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by

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SERIES C: GAME THEORY, MATHEMATICAL PROGRAMMING AND OPERATIONS RESEARCH

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Kuno Huisman
July 2001
Best

Contents

Chapter 1

INTRODUCTION

This chapter is organized as follows. The economic problem on which this book focuses is motivated in Section 1. The two tools used to study this economic problem, which are real options theory and game theory, are discussed in Sections 2 and 3, respectively. Section 4 surveys the contents of this book. In Section 5 some promising extensions of the research presented in this book are listed.

1. TECHNOLOGY INVESTMENT

Investment expenditures of companies govern economic growth. Especially investments in new and more efficient technologies are an important determinant. In particular, in the last two decades an increasing part of the investment expenditures concerns investments in information and communication technology. Kriebel, 1989 notes that (already) in 1989 roughly 50 percent of new corporate capital expenditures by major United States companies was in information and communication technology. Due to the rapid progress in these technologies, the technology investment decision of the individual firm has become a very complex matter. As an example of the very high pace of technological improvement consider the market for personal computers. IBM introduced its Pentium personal computers in the early 1990s at the same price at which it introduced its 80286 personal computers in the 1980s. Therefore it took less than a decade to improve on the order of twenty times in terms of both speed and memory capacities, without increasing the cost (Yorukoglu, 1998).

In the beginning of the twentieth century technological developments did not show such a rapid progress compared to recent years. Therefore, the technology investment problem of the firm mainly was a timing problem, in which the optimal time to replace the current technology had to be determined. For example, one of the technology investment decisions of a railway company dealt with the decision when to replace its steam shunters with diesel shunters. Up to the present day most railway companies still work with diesel shunters.

Nowadays, a firm should take into account that the current state of the art in information and communication technology will be old fashioned in a few years. Thus the investment decision problem is no longer only a question of when to adopt a new technology but also a question of which technology should be adopted. Therefore, in order to design a theoretical framework that is useful to analyze the technology investment decision, it is important to consider models in which several new technologies appear. The timing of the technology investment is (still) very relevant. The reason is that due to the rapid technological progress of information and communication products the prices of those products drop significantly over time. As an example in Figure 1.1 the price development is drawn of two Intel Pentium III processors within the Netherlands.

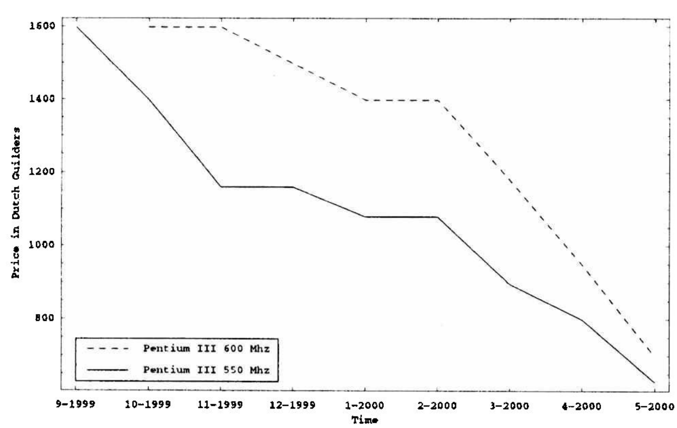

Figure 1.1. Price development of two Pentium III processors within the Netherlands (source: Personal Computer Magazine).

Another significant feature of the last decade is that firms more and more face competition on their output markets. One reason is the abolition of monopolistic markets created by government. In the Netherlands examples are the opening of the markets for telecommunication, railway, and power supply. Until September 1995 KPN Telecom was the only provider on the mobile telecommunication market in the Netherlands. Due to the legislation of the European Community concerning the liberalization of telecommunication markets, the Dutch government organized a contest with as prize a license to operate a mobile telephone company. Libertel won that contest and its network came into use in September 1995. Telfort entered the market in September 1998 and after that Ben and Dutchtone started their services at the end of 1998. Currently these five players are still active on this market. It is obvious that due to the entrance of these four rivals, KPN Telecom had to change its investment strategy dramatically.

Another reason for the existence of and development towards oligopolistic markets is the, still ongoing, process of mergers and takeovers, which due to legislation will not end up with only one supplier in a market. There are plenty of examples of mergers and takeovers in the last decade. In the car industry we have the merger of Daimler and Chrysler in 1998. In the telecommunications market examples are the takeover of AirTouch by Vodafone (partly owner of Libertel) in 1999 and this year's offer of Vodafone to the shareholders of Mannesmann, who entitled it a hostile takeover. However, when Vodafone succeeds in taking over Mannesmann, it has to hive off Orange (which is owned by Mannesmann), otherwise Vodafone's market share in the United Kingdom would become too large. The result of Vodafone's announcement is that there are already four potential buyers for Orange: France Telecom, KPN Telecom, NTT DoCoMo, and MCI Worldcom. This year's announcement of the merger of the Deutsche Bank and the Dresdner Bank is an example in the financial market. The lawsuit between Microsoft and the government of the United States of America is an example of governmental interference to try to reduce Microsoft's (supposed) monopoly power. The overall result of these mergers, takeovers, and governmental interference is that markets with only one supplier and markets with many suppliers seem to disappear in the long run. Thus, in their private investment decisions, more and more firms should take into account the investment behavior by its competitors nowadays.

The existing literature dealing with the technology investment decision of a single firm can be split up into two categories. The models that belong to the first category, which is called *decision theoretic models*, deal with the technology investment decision of one firm in isolation. On the other hand, in the *game theoretic models* the optimal technology investment strategy of the firm is derived while taking explicitly into account the technology investment actions of the firm's rival(s). From the economic observations described above, it can be concluded that there is a strong need to use game theory with respect to the theoretical modelling of technology investment by the individual firm. A literature overview of the decision theoretic models and the game theoretic models are given in the first sections of Chapters 2 and 4, respectively. Part I of this book deals with decision theoretic models and in Parts II and III two different game theoretic models are considered.

In the following section we discuss the topic of investment under uncertainty in more detail, whereas in Section 3 we concentrate on investment under competition.

2. INVESTMENT UNDER UNCERTAINTY

Investment is defined as the act of incurring an immediate cost in the expectation of future rewards (see p. 3 of Dixit and Pindyck, 1996). Most investment projects possess the following three characteristics: irreversibility, uncertainty, and possibility of delay.

An investment is irreversible when the investment cost is a sunk cost, that is it is impossible to recover the investment cost once the investment is made. This surely holds for investments in information and communication goods. It is impossible to sell a one-year-old personal computer for the same price as for which it was bought. More generally, most industry or firm specific investments are irreversible. For example, the marketing and advertisement expenditures of KPN Telecom are firm specific and cannot be recovered, i.e. KPN Telecom cannot sell this investment project to another telecommunication company. An example of an industry specific investment is the construction of a new mobile network by Libertel. This investment will be (at least partially) sunk, because whenever it is no longer profitable for Libertel to exploit this network it will not be profitable for another mobile provider as well. Due to the lemon's problem (see Akerlof, 1970) a lot of investments that are not firm or industry specific are also irreversible.

An investment project (almost) always has to deal with uncertainty. For most investments the future revenues are stochastic, due to uncertainties in, e.g., the firm's market share and the market price. It is also possible that the investment cost is uncertain, which is the case in many infrastructure projects. For example the actual costs of the *Oosterschelde Stormvloedkering*, which is one of the last projects of the Dutch Delta works, turned out to be much higher than what was forecasted.

From a technical point of view it is almost always possible to defer an investment for some time. This possibility to delay an investment gives a firm flexibility. Though, economically this postponement can be costly in the sense that the firm looses market share if it refrains from the investment. On the other hand, by postponing an investment the firm can acquire more information about the investment project, for example concerning the market conditions.

The net present value method is the commonly used (and taught) method to evaluate investment projects (see for example Brealey and Myers, 1991). This method states that an investment should be undertaken when the expected (discounted) present value of the revenue stream resulting from this investment project exceeds the expected present value of the expenditures. However, the underlying assumption of the net present value method contradicts the characteristics of investments we mentioned before. More precisely, the net present value method assumes that either an investment project is reversible or when it is irreversible it is a now or never decision, that is, the firm can undertake the investment project today or never. As a result, applying the net present value method leads to suboptimal investment decisions. Especially the ignorance of the possibility to delay is an important abuse, since most investment projects are irreversible. The real options literature succeeds in explicitly valuing this so-called option value of waiting.

In the real options theory the analogy between a firm's investment opportunity and a financial call option is exploited. A financial call option gives the holder the right, but not the obligation, to buy one piece of the underlying derivative (e.g. stock, bond) for a specified price (before or) at a specified time. See Hull, 1993 and Merton, 1992 for a detailed exposition of the financial options theory. Similar to a financial call option, an investment opportunity gives a firm the right, but not the obligation, to carry out some investment project. Note that, following the analogy, an investment project is an infinitely lived call option on a dividend paying derivative. From the financial options theory it is known that such an option should only be exercised when the option is sufficiently deep in the money, that is when the current price of the underlying derivative is sufficiently larger than the exercise price. Therefore an investment project should only be undertaken when the net present value exceeds the option value of waiting.

Due to the close link with financial options theory, most real options models assume that the revenue stream of the investment project follows some geometric Brownian motion process. A geometric Brownian motion process is a continuous time stochastic process of which the increments are distributed according to a normal distribution. In McDonald and Siegel, 1986 the basic continuous time real options model is examined. In that model a firm can acquire a project, of which the value follows a geometric Brownian motion process, by making an irreversible investment. Mcdonald and Siegel derive an explicit expression for the option value of waiting, and show that for reasonable parameters the optimal investment trigger is twice as large as the net present value trigger, i.e. for an investment to be optimal the value of the project should be twice as large compared to the required value under the net present value method. The basic real options model has been extended in various ways. An excellent overview is given in Dixit and Pindyck, 1996. In Trigeorgis, 1995, Trigeorgis, 1996, Smit, 1997, Pennings, 1998, Lander and Pinches, 1998, and Amram and Kulatilaka, 1998 practical applications of the real options theory are presented and discussed.

However, most of the extensions of the basic real options model assume that the firm is the only one having the investment opportunity, that is, strategic interactions are ignored. In the previous section we stressed the importance of taking strategic interactions into account. In the next section we give an overview of the models that do incorporate these strategic interactions.

3. INVESTMENT UNDER COMPETITION

Investment models that incorporate strategic interactions make use of game theory. In most of these models non-cooperative game theory is used since in general the firms are competing against each other and there is no willingness to cooperate. For a rigorous introduction to game theory we refer to Fudenberg and Tirole, 1991. In Tirole, 1988 a nice overview of industrial organization models is given. In this book we mainly use and extend the game theoretic concepts presented in Fudenberg and Tirole, 1985, in which a deterministic investment model of two competing firms is extensively analyzed, especially from a mathematical point of view.

One of the first real options models that incorporates strategic interactions is the duopoly model in Smets, 1991. This model is also considered in Chapter 9 of Dixit and Pindyck, 1996 and in Nielsen, 1999. As in the basic real options model the revenue stream of the investment project follows a geometric Brownian motion. However, in this model the actual revenue stream of one firm depends on the investment decision of the other firm. Nielsen proves that due to the introduction of a second identical firm, the first investment will be made sooner. Like in Smets, 1991, also in Pennings and Sleuwaegen, 1998 a model of foreign direct investment in a real options setting is studied.

Other continuous time real options models with strategic interactions are studied in Grenadier, 1996, Baldursson, 1998, Lambrecht and Perraudin, 1999, and Weeds, 1999. Grenadier models the real estate development. In Baldursson's model the firms can adjust their capacity continuously over time and optimal strategies to do so are derived. Lambrecht and Perraudin consider a model with incomplete information, in which they assume that the other firm's profitability of the investment project is not known and there is only one firm that can implement the project. Finally, Weeds models a research and development race between two firms.

Also related are the models in Smit, 1996, Smit and Ankum, 1993, Kulatilaka and Perotti, 1998, and Somma, 1999. The difference with the contributions mentioned above is that, instead of a continuous time model where uncertainty is incorporated by, e.g., a geometric Brownian motion process, in each of these models binomial trees are used to model strategic interactions between firms. Consequently, most of these models are in discrete time.

4. OVERVIEW

This book is divided into three parts. The first part consists of two decision theoretic models in a real options setting. In the second part three game theoretic technology adoption models are considered, whereas in the third part three general game theoretic real options models are presented.

4.1 DECISION THEORETIC MODELS

Chapter 2 starts with a literature overview of the decision theoretic models of technology adoption. The model of Chapter 2, which is a generalization of Farzin et al., 1998, studies the technology adoption of a single firm. A firm can adopt a better technology by making an irreversible investment. The investment cost of a certain technology is assumed to be constant over time. With a better technology the firm can produce more efficiently and will therefore make higher profits. New technologies arrive over time according to a stochastic process and the efficiency increment of a new technology is also stochastic. First we solve the model for the case that the firm may invest only once and after that the multiple switch case is discussed. The multiple switch case is only solvable when the efficiency increments of the new technologies are known beforehand. Finally, the optimal investment strategy is compared with the strategy resulting from the net present value method. It turns out that in making the investment decision the option value of waiting cannot be ignored, which is also shown in a numerical example. In the Appendix to Chapter 2 we give an introduction to a technique that is frequently used in this book: optimal stopping.

The model of Chapter 2 is extended in Chapter 3 by making the investment cost decreasing over time. The motivation for this model feature is illustrated in Figure 1.1. The efficiencies of the new technologies are assumed to be known beforehand. The optimal investment strategy for the single switch case is derived and compared with its net present value counterpart. After that, it is explained why it is not possible to solve this model analytically for the multiple switch case.

4.2 GAME THEORETIC ADOPTION MODELS

In Chapter 4 we first give a literature overview of game theoretic models of technology investment. After that we analyze the most important and basic deterministic model in this research area (see Reinganum, 1981 and Fudenberg and Tirole, 1985) in detail. Two identical firms that are currently active on an output market can make an irreversible investment that will increase their own and decrease their rival's profit. The investment cost is decreasing over time. This investment game is solved using timing games. In the Appendix to Chapter 4 we present an introduction to this specific class of games. The player that moves first in a timing game is called the leader and the other is the follower. Reinganum assumes in her analysis that one of the firms is given the leader role beforehand. In Fudenberg and Tirole's analysis the firm roles are determined endogenously, that is both firms can become the leader by making the investment before its rival. It turns out that the result is that each firm's payoff is equal in equilibrium. The remainder of Chapter 4 deals with the extension of Stenbacka and Tombak, 1994 to the Reinganum-Fudenberg-Tirole model, which is also is considered in Huisman and Kort, 1998a and in Götz, 2000. Stenbacka and Tombak assume that the time between the adoption and successful implementation of the new technology is stochastic.

Chapter 5 is based on Huisman and Kort, 1998b. The model of that chapter is an extension of the basic model by incorporating two new technologies and upgrading. At the beginning of the game none of the two firms is active on the output market. To become active a firm has to pay a sunk cost, for which the firm receives the current best technology. The firm can also decide to postpone the entrance and buy the better technology that becomes available at a known point of time in the future. Furthermore, there is a possibility to upgrade the current technology with the new technology. There are learning effects involved in this upgrading strategy, since it is cheaper to buy the new technology when the firm already produces with the current technology. Two of the nine possible scenarios are worked out in detail.

Chapter 6, which is based on Huisman and Kort, 2001, extends the model of Chapter 4 by adding uncertainty to the arrival process and by considering multiple new technologies. Further it is assumed that the two firms can invest only once. After introducing a new concept in timing games, namely the waiting curve, a general algorithm for solving