varepsilon_{0,\underline{1}}^{p\ell} \end{cases} \tag{34}$$

As shown in Proposition 4, the leader's decision to adopt the first technology is independent of technological uncertainty (**Hypothesis 3**). Intuitively, the leader's loss in value due to the follower's entry creates an opposing force that offsets the leader's incentive for earlier investment due to the likely arrival of the second technology.

Proposition 4. *Competition induces the non-pre-emptive leader to adopt a myopic technology adoption strategy.*

5.2. Pre-emptive Duopoly

With two firms in the market fighting for the leader's position, each one of them faces the risk of pre-emption. Note that, under a compulsive strategy, the follower will invest in each technology after the leader has already adopted it. Consequently, the value function of the follower in each state is the same as in Section 5.1. However, to determine the pre-emptive leader's optimal investment policy, starting with the second technology, we must consider the strategic interactions between the leader and the follower. Note that the leader's value function in state $\underline{2}$ is already described in (28), i.e. $\Phi_{\underline{2}}^{n\ell}(E) \equiv \Phi_{\underline{2}}^{p\ell}(E)$. Intuitively, if both firms hold a single investment option (Takashima *et al.*, 2008), then the pre-emption threshold is defined as the point of intersection between the option value of the follower, $F_{\overline{1},\underline{2}}^{f}(E)$, and the value of the active project of the leader, $\Phi_{\underline{2}}^{n\ell}(E)$. Intuitively, if we denote this point by $\varepsilon_{\overline{1},\underline{2}}^{n\ell}$, then:

i. If $E < \varepsilon_{\overline{1},\underline{2}}^{n\ell}$, then a firm is better off being the follower because $F_{\overline{1},\underline{2}}^{f}(E) > \Phi_{\underline{2}}^{n\ell}(E)$.

ii. If $E > \varepsilon_{\overline{1},\underline{2}}^{n\ell}$, then a firm is better off being a leader because $F_{\overline{1},\underline{2}}^{f}(E) < \Phi_{\underline{2}}^{n\ell}(E)$.

Consequently, the point of indifference between being a leader and a follower, which is indicated in Figure 6, is determined numerically by solving (35). Formally, the pre-emption threshold is determined using the subgame perfect equilibrium concept of Riedel & Steg (2017) for timing stochastic games. If there exists a first mover advantage, then there must be an interval $\mathcal{P} = \left(\varepsilon_{\overline{1},\underline{2}}^{n\ell}, \varepsilon_{\overline{1},\underline{2}}^{f}\right)$ where $\Phi_{\underline{2}}^{n\ell}(E) > F_{\overline{1},\underline{2}}^{f}(E)$ given that $E \in \mathcal{P}$. We are searching for the pre-emption time $\tau_{\underline{2}}^{n\ell}$, which is defined as the first hitting time of the interval $\mathcal{P}$, i.e. $\tau_{\underline{2}}^{n\ell} = \inf\{t \geq \varphi | E_t \in \mathcal{P}\}$, where $\varphi \in \mathcal{C}$ is an admissible stopping time where a subgame between the players is played.[3]

$$F_{\overline{1},\underline{2}}^{f}(E) \quad = \quad \Phi_{\underline{2}}^{n\ell}(E) \tag{35}$$

However, in the presence of sequential investment options, Proposition 5 indicates that $\varepsilon_{\overline{1},\underline{2}}^{n\ell}$ is not necessarily the pre-emption threshold. In fact, to determine the pre-emption threshold we need to compare $\varepsilon_{\overline{1},\underline{2}}^{n\ell}$ with the threshold at which the follower will adopt the first technology. Note that the follower may invest in the first technology either before or after the indifference threshold of the second one, as shown in Figure 6. If $\varepsilon_{0,1}^{f} > \varepsilon_{\overline{1},\underline{2}}^{n\ell}$, then the leader does not face the risk of pre-emption, because the follower is assumed here to adopt a compulsive strategy, and, therefore, will not skip the first technology. However, if the follower adopts the first technology before the indifference threshold $\left(\varepsilon_{0,1}^{f} < \varepsilon_{\overline{1},\underline{2}}^{n\ell}\right)$, then the leader faces the threat of pre-emption. The shaded area in Figure 6 indicates the output price range within which pre-emption of the second technology is possible, while, in Proposition 5, we show that the leader's

[3] Finally we can rule out coordination failures when the stochastic process is approaching the pre-emption threshold from below (Thijssen et al., 2012).

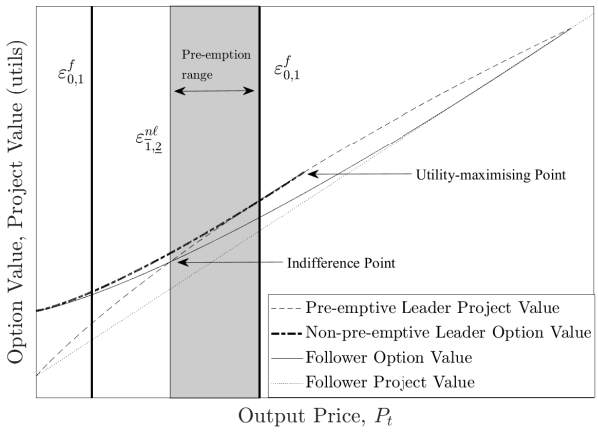

Figure 6: Leader's investment in the second technology under pre-emptive competition.

optimal investment threshold in the second technology is $\max\left\{\varepsilon^{f}_{0,1}, \varepsilon^{n\ell}_{\underline{1},\underline{2}}\right\}$. Intuitively, although the leader can pre-empt the second technology at $\varepsilon^{n\ell}_{\underline{1},\underline{2}}$, she may choose to *delay* adoption until the follower's entry at $\varepsilon^{f}_{0,1}$, provided that $\varepsilon^{f}_{0,1} > \varepsilon^{n\ell}_{\underline{1},\underline{2}}$. Doing so, the leader captures the same value function, albeit at a higher threshold, closer to the utility-maximising one.

Proposition 5. *The optimal investment threshold of the pre-emptive leader for the second technology is* $\epsilon = \max\left\{\varepsilon^{f}_{0,1}, \varepsilon^{n\ell}_{\underline{1},\underline{2}}\right\}$, *where* $\varepsilon^{n\ell}_{\underline{1},\underline{2}}$ *satisfies the condition* $F^{f}_{\underline{1},\underline{2}}(E) = \Phi^{n\ell}_{\underline{2}}(E)$.

Next, we step back, prior to the arrival of the second technology, and assume that, although the firms were identical in the beginning, pre-emption of the first technology by one of the firms offers a strategic advantage that enables the same firm to also pre-empt the second one. The pre-emptive leader's value function is indicated in (36). The first two terms reflect the expected utility of the monopoly profits from operating the first technology and the third term reflects the expected reduction in utility due to the followers entry, where $\epsilon = \max\left\{\varepsilon^{f}_{0,1}, \varepsilon^{n\ell}_{\underline{1},\underline{2}}\right\}$.

$$\Phi^{n\ell}_{\underline{1}}(E) = \Upsilon U\left(ED_{\underline{1}}\right) - \frac{U\left(rI_1\right)}{\rho} + \left(\frac{E}{\epsilon}\right)^{\beta_1}\left[F^{n\ell}_{\underline{1},\underline{2}}(\epsilon) - \Upsilon U\left(\epsilon D_{\underline{1}}\right) + \frac{U\left(rI_1\right)}{\rho}\right] \tag{36}$$

Unlike (33), the expected reduction in the value of the leader due to the follower's entry now depends on whether the follower invests in the first technology before or after $\varepsilon^{n\ell}_{\underline{1},\underline{2}}$. Once the follower invests in the first technology, the two firms will share the market, but, unlike the follower, the pre-emptive leader will receive the expected discounted value from pre-empting the second technology, as indicated in (37). As the top part of (37) indicates, if $\varepsilon^{f}_{0,1} < \varepsilon^{n\ell}_{\underline{1},\underline{2}}$, then the leader will receive the reduced cash flows from operating the first technology and the discounted value from pre-empting the second technology at the indifference threshold, $\epsilon = \varepsilon^{n\ell}_{\underline{1},\underline{2}}$. Similarly, the bottom part indicates that if $\varepsilon^{f}_{0,1} \geq \varepsilon^{n\ell}_{\underline{1},\underline{2}}$, then upon the follower's entry the leader

will pre-empt the second technology immediately, i.e. $\epsilon = \varepsilon_{0,1}^{f}$.

$$F_{\bar{1},\underline{2}}^{n\ell}(E) = \begin{cases} \Upsilon U\left(ED_{\bar{1}}\right) - \frac{U(rI_1)}{\rho} + \left(\frac{E}{\varepsilon_{\bar{1},\underline{2}}^{n\ell}}\right)^{\beta_1}\left[\Phi_{\underline{2}}^{p\ell}\left(\varepsilon_{\bar{1},\underline{2}}^{n\ell}\right) - \Upsilon U\left(ED_{\bar{1}}\right) + \frac{U(rI_1)}{\rho}\right] & , \varepsilon_{0,1}^{f} < \varepsilon_{\bar{1},\underline{2}}^{n\ell} \\ \Phi_{\underline{2}}^{p\ell}\left(E\right) & , \varepsilon_{0,1}^{f} \geq \varepsilon_{\bar{1},\underline{2}}^{n\ell} \end{cases} \quad (37)$$

The first term in (38) is the instantaneous utility of the leader's reduced profits due to follower's entry. As the second term indicates, with probability λdt the second technology will become available and the leader will get to pre-empt it, whereas with probability $1 - \lambda dt$ the leader will continue sharing the first technology with the follower.

$$\Phi_{\bar{1}}^{n\ell}(E) = \left[U\left(ED_{\bar{1}}\right) - U\left(rI_1\right)\right]dt + e^{-\rho dt}\mathbb{E}_E\left[\lambda dt F_{\bar{1},\underline{2}}^{n\ell}(E+dE) + (1-\lambda dt)\,\Phi_{\bar{1}}^{n\ell}(E+dE)\right] \quad (38)$$

By extending the right-hand side of (38) using Itô's lemma we obtain the ODE (39), which must be solved for each expression of $F_{\bar{1},\underline{2}}^{n\ell}(E)$ indicated in (37).

$$\left[\mathcal{L} - (\rho+\lambda)\right]\Phi_{\bar{1}}^{n\ell}(E) + \lambda F_{\bar{1},\underline{2}}^{n\ell}(E) + U\left(ED_{\bar{1}}\right) - U\left(rI_1\right) = 0 \quad (39)$$

Following the same reasoning as in (35), the leader's pre-emption threshold in the first technology, $\varepsilon_{0,\underline{1}}^{n\ell}$, is determined numerically by solving (40).

$$F_{0,1}^{f}\left(E\right) = \Phi_{\underline{1}}^{n\ell}\left(E\right) \quad (40)$$

6. Leapfrog Strategy

The competitive advantage created by ignoring the first technology, and, thus not incurring the associated investment cost, may motivate the direct adoption of the second one instead of a compulsive strategy. The game structure we consider in this section is similar to the one discussed in Section 5.2, except that the follower only considers the second technology. Like Takashima *et al.* (2008), we take the perspective of each firm separately and analyse their value functions assuming that it is possible for each firm to assume both roles, i.e. leader and follower. Then, we compare the corresponding investment triggers to conclude which role is feasible for each firm. Having already determined the pre-emption threshold for the second technology under a compulsive strategy in (35), we will now determine the same pre-emption threshold under the assumption that the first technology is ignored. We denote as follower the firm that is pre-empted in the adoption of the first technology, and, therefore, may have a greater incentive to pre-empt the second technology. The follower's value function is described in (41), where the top part is the value of the option to invest and the bottom part is the expected utility of the active project.

$$F_{0,2}^{f}(E) = \begin{cases} A_{0,2}^{f}E^{\beta_1} & , E < \varepsilon_{0,2}^{f} \\ \Upsilon U\left(ED_{\bar{2}}\right) - \frac{U(rI_2)}{\rho} & , E \geq \varepsilon_{0,2}^{f} \end{cases} \quad (41)$$

Note that $A^f_{0,2}$ and $\varepsilon^f_{0,2}$ are obtained analytically via value-matching and smooth-pasting conditions and are indicated in (42).

$$\varepsilon^f_{0,2} = \frac{rI_2}{D_{\overline{2}}}\left[\frac{\beta_2-\gamma}{\beta_2}\right]^{\frac{1}{\gamma}} \quad \text{and} \quad A^f_{0,2} = \left(\frac{1}{\varepsilon^f_{0,2}}\right)^{\beta_1}\left[\Upsilon U\left(\varepsilon^f_{0,2}D_{\overline{2}}\right) - \frac{U\left(rI_2\right)}{\rho}\right] \tag{42}$$

The corresponding pre-emptive leader's value function is denoted by $\widetilde{\Phi}^{n\ell}_{\underline{2}}(\cdot)$ and is described in (43) for $\widetilde{\varepsilon}^{n\ell}_{0,\underline{2}} < E \leq \varepsilon^f_{0,2}$. The first term represents the monopoly profits from operating the second technology and the second term is the loss in expected utility due to the follower's entry.

$$\begin{aligned}\widetilde{\Phi}^{n\ell}_{\underline{2}}(E) &= \mathbb{E}_E\left[\int_0^{\tau^f_{0,2}}\left[U\left(E_tD_{\overline{2}}\right) - U\left(rI_2\right)\right]dt\right. \\ &\left. +\mathbb{E}_E\left[e^{-\rho\tau^f_{0,2}}\right]\mathbb{E}_{\varepsilon^f_{0,2}}\int_{\tau^f_{0,2}}^{\infty}\left[U\left(E_tD_{\underline{2}}\right) - U\left(E_tD_{\overline{2}}\right)\right]dt\right]\end{aligned} \tag{43}$$

By decomposing the first integral and substituting for $\mathbb{E}_E\left[e^{-\rho\tau^f_{0,2}}\right]$ we can rewrite (43) as in (44).

$$\widetilde{\Phi}^{n\ell}_{\underline{2}}(E) = \Upsilon U\left(ED_{\underline{2}}\right) - \frac{U\left(rI_2\right)}{\rho} + \left(\frac{E}{\varepsilon^f_{0,2}}\right)^{\beta_1}\left[\Upsilon U\left(\varepsilon^f_{0,2}\right)\left(D^{\gamma}_{\overline{2}} - D^{\gamma}_{\underline{2}}\right)\right] \ , \widetilde{\varepsilon}^{n\ell}_{0,\underline{2}} < E \leq \varepsilon^f_{0,2} \tag{44}$$

Note that the point of intersection between $F^f_{0,2}\left(\widetilde{\varepsilon}^{n\ell}_{0,\underline{2}}\right)$ and $\widetilde{\Phi}^{n\ell}_{\underline{2}}\left(\widetilde{\varepsilon}^{n\ell}_{0,\underline{2}}\right)$ indicates the point of indifference between being the leader and the follower, and, thus, the pre-emptive leader's threshold, $\widetilde{\varepsilon}^{n\ell}_{0,\underline{2}}$, satisfies the condition $F^f_{0,2}\left(\widetilde{\varepsilon}^{n\ell}_{0,\underline{2}}\right) = \widetilde{\Phi}^{n\ell}_{\underline{2}}\left(\widetilde{\varepsilon}^{n\ell}_{0,\underline{2}}\right)$. Hence, skipping the first technology in order to pre-empt the second one requires that $\widetilde{\varepsilon}^{n\ell}_{0,\underline{2}} < \varepsilon^{n\ell}_{\overline{1},\underline{2}}$, i.e. that the pre-emption threshold of the compulsive leader is greater than the threshold of directly pre-empting the second technology. The feasibility of skipping the first technology to pre-empt the second one can be quantified by comparing the relative value of the two strategies, i.e., $\widetilde{\Phi}^{n\ell}_{\underline{2}}(E)/F^f_{0,1}(E)$, to provide evidence relative to **Hypothesis 4**.

7. Numerical Examples

Compulsive strategy

For the numerical examples, the parameter values are $\mu = 0.01$, $\rho = r = 0.08$, $\sigma \in [0.1, 0.25]$, $\gamma \in [0.7, 1.3]$, $I_1 = 500$, $I_2 = 1500$, $D_{\overline{1}} = 8$, $D_{\overline{2}} = 15$, $D_{\underline{1}} = 12$, $D_{\underline{2}} = 21$ and $\lambda > 0$. These values ensure that there is a trade-off between the two technologies, as in Proposition 1. Figure 7 illustrates the value function of the leader and the follower with respect to the first technology when the second one has yet to become available (left panel), as well as the impact of risk aversion on $\varepsilon^m_{\overline{1},2}$, $\varepsilon^{p\ell}_{\overline{1},\underline{2}}$, $\varepsilon^f_{0,1}$ and ε^m (right panel). According to the left panel, the non-pre-emptive leader does not faces the risk of pre-emption and adopts the first technology at $E = 5.27$. For $5.27 < E \leq 7.88$, the leader enjoys monopoly profits, yet, once the follower

adopts the second technology at 7.88, then both firms share the market. Notice that, upon adoption of the first technology by the follower at $E = 7.88$, the value function of the non-pre-emptive leader (thin curve) is greater than that of the follower (thick curve), because the leader holds the option to invest in the second technology first. Hence, the value function of the non-pre-emptive leader value matches with her own value function in state $\overline{1}$ at $E = 7.88$ and not with the follower's. In line with **Hypothesis 1**&**2**, the right panel indicates that $\varepsilon^{f}_{0,1} < \varepsilon^{p\ell}_{\overline{1},\underline{2}} < \varepsilon^{m}_{1,2}$, as shown in Proposition 3.

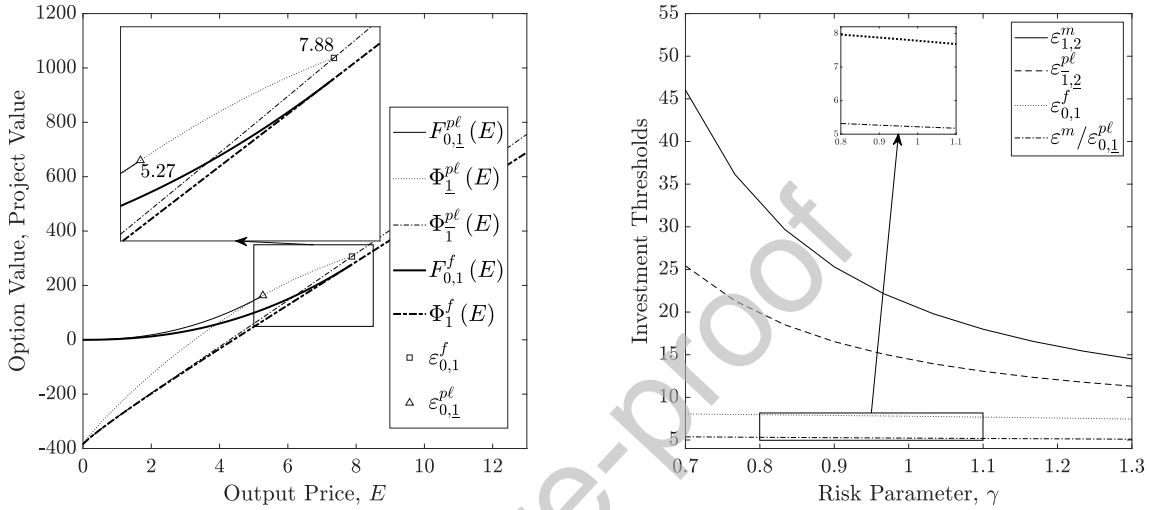

Figure 7: Option and project value of the leader and the follower in the first technology for $\gamma = 0.9$ (left panel) and the follower, non-pre-emptive leader and monopolists investment thresholds (right panel) for $\lambda = 0.1$ and $\sigma = 0.2$.

Figure 8 illustrates the impact of λ and γ on the required investment threshold of the non-pre-emptive leader (left panel) and the follower (right panel) for $\sigma = 0.18, 0.20$. Note that, lower γ implies greater risk aversion, which raises the required investment threshold. Furthermore, price uncertainty increases the required investment threshold of both the leader and the follower by raising the opportunity cost of investing, and, in turn, the value of waiting. Interestingly, although the impact of technological uncertainty on the required investment threshold of the follower is non-monotonic, the non-pre-emptive leader's decision to invest is not affected by technological uncertainty. Intuitively, the former result happens because, in view of maintaining a compulsive strategy, greater λ increases a firm's incentive to adopt the currently available technology in order to have a shot at the yet unreleased version (Chronopoulos & Siddiqui, 2015). Hence, the likely arrival of a new technology raises the value of the option to invest in the existing one, thereby mitigating the loss in the expected utility of the project due to risk aversion. The latter result happens because the follower invests in the first technology before the leader can adopt the second one, as shown in Proposition 3. In turn, this lowers the monopoly profits of the leader, who has to share the first technology with the follower before adopting

the second one. This mitigates the incentive to invest earlier in the first technology (like the follower) when the second one is more likely to become available, thus resulting in a myopic strategy, as stipulated in **Hypothesis 3** and shown in Proposition 4. Hence, the presence of a rival and the trade-off between the two technologies, as expressed in Proposition 1, alter the non-pre-emptive leader's adoption strategy relative to the monopoly case, significantly.

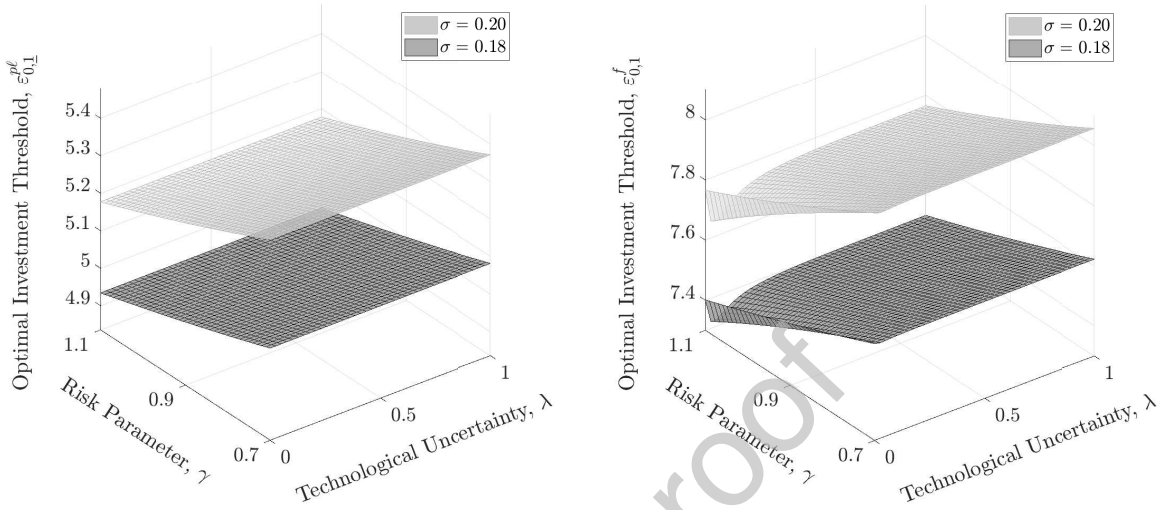

Figure 8: Impact of λ and γ on the optimal investment threshold of the non-pre-emptive leader (left panel) and the follower (right panel).

The left panel of Figure 9 illustrates the impact of λ and γ on the required investment threshold of the pre-emptive leader. Interestingly, greater λ induces later adoption for the leader, which is in line with the accordion effect of Bouis *et al.* (2009). Indeed, this happens because earlier entry of the follower due to technological uncertainty, as illustrated in the right panel of Figure 8, reduces the period of monopoly profits for the pre-emptive leader, thereby decreasing the attractiveness of the first technology. Hence, unlike the benchmark case of monopoly, we observe that a higher innovation rate induces later investment for a given γ. Also, to isolate the impact of a greater first-mover advantage with respect to the first technology, we hold $D_{\underline{2}}$ fixed and find that a greater $D_{\underline{1}}$ lowers the required entry threshold of the pre-emptive leader. The impact of greater first-mover advantage on the required investment threshold of the pre-emptive leader is also illustrated in the right panel in terms of both $D_{\underline{1}}$ and $D_{\underline{2}}$. In both cases, an increase in $D_{\underline{1}}$ or $D_{\underline{2}}$ raises the expected utility of the revenues and lowers the required investment threshold. However, an increase in $D_{\underline{1}}$ has a more pronounced impact on the required investment threshold due to the effect of discounting.

In order to determine the leader's relative loss in value due to the follower's entry, we use the follower's analysis from Section 5.1. Note that the value of the monopolist's option to invest in the first technology is denoted by $F^m_{0,1}(E) = A^m_{0,1}E^{\beta_1}$ for $E < E^m_{0,1}$ and is obtained by replacing $D_{\bar{i}}$ with $D_{\underline{i}}$, $i = 1, 2$ in (25). The impact of γ and σ on the relative loss in the value

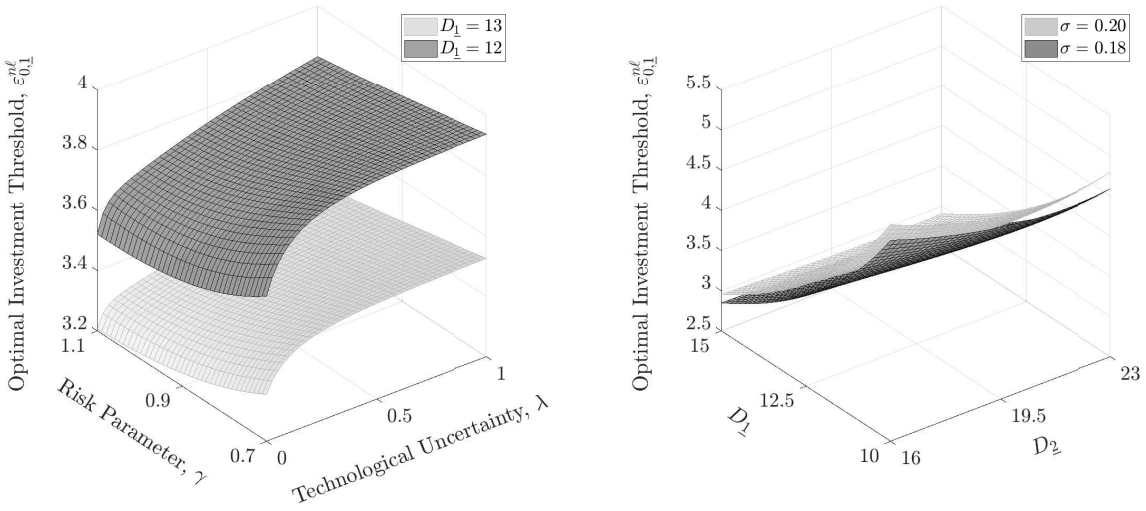

Figure 9: Impact of λ and γ on $\varepsilon^{n\ell}_{0,\underline{1}}$ for $\sigma = 0.18, 0.2$ and $D_{\underline{2}} = 21$ (left panel) and impact of $D_{\underline{1}}$ and $D_{\underline{2}}$ on $\varepsilon^{n\ell}_{0,\underline{1}}$ (right panel).

of the non-pre-emptive and pre-emptive leader is indicated in the left- and the right-hand side expression of (45), respectively, and is illustrated in Figure 10.

$$\frac{A^m_{0,1}\varepsilon^{n\ell\,\beta_1}_{0,\underline{1}} - A^{p\ell}_{0,\underline{1}}\varepsilon^{n\ell\,\beta_1}_{0,\underline{1}}}{A^m_{0,1}\varepsilon^{n\ell\,\beta_1}_{0,\underline{1}}} \quad \text{and} \quad \frac{A^m_{0,1}\varepsilon^{n\ell\,\beta_1}_{0,\underline{1}} - \Phi^{n\ell}_{\underline{1}}(\varepsilon^{n\ell}_{0,\underline{1}})}{A^m_{0,1}\varepsilon^{n\ell\,\beta_1}_{0,\underline{1}}} \tag{45}$$

The left panel in Figure 10 indicates that the impact of price uncertainty on the relative loss in the value of the non-pre-emptive leader is ambiguous and depends critically on the discrepancy in market share. Specifically, the overall impact of σ on the relative loss in the leader's value is twofold, as a higher σ: i. postpones the entry of the follower and raises the period of monopoly profits for the leader; and ii. entails a higher expected loss for the leader at the point when the follower enters the market. The latter effect is more pronounced as the discrepancy in market share increases. As the left panel indicates, when price uncertainty is low a higher σ raises the relative loss in the leader's value for both values of $D_{\underline{1}}$, since the latter effect dominates. However, for higher levels of price uncertainty, the impact of σ on the leader's relative loss in value depends on the discrepancy in market share. Indeed, for $D_{\underline{1}} = 13$ the latter effect dominates, since the follower's entry entails a greater loss for the leader's value despite the delayed entry. However, if the discrepancy in market share is low, i.e. $D_{\underline{1}} = 12$, then the leader's loss in value is not as pronounced and is thus offset by the extra value due to the followers delayed entry. Similarly, as the right panel illustrates, greater price uncertainty and a lower first-mover advantage decreases the relative loss in value for the pre-emptive leader.

The impact of γ and λ on the relative loss in value for the non-pre-emptive (left panel) and pre-emptive leader (right panel) is illustrated in Figure 11. As both panels illustrate, a higher innovation rate lowers the relative loss in the value of the leader by raising the expected utility

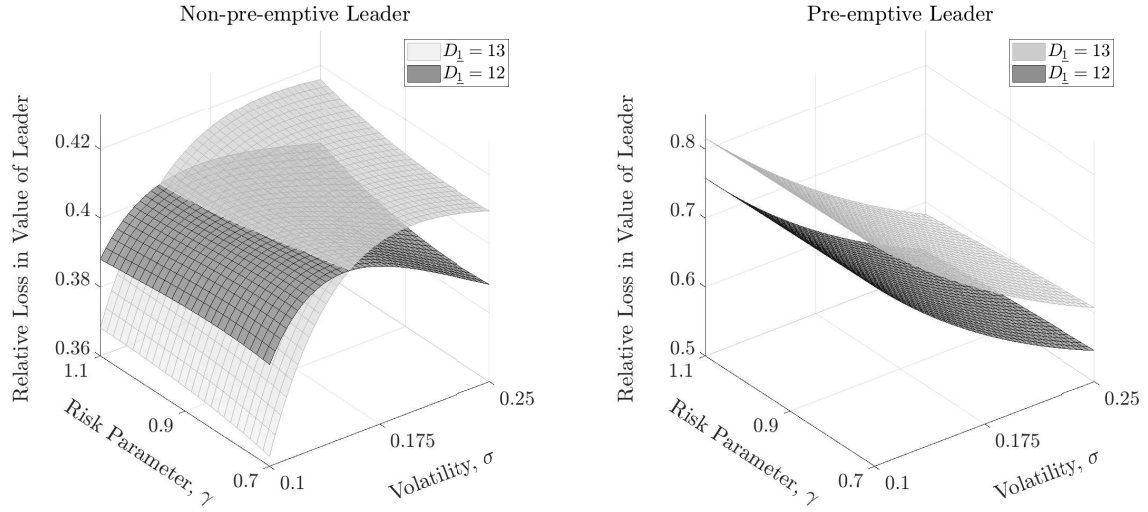

Figure 10: Relative loss in the value of the non-pre-emptive (left panel) and pre-emptive leader (right panel) versus γ and σ for $\lambda = 0.1$ and $D_{\underline{2}} = 21$.

of the embedded option to adopt an improved technology version. Interestingly, risk aversion has an ambiguous impact on the relative loss in the value of the leader. More specifically, under a low (high) rate of innovation, greater risk aversion decreases (increases) the relative loss in the value of the leader. This happens because greater risk aversion postpones the entry of the follower and allows the leader to enjoy monopoly profits for a longer time. However, when λ is high, the second technology is more likely to become available, which gives the leader a greater incentive to invest relative to the monopolist, as shown in Proposition 3. Consequently, like the impact of price uncertainty on the leader's relative loss in value, the likely arrival of the second technology makes the impact of the follower's entry more pronounced in terms of the loss in value it entails for the leader.

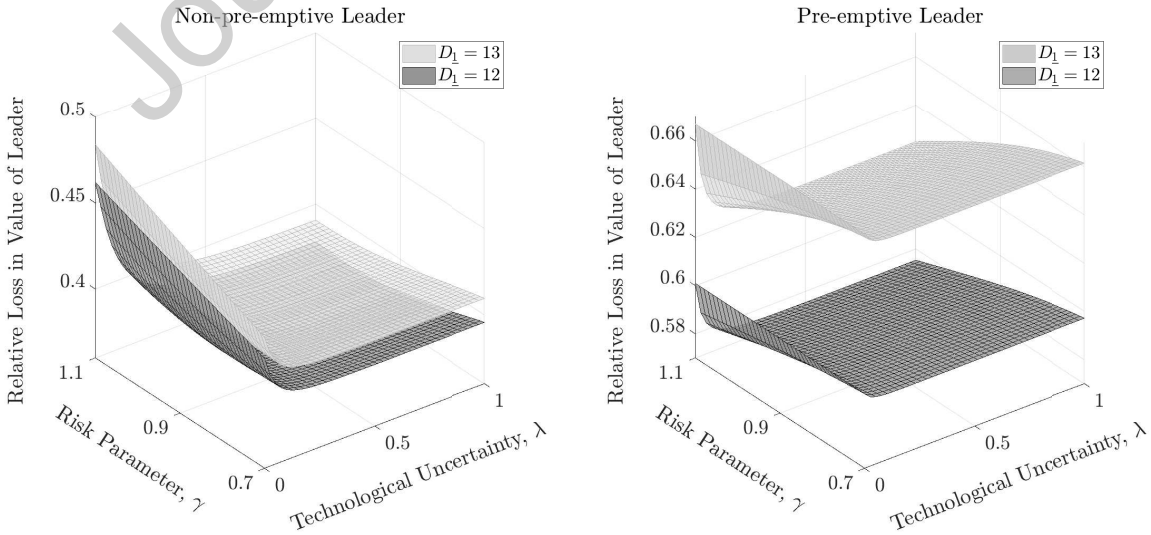

Figure 11: Relative loss in the value of the non-pre-emptive (left panel) and pre-emptive leader (right panel) versus γ and λ for $D_{\underline{2}} = 21$.

Leapfrog Strategy

The left panel in Figure 12 illustrates the feasibility of the leapfrog strategy for $D_{\overline{1}} = 9$, $D_{\underline{2}} = 30$ and $\sigma = 0.3, 0.5$, by identifying the range of values of γ for which the pre-emption threshold of the compulsive leader is greater than the threshold of directly adopting the second technology, i.e. $\widetilde{\varepsilon}^{n\ell}_{0,\underline{2}} < \varepsilon^{n\ell}_{\overline{1},\underline{2}}$. Note that the range of γ for which the leapfrog strategy is feasible increases with lower price uncertainty, which provides evidence in support of **Hypothesis 4**. Intuitively, a less volatile economic environment mitigates the implication of risk aversion by reducing the reluctance to skip the first technology in order to pre-empt the second one. Also, the right panel illustrates the relative value (RV) of skipping the first technology to pre-empt the second technology directly, which is described in (46), under a low and a high output price. Here, we ignore technological uncertainty by assuming that both technologies are available.

$$RV = \frac{\widetilde{\Phi}^{n\ell}_{\underline{2}}(E)}{F^{f}_{0,1}(E)} \tag{46}$$

Note that if the output price is low, then it is always better to be a compulsive follower (two bottom lines). This is in contrast to Huisman & Kort (2004), who find that only the final technology will be adopted when it is likely to become available, whereas in our case a compulsive strategy may be optimal for low output prices due to the trade-off between the two technologies (Proposition 1). However, under a high output price (two top lines), increasing price uncertainty makes it optimal to skip the first technology in order to pre-empt the second one, while lower risk aversion also increases the relative value of pre-empting the second technology. Interestingly, however, even under risk aversion it may be optimal to ignore the first technology and pre-empt the second one directly, provided that price uncertainty is adequately high. Note that this result is in line with Kort *et al.* (2010), who show how the value of stepwise investment decreases with greater economic uncertainty relative to a lumpy investment strategy. However, unlike Kort *et al.* (2010), we do not assume that stepwise investment is associated with an investment cost premium.

8. Conclusions

We analyse how risk aversion interacts with price and technological uncertainty to impact sequential green investment decisions under duopolistic competition. The analysis is motivated by four main features of the modern economic environment: **i.** increasing competition due to the deregulation of many industries; **ii.** market incompleteness and attitudes towards risk; **iii.** the sequential nature of investment decisions in emerging technologies, e.g. energy and R&D; and **iv.** increasing rate of technological innovation/obsolescence. We incorporate these features into a utility-based, real options framework for duopolistic competition, where two identical

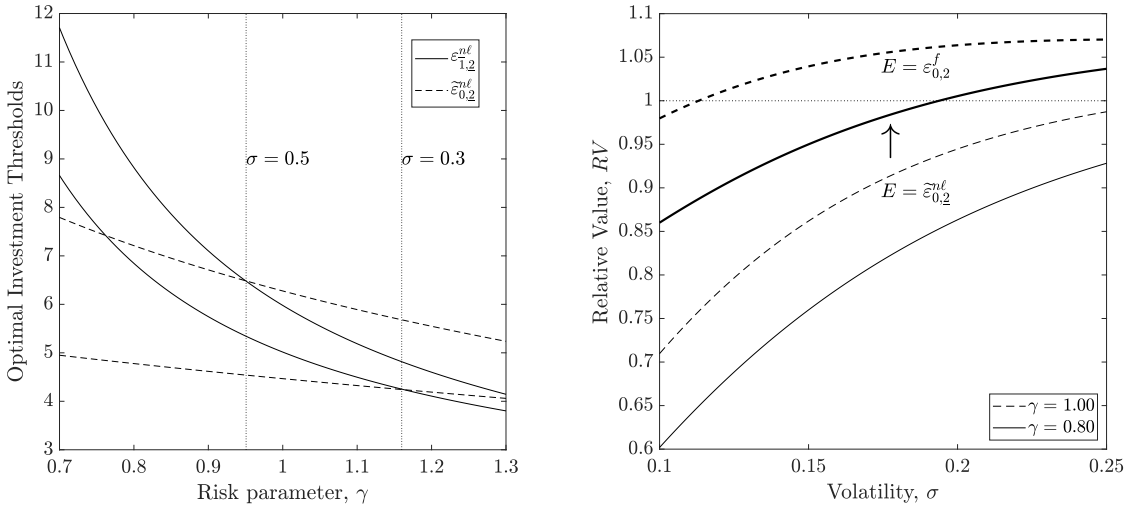

Figure 12: Pre-emption investment thresholds under compulsive and directly adopting the second technology (left panel), and relative value of the leapfrog strategy compared to the compulsive strategy for the follower evaluated at $E = \widetilde{\varepsilon}^{n\ell}_{0,\underline{2}}$ and $E = \varepsilon^{f}_{0,2}$ (right panel).

firms compete in the sequential adoption of technological innovations. Specifically, we assume that the firms compete in the adoption of two technologies, of which the first is available, while the arrival of the second, more improved version, is subject to technological uncertainty.

Results indicate that insights from traditional real options models do not extend naturally to a competitive setting with interacting uncertainties and risk aversion. We find that technological uncertainty increases the follower's incentive to adopt the existing technology. This is in line with Chronopoulos & Siddiqui (2015), who address sequential investment under technological uncertainty, ignoring however strategic interactions and risk aversion. Interestingly, we also show that the non-pre-emptive leader's optimal investment threshold in the existing technology is independent of technological uncertainty and the same as the monopolist's (**Hypothesis 3**). This result is also shown in Siddiqui & Takashima (2012), however, it is derived here within a more general context and reflects the interaction between two opposing forces: i. the incentive for earlier investment due to technological uncertainty (Chronopoulos & Siddiqui, 2015) and ii. the loss in value due to the follower's adoption of the first technology before the leader can adopt the second one. Hence, the leader's loss in value due to the follower's earlier investment mitigates the increase in option value implied by the likely arrival of the second technology. In addition, we show how technological uncertainty delays the entry of the pre-emptive leader and that competition induces earlier adoption of the second technology by the non-pre-emptive leader relative to the monopolist (**Hypothesis 1&2**).

Furthermore, we find that, although greater price uncertainty lowers the relative loss in the value of the pre-emptive leader, the impact of price uncertainty on the relative loss in the non-pre-emptive leader's option value depends crucially on the discrepancy in market share. Also, a

higher innovation rate lowers the relative loss in the value of both the non-pre-emptive and the pre-emptive leader. With respect to the technology adoption strategy, we show how the threat of pre-emption creates an incentive to ignore the existing technology in order to adopt the new one directly, and we identify when this strategy dominates under different levels of economic uncertainty and risk aversion (**Hypothesis 4**).

Extensions in the same line of work may include the flexibility to choose both the time of investment and the size of the project. In line with Huisman & Kort (2015), this will also enable the analysis of how strategic interactions impact social welfare in terms of the time of investment and the amount of installed capacity. Additionally, regulatory risk regarding the availability of subsidies for specific technologies may also be included, as it may impact strategic interactions significantly. Other technology adoption strategies may also be analysed as in Grenadier & Weiss (1997), or asymmetries can be included to analyse non-pre-emptive duopoly as in Takashima *et al.* (2008). Also, our framework may be extended by explicitly modelling the expected delay between the leader's investment decision and the time of that the knowledge spillover takes place, as in Femminis & Martini (2011). Finally, it would interesting to explore the robustness of the analytical and numerical results by allowing the subjective and the risk-free discount rate to differ, by applying an alternative stochastic process, such as a GBM with mean-reversion, or by applying a different utility function.

Acknowledgements: The authors are grateful for the support from the Research Council of Norway through project 268093 and 274569.

Appendix

A. Compulsive Strategy

Each firm's risk preferences are described by the functional $U(\cdot)$, indicated in (A–1), denoting an increasing and concave utility function.

$$E \longmapsto \int_0^{\infty} e^{-\rho t} U\left(E_t\right) dt \tag{A–1}$$

By applying Theorem 9.18 of Karatzas & Shreve (1999) for the HARA utility function described in (2), we obtain (A–2)

$$\begin{aligned} \mathbb{E}_E\left[\int_0^{\infty} e^{-\rho t} U\left(E_t\right) dt\right] &= \frac{2}{\sigma^2(\beta_1-\beta_2)}\left[E^{\beta_2}\int_0^{E}\frac{x^{\gamma}}{\gamma}x^{-\beta_2-1}dx + E^{\beta_1}\int_E^{\infty}\frac{x^{\gamma}}{\gamma}x^{-\beta_1-1}dx\right] \\ &= \Upsilon U(E) \end{aligned} \tag{A–2}$$

where $\Upsilon = \frac{\beta_1\beta_2}{\rho(\beta_1-\gamma)(\beta_2-\gamma)}$ and $\beta_1\beta_2 = -\frac{2\rho}{\sigma^2}$.

Proof of Proposition 1: The expected utility of the profits from operating the first and the second technology is described in (A–3) and (A–4), respectively.

$$\Phi_1^{ab}(E) = \Upsilon U\left(D_1 E\right) - \frac{U\left(rI_1\right)}{\rho} \tag{A–3}$$

$$\Phi_2^{ab}(E) = \Upsilon U\left(D_2 E\right) - \frac{U(rI_2) + U(rI_1)}{\rho} \tag{A–4}$$

Let ε denote the indifference point between the two projects, i.e. the point of intersection of the NPVs of the two projects. First, note that $U(D_i E) = D_i^{\gamma} U(E)$, which implies that the $U(\cdot)$ is homogeneous of degree γ. Also, $\Phi_i^{ab}(E)$ is $\mathcal{C}^1$, $\frac{d}{dE}\Phi_i^{ab}(E) > 0$, $i = 1, 2$ and

$$\frac{d}{dE}\Phi_i^{ab}(E) = \gamma \Upsilon D_1^{\gamma} U\left(E\right)/E < \gamma \Upsilon D_2^{\gamma} U\left(E\right)/E = \frac{d}{dE}\Phi_2^{ab}(E), \quad \forall E > 0. \tag{A–5}$$

Consequently, $\exists! \varepsilon : \Phi_1^{ab}\left(\varepsilon\right) = \Phi_2^{ab}\left(\varepsilon\right)$. The expression of ε is described in (A–6).

$$\Phi_1^{ab}\left(\varepsilon\right) = \Phi_2^{ab}\left(\varepsilon\right) \quad \Rightarrow \quad \varepsilon = \left(\frac{\gamma U(rI_2)}{\Upsilon \rho \left(D_2^{\gamma} - D_1^{\gamma}\right)}\right)^{\frac{1}{\gamma}} \tag{A–6}$$

A trade-off between the technologies requires that $\Phi_i^{ab}\left(\varepsilon\right) > 0$, $i = 1, 2$.

$$\Phi_1^{ab}\left(\varepsilon\right) > 0 \Rightarrow \Upsilon U\left(D_1 \varepsilon\right) - \frac{U\left(rI_1\right)}{\rho} > 0 \Rightarrow \frac{D_1^{\gamma}}{I_1^{\gamma}} > \frac{D_2^{\gamma}}{I_1^{\gamma} + I_2^{\gamma}} \tag{A–7}$$

□

Proof of Proposition 2: The expected utility of the perpetual stream of profits from operating the second technology is described in (A–8)

$$\Phi_2^{f}(E) = \Upsilon U\left(E D_{\overline{2}}\right) - \frac{U\left(rI_1\right) + U\left(rI_2\right)}{\rho} \tag{A–8}$$

and the value function of the follower in state $(1, 2)$ is indicated in (A–9).

$$F_{1,2}^{f}\left(E\right) = \begin{cases} \left[U\left(E D_{\overline{1}}\right) - U\left(rI_1\right)\right] dt + e^{-\rho dt} \mathbb{E}_E\left[F_{1,2}^{f}(E + dE)\right] & , E < \varepsilon_{1,2}^{f} \\ \Phi_2^{f}(E) & , E \geq \varepsilon_{1,2}^{f} \end{cases} \tag{A–9}$$

By expanding the top part on the right-hand side of (A–9) using Itô's lemma, we obtain the ODE (A–10), where $\mathcal{L} = \frac{1}{2}\sigma^2 E^2 \frac{d^2}{dE^2} + \mu E \frac{d}{dE}$ is the differential generator

$$\left[\mathcal{L} - \rho\right] F_{1,2}^{f}(E) + U\left(E D_{\overline{1}}\right) - U\left(rI_1\right) = 0 \tag{A–10}$$

and, solving (A–10), we obtain (A–11).

$$F_{1,2}^{f}(E) = \Upsilon U\left(E D_{\overline{1}}\right) - \frac{U\left(rI_1\right)}{\rho} + A_{1,2}^{f} E^{\beta_1} + C_{1,2}^{f} E^{\beta_2}, \quad E < \varepsilon_{1,2}^{f} \tag{A–11}$$

Note that $\beta_2 < 0 \Rightarrow C_{1,2}^{f} E^{\beta_2} \to \infty$ as $E \to 0$. Hence, we must have $C_{1,2}^{f} = 0$. Also, $A_{1,2}^{f}$ and $\varepsilon_{1,2}^{f}$ are obtained via the value-matching and smooth-pasting conditions between the two

branches of (14) that are described in (A–12) and (A–13), respectively.

$$\Upsilon U\left(ED_{\bar{1}}\right)-\frac{U\left(rI_1\right)}{\rho}+A_{1,2}^{f}E^{\beta_1}\Big|_{E=\varepsilon_{1,2}^{f}} = \Phi_2^{f}(E)\Big|_{E=\varepsilon_{1,2}^{f}} \tag{A–12}$$

$$\frac{d}{dE}\Upsilon U\left(ED_{\bar{1}}\right)-\frac{U\left(rI_1\right)}{\rho}+A_{1,2}^{f}E^{\beta_1}\Big|_{E=\varepsilon_{1,2}^{f}} = \frac{d}{dE}\Phi_2^{f}(E)\Big|_{E=\varepsilon_{1,2}^{f}} \tag{A–13}$$

Thus, the follower's value function in state $(1,2)$ is described in (15). □

Proof of Proposition 3: From Chronopoulos & Siddiqui (2015), we know that uncertainty in the arrival of a new technology increases a firm's incentive to invest in the existing one. Therefore, we denote by $\bar{\varepsilon}_{0,1}^{f}$ the follower's maximum critical threshold taken over all possible values of λ, i.e. $\bar{\varepsilon}_{0,1}^{f}=\max\left\{\varepsilon_{0,1}^{f}:\lambda\in[0,\infty)\right\}$. This is indicated in (A–14).

$$\bar{\varepsilon}_{0,1}^{f} = \frac{rI_1}{D_{\bar{1}}}\left[\frac{\beta_2-\gamma}{\beta_2}\right]^{\frac{1}{\gamma}} \tag{A–14}$$

Also, the follower's optimal investment threshold in the second technology, $\varepsilon_{\bar{1},\underline{2}}^{p\ell}$, is indicated in in (A–15).

$$\varepsilon_{\bar{1},\underline{2}}^{p\ell} = rI_2\left[\frac{\beta_2-\gamma}{\beta_2\left(D_{\underline{2}}^{\gamma}-D_{\bar{1}}^{\gamma}\right)}\right]^{\frac{1}{\gamma}} \tag{A–15}$$

Consequently,

$$\begin{aligned}\varepsilon_{\bar{1},\underline{2}}^{p\ell}>\bar{\varepsilon}_{0,1}^{f} \;&\Leftrightarrow\; rI_2\left(\frac{\beta_2-\gamma}{\beta_2}\right)^{\frac{1}{\gamma}}\left(\frac{1}{D_{\underline{2}}^{\gamma}-D_{\bar{1}}^{\gamma}}\right)^{\frac{1}{\gamma}}>\frac{rI_1}{D_{\bar{1}}}\left(\frac{\beta_2-\gamma}{\beta_2}\right)^{\frac{1}{\gamma}}\\ &\Leftrightarrow\; D_{\bar{1}}^{\gamma}I_2^{\gamma}>I_1^{\gamma}\left(D_{\underline{2}}^{\gamma}-D_{\bar{1}}^{\gamma}\right)\\ &\Leftrightarrow\; \frac{D_{\bar{1}}^{\gamma}}{I_1^{\gamma}}>\frac{D_{\underline{2}}^{\gamma}}{I_1^{\gamma}+I_2^{\gamma}}\end{aligned} \tag{A–16}$$

which holds due to Proposition 1. Therefore, $\varepsilon_{\bar{1},\underline{2}}^{p\ell}>\bar{\varepsilon}_{0,1}^{f}>\varepsilon_{0,1}^{f},\ \forall\lambda\in[0,\infty)$.

Next, because the only difference between a monopolist and a follower is the demand coefficient, we can use (19) to determine $\varepsilon_{1,2}^{m}$ by replacing $D_{\bar{i}}$ with $D_{\underline{i}}$, $i=1,2$. Based on the analytical expression of $\varepsilon_{\bar{1},\underline{2}}^{p\ell}$ and $\varepsilon_{1,2}^{m}$, we obtain (A–17), which holds because $D_{\underline{1}}>D_{\bar{1}}$.

$$\varepsilon_{\bar{1},\underline{2}}^{p\ell}=rI_2\left[\frac{\beta_2-\gamma}{\beta_2\left(D_{\underline{2}}^{\gamma}-D_{\bar{1}}^{\gamma}\right)}\right]^{\frac{1}{\gamma}}<rI_2\left[\frac{\beta_2-\gamma}{\beta_2\left(D_{\underline{2}}^{\gamma}-D_{\underline{1}}^{\gamma}\right)}\right]^{\frac{1}{\gamma}}=\varepsilon_{1,2}^{m} \tag{A–17}$$

□

Proof of Proposition 4: The leader's option to invest in the first technology can alternatively be expressed as in (A–18). This formulation enables the further investigation on the impact of λ on the optimal investment threshold.

$$F_{0,\underline{1}}^{p\ell}(E) = \max_{E_{0,\underline{1}}^{p\ell}>E}\left(\frac{E}{E_{0,\underline{1}}^{p\ell}}\right)^{\beta_1}\left[\Upsilon U\left(E_{0,\underline{1}}^{p\ell}D_{\underline{1}}\right)-\frac{U\left(rI_1\right)}{\rho}+A_{\underline{1}}^{p\ell}E_{0,\underline{1}}^{p\ell\beta_1}\right] \tag{A–18}$$

Note that technological uncertainty, reflected in λ, is embedded in $A_{\underline{1}}^{p\ell}$. However, from Proposition 1 and Proposition 3, we know that $\varepsilon_{0,1}^{f} < \varepsilon_{\overline{1},\underline{2}}^{p\ell}$, i.e. the non-pre-emptive leader cannot adopt the second technology before the follower adopts the first one. This implies that at the follower's optimal investment threshold, $\varepsilon_{0,1}^{f}$, we have $\Phi_{\underline{1}}^{p\ell}\left(\varepsilon_{0,1}^{f}\right) = \Phi_{\overline{1}}^{p\ell}\left(\varepsilon_{0,1}^{f}\right)$. This condition reduces the degrees of freedom of $A_{\underline{1}}^{p\ell}$ to zero and yields the expression (A–19). Consequently, $\frac{d}{dE}A_{\underline{1}}^{p\ell} = 0$.

$$A_{\underline{1}}^{p\ell} = \left(\frac{1}{\varepsilon_{0,1}^{f}}\right)^{\beta_1}\left[\Upsilon U\left(\varepsilon_{0,1}^{f}\right)\left[D_{\overline{1}}^{\gamma} - D_{\underline{1}}^{\gamma}\right] + A_{\overline{1},\underline{2}}^{p\ell}\varepsilon_{0,1}^{f\beta_1} + A_{\overline{1}}^{p\ell}\varepsilon_{0,1}^{f\delta_1}\right] \tag{A–19}$$

Next, the unconstrained optimisation problem (A–18) is solved by applying the FONC to (A–18) with respect to $E_{0,\underline{1}}^{p\ell}$ and the optimal investment rule is outlined in (A–20). The left-hand side of (A–20) can be interpreted as the marginal benefit (MB) of delaying investment and the right-hand side as the corresponding marginal cost (MC). Specifically, the first term on the left-hand side reflects the extra benefit from allowing the project to start at a higher price threshold and the second term is the increase in MB form postponing the investment cost. Similarly, the first term on the right-hand side represents the opportunity cost of forgone cash flows. The third term on the left-hand side represents the MB of postponing the loss in value due to the follower's entry, and the second term on the right-hand side is the MC from waiting, thereby incurring a greater loss in value when the follower enters.

$$\gamma\Upsilon U\left(D_{\underline{1}}\right)\varepsilon_{0,\underline{1}}^{p\ell\ \gamma-1} + \frac{\beta_1 U\left(rI_1\right)}{\varepsilon_{0,\underline{1}}^{p\ell}\rho} - \beta_1 A_{\underline{1}}^{p\ell}\varepsilon_{0,\underline{1}}^{p\ell\ \beta_1-1} = \beta_1\Upsilon U\left(D_{\underline{1}}\right)\varepsilon_{0,\underline{1}}^{p\ell\ \gamma-1} - \beta_1 A_{\underline{1}}^{p\ell}\varepsilon_{0,\underline{1}}^{p\ell\ \beta_1-1} \tag{A–20}$$

The third and second term on the left- and right-hand side of (A–21) cancel and the optimal investment threshold is obtained analytically as indicated in (A–21).

$$\varepsilon_{0,\underline{1}}^{p\ell} = \frac{rI_1}{D_{\underline{1}}}\left[\frac{\beta_2 - \gamma}{\beta_2}\right]^{\frac{1}{\gamma}} \quad \text{and} \quad A_{0,\underline{1}}^{p\ell} = \left(\frac{1}{\varepsilon_{0,\underline{1}}^{p\ell}}\right)^{\beta_1}\Phi_{\underline{1}}^{p\ell}\left(\varepsilon_{0,\underline{1}}^{p\ell}\right) \tag{A–21}$$

□

Pre-emptive Leader

In state $\underline{2}$, the value function of the leader, described in (28), value-matches with the bottom part of the follower's value function, described in (15), at $\varepsilon_{1,2}^{f}$, because for $E \geq \varepsilon_{1,2}^{f}$ the two firms share the market. Thus, the expected reduction due to the follower's entry can be determined from (A–22).

$$\Phi_{\underline{2}}^{p\ell}\left(\varepsilon_{1,2}^{f}\right) = \Phi_{\underline{2}}^{f}\left(\varepsilon_{1,2}^{f}\right) \Rightarrow \left(\frac{E}{\varepsilon_{1,2}^{f}}\right)^{\beta_1}\Upsilon U\left(\varepsilon_{1,2}^{f}\right)\left[D_{\overline{2}}^{\gamma} - D_{\underline{2}}^{\gamma}\right] \tag{A–22}$$

Analogously, in state $\underline{1}$, the discounted change in project value is obtained by value matching (33) with the top branch in (32) at $\varepsilon_{0,1}^{f}$. Hence, $A_{\underline{1}}^{p\ell}$ can be determined from (A–23).

$$\Phi_{\underline{1}}^{p\ell}\left(\varepsilon_{0,1}^{f}\right) = \Phi_{\overline{1}}^{p\ell}\left(\varepsilon_{0,1}^{f}\right) \Rightarrow \left(\frac{E}{\varepsilon_{0,1}^{f}}\right)^{\beta_1}\left[\Upsilon U\left(\varepsilon_{0,1}^{f}\right)\left[D_{\overline{1}}^{\gamma} - D_{\underline{1}}^{\gamma}\right] + A_{\overline{1},\underline{2}}^{p\ell}\varepsilon_{0,1}^{f\beta_1} + A_{\overline{1}}^{p\ell}\varepsilon_{0,1}^{f\delta_1}\right] \tag{A–23}$$

In terms of the first technology, specifically in state $\overline{1}$, the value function of the leader is obtained by solving (38) and the solution is indicated in (A–24).

$$\Phi_{\overline{1}}^{n\ell}(E)=\begin{cases}\Lambda\left[\lambda\Upsilon U\left(ED_{\underline{2}}\right)+U\left(ED_{\overline{1}}\right)\right]-\frac{U(rI_1)}{\rho}-\frac{\lambda U(rI_2)}{\rho(\rho+\lambda)}+A_{\underline{2}}^{p\ell}E^{\beta_1}+A_{\overline{1}}^{n\ell}E^{\delta_1} & ,E<\varepsilon_{1,2}^{f}\\ \Lambda\left[\lambda\Upsilon U\left(ED_{\overline{2}}\right)+U\left(ED_{\overline{1}}\right)\right]-\frac{U(rI_1)}{\rho}-\frac{\lambda U(rI_2)}{\rho(\rho+\lambda)} & ,E\geq\varepsilon_{1,2}^{f}\end{cases} \tag{A–24}$$

□

Proof of Proposition 5: Ideally, the leader would invest at the threshold that maximises her expected utility, i.e. at $\varepsilon_{\overline{1},\underline{2}}^{p\ell}$. However, the threat of pre-emption lowers the adoption threshold to $\varepsilon_{\overline{1},\underline{2}}^{n\ell}$. The price threshold at which the firm is indifferent between being the leader or the follower is defined implicitly via the condition $F_{1,2}^{f}(E)=\Phi_{\underline{2}}^{n\ell}(E)$. Given that the follower adopts a compulsive strategy, there are two possible scenarios: **i.** $\varepsilon_{0,1}^{f}>\varepsilon_{\overline{1},\underline{2}}^{n\ell}$ and **ii.** $\varepsilon_{0,1}^{f}<\varepsilon_{\overline{1},\underline{2}}^{n\ell}$. In the former scenario, the threat of pre-emption is eliminated, however, in the latter the threat still exists. If $\varepsilon_{0,1}^{f}>\varepsilon_{\overline{1},\underline{2}}^{n\ell}$, then the leader will invest at $\varepsilon_{0,1}^{f}$, because $F_{\overline{1},\underline{2}}^{n\ell}\left(\varepsilon_{0,1}^{f}\right)>F_{\overline{1},\underline{2}}^{n\ell}\left(\varepsilon_{\overline{1},\underline{2}}^{n\ell}\right)$. By contrast, if $\varepsilon_{0,1}^{f}<\varepsilon_{\overline{1},\underline{2}}^{n\ell}$, then the leader will have to pre-empt the first technology at $\varepsilon_{\overline{1},\underline{2}}^{n\ell}$. Consequently, the optimal investment threshold is $\max\left\{\varepsilon_{0,1}^{f},\varepsilon_{\overline{1},\underline{2}}^{n\ell}\right\}$. □

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