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Strategic technology adoption and hedging under incomplete markets☆

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ABSTRACT

We investigate the implications of technological innovation and non-diversifiable risk on entrepreneurial entry and optimal portfolio choice. In a real options model where two risk-averse individuals strategically decide on technology adoption, we show that the impact of non-diversifiable risk on the option timing decision is ambiguous and depends on the frequency of technological change. Compared to the complete market case, non-diversifiable risk may accelerate or delay the optimal investment decision. Moreover, strategic considerations regarding technology adoption play a central role for the entrepreneur's optimal portfolio choice in the presence of non-diversifiable risk.

1. Introduction

Entrepreneurs are considered to be an engine of innovation and technological progress for the economy. Their behavior significantly influences aggregate economic fluctuations. They account for a substantial share of aggregate investment, production, and savings.[1] The decision to become an entrepreneur is driven by, among other things, strategic considerations regarding technology adoption, future innovations, and non-diversifiable risk in business projects. We study the implications of these factors on entrepreneurial entry and optimal portfolio choice. In a continuous-time model, we incorporate strategic interactions between two risk-averse agents within the real options paradigm.

For our model design, we focus on two important aspects: market incompleteness and technological change and their impact on investments in industries with competitive pressure. Entrepreneurship is risky due to uncertain future income streams.[2] In addition, entrepreneurship generates a non-diversifiable income risk, as it generally requires substantial ownership in the business.[3] The presence of non-diversifiable risk implies market incompleteness. At the same time, entrepreneurship is widely considered to be a driving factor for technological change and economic growth.[4] As pointed out by Huisman and Kort (2004) in a complete market setting, strategic aspects regarding technology adoption have important implications for both the valuation and timing of investment decisions. In our paper, we combine the incomplete market setup with technology adoption and we study their effects on entrepreneurial investment decisions, thereby extending Huisman and Kort (2004) by adding market incompleteness, as Miao and Wang (2007) do in a monopolistic framework.

Standard real options theory dictates that the optimal time to invest is given by the moment at which productivity reaches a threshold such that the benefit of investment equals the direct cost plus the opportunity cost of investment. The general prediction in

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[1] See, e.g., Rampini (2004) and Cagetti and De Nardi (2006).

[2] Concerned about the low level of entrepreneurial activity in Europe, the European Commission published a survey in which the participants were asked a range of questions related to entrepreneurship, see European-Commission (2010). Asked about the greatest fears when starting up a business, the uncertainty of not having a regular income was mentioned by 40% of the Europeans (and by nearly 50% of the people in the US) as being the most important risk of becoming an entrepreneur.

[3] See, e.g., Gentry and Hubbard (2004); Hall and Woodward (2010) and (Moskowitz and Vissing-Jorgensen, 2002).

[4] This model component is consistent with the general notion from Schumpeter (1934) that technological innovation is a central dimension of entrepreneurship.

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these models is that an increase in volatility leads to a delay in investments. From Miao and Wang (2007) we know that this result does not hold for a lump-sum investment payoff under incomplete markets, but still holds for a flow-payoff investment. However, we show that the joint interaction of technological change and market incompleteness can cause an accelerated investment when volatility increases, even in a model with flow payoff.

It is useful to motivate our model setup in terms of a real world example. In the market for zero-emission vehicles, technological innovation plays a crucial role. While there is mounting political pressure to introduce zero-emission cars, it is not at all clear what these cars should look like:

> "The market outlook for electric vehicles seems bright [...] Yet the future of electric vehicles is far from assured. [...] Will other technologies—such as hybrid cars or vehicles powered by natural gas, ethanol, or hydrogen—emerge and win the competition against electric cars?" ((Graham and Messer, 2011))

The market is relatively uncertain regarding the technology that should power the next generation of cars. Hence, large car companies are reluctant to invest on a large scale, leaving the market open to entrepreneurs. In 2007, the entrepreneur Shai Agassi founded the California-based company *Better Place*, an electric vehicles service provider with a vision of making zero-emission cars. In the *Harvard Business Review*, May 2009, Shai Agassi talks about technology adoption:

> "Every night I went to Wikipedia, picked a term like 'ethanol' or 'natural gas,' and studied for hours. Eventually I wrote a white paper proposing a plan that relies on existing technology: cars that run on lithium-ion batteries recharged by renewable energy." (Akresh-Gonzales, 2009)

Obviously, Shai Agassi decided to rely on an existing technology and not to wait for the arrival of a new technology. However, once a more efficient technology becomes available, competing entrepreneurs may switch to this new technology. Furthermore, the decision to produce and develop zero-emission vehicles is exposed to risks unique to the business that cannot be completely hedged by trading in financial markets. For instance, it may include risks regarding potential suppliers' willingness to set up recharging stations or political initiatives that may foster investment and support for infrastructure in a particular technology. Hence, we believe that the interaction between strategic investments, the timing of technology adoption, and portfolio choice in an incomplete market setting is a highly relevant avenue of research.

Our paper is an extension of two previous studies. On the one hand, we extend (Miao and Wang, 2007) to a setting where *(a)* technology may change and *(b)* not one, but two risk-averse entrepreneurs have access to an investment opportunity. On the other hand, we generalize the equilibrium model of Huisman and Kort (2004) to an incomplete market framework. Each entrepreneur has to strategically decide when to invest and whether to adopt an existing technology for production or wait for a more efficient technology to become available for adoption. In addition, we let our entrepreneurs hedge at least the systematic part of their investment risk in the financial market. Hence, they decide on the optimal time to exercise their real investment option and, in contrast to Huisman and Kort (2004) where entrepreneurs have no access to financial markets, they also have to make optimal intertemporal portfolio decisions. In our model, we also provide an answer to how the optimal portfolio choice is affected by strategic considerations regarding technology adoption.

The joint presence of technological innovation and non-diversifiable risks has two main implications. First, we show that the impact of non-diversifiable risk on the timing of the entrepreneurs' option is ambiguous, and depends on the frequency of technological change and risk aversion. Consequently, the presence of non-diversifiable risk may accelerate or delay the optimal investment timing compared to complete markets. This result contrasts the finding in Miao and Wang (2007). They show that the investment timing decision for a single agent should always be delayed in the presence of non-diversifiable risk compared to complete markets. Their finding has an intuitive explanation. Recalling the standard result from real options theory under complete markets that the option value of waiting is increasing in project volatility (e.g., Dixit and Pindyck, 1994), the presence of non-diversifiable risk should lead to delayed investment. However, when taking into account future technological innovations, we show that this intuition may no longer be reliable.

Second, the model offers new insight into the determinants of optimal portfolio choice for both current and prospective entrepreneurs. The greater the technological innovation and the higher the correlation between operating net income and the risky asset, the more the prospective entrepreneur (follower) should reduce the portfolio allocation to the risky asset. At the same time, the current entrepreneur (leader) should increase the portfolio allocation to the risky asset, in anticipation that the follower optimally exercises their investment option, should the more efficient technology arrive. When the follower decides to exercise the investment option, the leader will experience a reduction in operating income from managing the business and also be less exposed to non-diversifiable income risk, which induces a lower hedging demand. These findings have practical relevance for optimal portfolio choice for both current and prospective entrepreneurs in environments where technological innovation is important.

Two streams of the literature are related to our paper. The first is concerned with extending the real options paradigm to incomplete markets. Miao and Wang (2007) study the optimal consumption and portfolio choice for a single entrepreneur who has a single investment opportunity. Henderson (2007) considers a single entrepreneur who has a single investment opportunity to receive a lump-sum payoff. Managerial investment behavior has been analyzed in Hugonnier and Morellec (2007). Evans et al. (2008) study the optimal time to sell an asset in the presence of wealth effects. Chen et al. (2010) combines a real options model under incomplete markets with Leland (1994)'s capital structure model. Wang et al. (2011) study the effects of non-diversifiable risk on the optimal investment and exit decisions of a single entrepreneur in the presence of financing and liquidity constraints.[5]

A common theme in the above papers is that they only consider the investment decision of a single entrepreneur. In reality, real investment opportunities can rarely be considered in isolation. The second stream of the literature to which our paper is related is concerned with strategic interactions in various forms. An early prominent contribution is Fudenberg and Tirole (1985). In a deterministic setting, they present a theoretical formalization of games in continuous time. Studying technology adoption for two identical firms, they show that preemption should happen at the point where rent equalization occurs between the leader and the follower. Stenbacka and Tombak (1994) extend the model setup in Fudenberg and Tirole (1985) by introducing uncertainty into the length of time from the initial adoption of a technology until its successful implementation. Similarly, Hoppe (2000) extends the setting in Fudenberg and Tirole (1985) to consider uncertainty regarding the profitability of adopting a new technology. Recently, Thijssen et al. (2002) have extended the Fudenberg and Tirole (1985) model to a stochastic setting and in a follow-up paper, Huisman and Kort (2004)

[5] Empirical papers concerned with entrepreneurship and non-diversifiable risk include Heaton and Lucas (2000); Moskowitz and Vissing-Jorgensen (2002) and Hall and Woodward (2010).