Real Options and Strategic Competition: A survey

by

Marcel Boyer,
Economics and CIRANO, Univ. de Montréal

Éric Gravel,
CIRANO

Pierre Lasserre,
Economics and CIRANO, Univ. du Québec à Montréal

May 2004

Note to the reader:
This version of the paper is preliminary.
A more complete and integrated version
will be available at the time of the conference.

We review in this paper the main contributions to the joint analysis of real options and strategic competition in a dynamic setting. We use the modeling structure of Boyer, Lasserre, Mariotti and Moreaux (2004) in surveying and integrating the literature.

As stated by Boyer, Lasserre, Mariotti and Moreaux (2004), real option theory is reaching advanced textbook status and is rapidly gaining reputation and influence. Although both popular writers and specialists warn against its often daunting complexity, they also stress its unique ability to take account of future flexibility and the importance of future moves and decisions in valuing current investments.

The real options approach emphasizes the indivisibility and irreversibility of investments; indivisibilities often imply a limited number of players, hence imperfect competition. Yet, while it is often stressed that real option theory is best to analyze investments of strategic importance – the word 'strategic' appears repeatedly in the real-options literature – the bulk of that literature involves decision makers playing against nature rather than against other players. The analysis of strategic considerations, in a game theoretic sense, is still in its infancy and should be high in the real-option research agenda. The objective of this paper is to review those contributions.

Notable exceptions are Grenadier (1996) who uses a game-theoretic approach to option exercise in the real estate market; Smets (1995) who provides a treatment of the duopoly in a multinational setup, which serves as a basis for the oligopoly discussion in Dixit and Pindyck (1994, pp. 309-14); Lambrecht and Perraudin (1997) and Mariotti and Décamps (2000) who investigate the impact of asymmetric information about costs on firms' investment strategies; Weeds (2002) and Huisman (2001) who study option games in a technology adoption context. To this list, one could add the book by Smit and Trigeorgis (forthcoming).

Boyer, Lasserre, Mariotti and Moreaux (2004) extend these pioneering contributions while bringing to bear the older, and highly relevant, literature on strategic investment, most notably Gilbert and Harris (1984), Fudenberg and Tirole (1985), and Mills (1988). These papers help address surprisingly modern questions at the dawn of the information technology revolution: what is the role of investment decisions in shaping the structure of a developing sector? Do competing investments lead to preemption, rent equalization, and rent dissipation as in Fudenberg and Tirole? Or are firms able to tacitly collude in a non cooperative way and avoid cannibalism despite the threat of preemption? Can a first-mover advantage be maintained and reinforced as in Gilbert and Harris (1984) or Mills (1988) or does the laggard catch up? In which ways are option values and exercise rules affected by such strategic considerations?

The recent synthetic work of Athey and Schmutzler (2001) brings more generality and clarity to our understanding of the role of investment in market dominance. They provide conditions on current payoffs for weak increasing dominance, in a framework that encompasses as special cases such models as Bertrand or Cournot competition with differentiated goods, horizontal competition on the line, and vertical quality differentiation. However, they also show that, when firms are farsighted and are not forced to commit to strategic investment plans in advance, there is little hope to obtain definitive predictions outside more specific models. This is precisely the setup considered in Boyer, Lasserre, Mariotti and Moreaux (2004): dynamic investment without commitment, Markov perfect strategies. They restrict their attention to duopoly on a homogeneous product market with incremental indivisible capacity investments, while paying particular attention to the role of uncertainty and the speed of market development on investment strategies and competition.

¿From a methodological point of view, their paper uses the formalism of real options: they find optimal exercise rules and evaluate the corresponding options. However these options correspond to the payoffs of particular strategies in a game-theoretic sense. In order to investigate the above game-theoretic issues in a real-options framework, they need to address them in a continuous-time context where irreversible investment decisions are made by rival firms under uncertainty about the future evolution of the market and the industry. they achieve this by extending Fudenberg and Tirole (1985)'s formalism for modelling games of timing to such an environment.

While the basic economic model used throughout Boyer, Lasserre, Mariotti and Moreaux (2004) is very similar to Gilbert and Harris' (an industry faces growing demand with indivisibilities in installing new capacity; firms have access to the same technology; time is continuous), using these more recent contributions allows them to avoid any technical assumption that gives a first-mover advantage to a player. Since they want to investigate preemption and other strategic aspects, they assume that the firms cannot commit *ex ante* to any sequence of investments, an important characteristic of real life contexts.

Boyer, Lasserre, Mariotti and Moreaux (2004) show that both the size of capacity units relative to the market and the relative existing capacities of the firms are important in their own way. In their model, market develops indefinitely, but the basic unit of capacity never becomes negligible relative to market size. Yet excess capacity cannot be used by one firm to hold the other one at bay permanently. If one firm holds excess capacity, the other firm will eventually hold enough capacity to serve half the market. This is in sharp contrast with Gilbert and Harris' famous preemption equilibrium where a single firm accounts for the totality of industry capacity, although without enjoying any more profits than its dwarfed rivals. If both firms are restricted to one more investment at most, a setup similar in that respect to Fudenberg and Tirole (1985), Grenadier (1996), Weeds (2002), and others, Boyer, Lasserre, Mariotti and Moreaux (2004) show that the smaller firm moves first in a preemption equilibrium.

As other authors have already found in related models, two types of equilibria may arise: preemption equilibria involving rent equalization and dissipation, and equilibria involving tacit collusion. Although collusion equilibria do not necessarily maximize joint profits, they are Pareto superior to preemption equilibria from the firms' point of view as the firms implicitly agree to postpone their investment in such a way as to preserve existing rents.

In Boyer, Lasserre, Mariotti and Moreaux (2004), low initial capacities are of particular interest in the case of emerging sectors. When a firm does not hold any existing capacity it cannot be threatened with the loss of any existing rent; as a result a tacit-collusion equilibrium cannot be enforced and preemption is the sole equilibrium. Thus the initial development of an industry is highly competitive although the preemption equilibrium is characterized by the presence of only one active firm at first. Paradoxically, once both firms are active, tacit-collusion equilibria may be possible so that the industry may become less competitive despite the presence of more active firms. Collusion is also more efficient between firms of equal size in the sense that, when collusion equilibria exist, the joint investment date that maximizes combined profits is an equilibrium; in contrast collusive strategies that maximize combined profits do not yield an equilibrium when firms are not of equal size.

It is well known that higher volatility raises the value of investment (call) options because the decision maker can achieve higher exposition to upside movements while being protected from downside ones. In a strategic setup, volatility further affects collusion opportunities. More precisely Boyer, Lasserre, Mariotti and Moreaux (2004) find that above some threshold level of uncertainty, collusion equilibria always exist among firms that hold positive capacity. The speed of market development plays a role similar to the drift of the underlying asset in financial options. Under usual assumptions, the drift does not affect the value of a financial option; volatility alone matters. However such result does not obtain in their paper; market growth affects investment option values, together with volatility and other parameters. This is because, in a non perfectly competitive context, one cannot adopt the spanning assumption frequently made in financial and real options analyses (see Dixit and Pindyck, 1994) and which make expected capital gains on the underlying asset irrelevant. Moreover, Boyer, Lasserre, Mariotti and Moreaux (2004) show that in such a context of strategic real options, market growth can affect collusion opportunities: there is an expected market growth rate above which tacit-collusion equilibria exist.

Rather than trying to derive a general characterization of the solution, which would be quite involved, Boyer, Lasserre, Mariotti and Moreaux (2004) consider a succession of special cases which bring up the issues and mechanisms involved. This highlights the important role played by capacity acquisitions and existing capacity, and by the volatility and speed of the market growth process.

Following are some of the important works that will be more intensely reviewed in light of Boyer, Lasserre, Mariotti and Moreaux (2004) in the forthcoming version to be made available at the conference.

I. The decision theoretic exogenous competition (one-shot) approach.

Trigeorgis (1991) studies the impact of competition on the optimal timing of project initiation using option methodology. Consistent with option pricing, in the absence of competition and other costs of waiting, an incumbent firm would delay project initiation. However, as recognized in the literature, the presence of competition may speed up a firm's planned investment. Results of the analysis show that, in the case of early investment that can preempt anticipated competitors, option valuation may enable management to determine whether and when to invest early for preemptive reasons or whether to wait despite anticipated competitive erosion.

Ankum and Smit (1993) consider that an investment strategy encompasses a sequence of tactical investment projects, of which several may yield a low return when considered in isolation. The net present value method has serious shortcomings in analyzing projects when future decisions are contingent on intermediate developments in an uncertain environment. Option theory provides a better analytical tool to evaluate such projects. Using simple numerical examples, the influence of competition on project value and investment timing is illustrated. Postponement under perfect competition implies a loss in the expected value of the project due to anticipated competitive entry. Absence of a structural competitive advantage may thus result in a tendency to invest early if the firm can preclude this erosion of value.

Ankum and Smit use numerical examples and the binomial valuation method to study the effect of competitive interactions on the decision of waiting to invest. The settings considered are monopoly, perfect competition, symmetric and asymmetric duopoly. To conceive their model, the authors exploit the parallel between the option of waiting to invest and a call option on a dividend paying stock. In the latter case, the opportunity cost of holding the option instead of the stock is the foregone dividend plus the return from dividend reinvestment. In the former case, the opportunity cost of waiting is that of renouncing to the cash flows of an operational project.

In this model, expected cash flows from the operational project are decomposed into two items. The first item is equal to the cash flows necessary to obtain a return equal to the cost of invested capital and the second item represents economic rents. The difference in competitive settings is accounted for by adjusting the expected economic rents. For a monopoly, expected economic rents are constant. For perfect competition, assuming initial rents, they are expected to decline exponentially with entry until the return on the project is equal to its cost of capital.[1] Finally, in a duopolistic setting, rents evolve according to the competitor's actions, if a firm is preempted, a portion of the rents is lost depending on the relative strength of the rival.

Compared to a monopoly, because of the temporal erosion of economic rents, there is a stronger incentive to invest early in perfect competition. In a duopoly, the project's cash flows fall as soon as a competitor enters the market, a firm can avoid this loss in value by preempting. In a symmetric duopoly, fearing preemption, both firms will invest early compared to the optimal case where coordination is possible. When one firm has a dominant position in the industry, because of the low threat of complete preemption, the dominant and dominated can safely delay investment. Finally, in each case, when the project has a high initial NPV, early investment is optimal.

Perotti and Rossetto (2001) investigate the timing and the valuation of strategic investment aimed at enhancing entry opportunities in related market segments. As demand is uncertain, entry options should be exercised at the optimal time, trading off the market share gain against the option to wait until more information is revealed, while anticipating competitors' entry behavior. When the strategic investment grants a strong competitive advantage, the innovator can optimally choose the timing of entry; in case of weaker advantage, the investing firm enters just before its competitor would. In a context of increased uncertainty, the value of waiting to invest rises, but the value of a strategic investment increases even more. In some cases, strategic investment can act as a threat to discourage cross-entry, making parallel monopoly sustainable.

Cottrell and Sick (2002) note that the value in real options comes from the firm's ability to wait until conditions are optimal before moving forward with a project. There may be a loss of this optimal value if decision-makers anticipate preemptive entry by a competitor.

[1] In the perfect competition case, initial economic rents are present because the firm gained an early foothold in the market by investing in a pilot project.

Pioneers that enter markets early might ignore or spoil the real option value from delay. Although market pioneers may gain first-mover advantages, followers have important advantages as well. They discuss these follower advantages, providing examples of successful delay in the context of a real option on innovation.

II. The strategic analysis (simultaneous, sequential) with single decisions.

Grenadier (1996) develops an equilibrium framework for strategic option exercise games. He focusses on a particular example: the timing of real estate development. An analysis of the equilibrium exercise policies of developers provides insights into the forces that shape market behavior. The model isolates the factors that make some markets prone to bursts of concentrated development. The model also provides an explanation for why some markets may experience building booms in the face of declining demand and property values. While such behavior is often regarded as irrational overbuilding, the model provides a rational foundation for such exercise patterns.

At the start, both developers own and lease a building at a rate of R per unit of time and each firm has the option to scrap the current asset and invest I (new building costs) to erect a superior property with a rental rate equal to $P(t) = X(t) \cdot D[Q(t)]$. Here $X(t)$ is a geometric Brownian motion governed stochastic demand shock and $D[Q(t)]$ with $D' < 0$ is a deterministic inverse demand function with $Q(t) \in \{0, 1, 2\}$ representing the number of new buildings at time t. A new building takes time δ to build (in years), if the developer starts construction at τ, he renounces to R and he starts receiving rental income from the new building only at $\tau + \delta$. Furthermore, the presence on the market of a superior building renders the older asset obsolete which causes its lease rate to fall to $(1 - \gamma) \cdot R$ with $\gamma \in (0, 1)$.

Working backwards in a stochastic dynamic-programming fashion, Grenadier first determines the follower's value $F(X)$ along with the optimal exercise threshold X_F, all this is conditional on the leader's presence in the market. The leader's value $L(X, \tau)$ conditional on the optimal follower strategy is then found with τ equal to the time remaining before completion. Part of the leader's value comes from a period of monopoly profits. With these values, the author establishes the existence of two classes of equilibria. Initially, if the market is at $X(0) < X_F$, a sequential equilibrium will occur as follows. If $X(0) < X_L$, both firms will wait until $X(t)$ reaches X_L, at that point, the leader will start building and the other will exercise when $X(t)$ attains X_F. Otherwise, if $X_L \leq X(0) < X_F$, each firm will be willing to build immediately and luck will determine the leader. Because of symmetry, any firm can be the leader.

Consider now the case where $X(0) \geq X_F$, in this situation, equilibrium will be characterized by simultaneous entry and two motives for this coexist depending on the evolution of demand. To distinguish these two motives, Grenadier defines a band of values (X_F, X_J), here X_J is equal to the Pareto optimal exercise threshold i.e. X_J maximizes the joint value of simultaneous entry.[2] When $X(t) \in (X_F, X_J)$ both firms are in an inactive range, if $X(t)$ is equal or superior to X_J simultaneous investment maximizes the value of both firms. Now for the second motive, according to proposition 2, if $X(t)$ falls bellow X_F, the value of being the leader is larger than that of the follower, fearing preemption, both will enter immediately if $X(t)$ ever falls to X_F.

Finally, the model is used to provide a rational explanation for observed phenomenons in the real estate market. Grenadier considers development cascades and recession-induced construction booms. A development cascade is defined as a rapid succession of building starts, in this case, construction is concentrated in short periods of time. For its part, a recession-induced construction boom is qualified as exercising after a fall in demand.[3]

Huisman and Kort (1998) analyze technology adoption in the context of a duopoly, where the time between adoption and successful implementation is uncertain. This framework is taken from Stenbacka and Tombak, and as such it adds uncertainty to the much cited work of Fudenberg and Tirole. The analysis is mainly focused on the case where the firm roles are endogenous. They find that under a certain scenario dispersed adoption timings turn into joint-adoption when firm roles become endogenous. Further, it is shown that for reasonable parameter values it can happen that the profit stream belonging to the preemption equilibrium is so low that both firms are even better off if they both decide to stick to producing with their old technology forever.

[2] An infinity of ranges (X_F, X_J) can be considered each giving the same type of equilibrium. However, the author argues that because the Pareto optimal equilibrium dominates all others, it is the most reasonable one to expect.

[3] Also deemed "irrational" construction.

Joaquin and Butler (1999) develop a strategic investment model in which a firm has a competitive advantage over another. Competitive advantage is modeled here through asymmetric payoffs arising from differential cost. Allowing for asymmetric costs makes identification of the competitive equilibrium simpler and more intuitive, with the lower-cost firm entering first. Their model is a continuous-time version of the second stage of the discrete-time strategic model of Smit and Trigeorgis (1997), which also allows for unequal costs and managerial flexibility in output decisions.

Grenadier (1999) notes that in many real-world situations, agents must formulate option exercise strategies with imperfect information but may infer the private signals of other agents through their observed exercise strategies. The building of an office building, the drilling of an exploratory oil well, and the commitment of a pharmaceutical company toward the research of a new drug all convey private information to other market participants. He develops an equilibrium framework for option exercise games with asymmetric private information. Many interesting aspects of the patterns of equilibrium exercise are analyzed. In particular, informational cascades, where agents ignore their private information and jump on the exercise bandwagon, may arise endogenously.

Huisman and Kort (1999) extend the results of Fudenberg and Tirole (1985) by introducing demand uncertainty. In this setting, two symmetrical competing firms have the option to adopt a new technology (or other investment) that increases the flow of profits. Furthermore, it is more profitable to be the single user of the technology compared to the case where both firms adopt and there is a first mover advantage. Three scenarios are identified. In the first scenario, a preemption equilibrium with dispersed investment timing is obtained, while in the second scenario, an equilibrium with joint investment prevails. In the third scenario preemption holds in case uncertainty is low, and joint investment is the Pareto dominating equilibrium if uncertainty is large. From the theory of real options it is known that it is optimal to invest when the net present value exceeds the option value of waiting. The authors modify the real options investment rule by taking into account strategic interactions. The net present value must now be compared with the so-called strategic option value of waiting. They show that, compared to the option value of waiting in the monopoly case, the strategic option value of waiting is the same in the joint investment case and lower in the preemption equilibrium. In the latter case it can even occur that investing is optimal, while the net present value is negative.

Huisman (2000) studies a dynamic duopoly in which firms compete in the adoption of new technologies. The innovation process is exogenous to the firms. Both firms have the possibility to adopt a current technology or to wait for a better technology that arrives at an unknown point of time in the future. At the moment that a firm invests it enters a new market with a profit flow that follows a stochastic Brownian motion process. Results turn out to largely depend on the probability that a new technology arrives in the immediate future. If this probability is low, firms only take the current technology into account, which results in the usual preemption game. Increasing this probability gradually changes the outcome from a preemption game where both firms adopt the current technology, to a preemption game where the follower will adopt the new technology. Increasing the probability of arrival of the new technology further turns the preemption game into a war of attrition where the follower is better off than the leader. Finally, when the probability of arrival of a new technology is really large, both firms will adopt the new technology.

Mason and Weeds (2000) examine the irreversible adoption of a technology whose returns are uncertain, when there is an advantage to being the first adopter, but a network advantage to adopting when others also do so. Two patterns of adoption emerge: sequential, in which the leader aggressively preempts its rival, and a more accommodating outcome in which the firms adopt simultaneously. They derive two main results. First, conditional on adoption being sequential, the follower adopts at the incorrect point, compared to the cooperative solution. The leader adopts at the cooperative point when there is no preemption, and too early if there is preemption. Secondly, there is insufficient simultaneous adoption in equilibrium. The paper examines the effect of uncertainty, network effects and preemption on these inefficiencies. Preemption may actually increase the time to first adoption, since simultaneous adoption is more likely to occur in equilibrium with preemption. The analysis also raises the unusual possibility that an increase in uncertainty may cause the first mover to adopt the technology earlier.

Boyer and Clamens (2001) note that American corporations spent some 50 billion US$ per year in the late 90's on reengineering projects. It is believed that two thirds of those efforts ended up in failure because of significant resistance to change and lack of consensus and commitment among senior executives. Very little effort has been exerted to foster our understanding of the strategic differences between adopting and implementing a new technology. Building on a model first proposed by Stenbacka and Tombak (1994), they show how the adoption timing decisions in a sequential duopoly framework are affected by more efficient implementation programs, higher relative gains of being the first (or second) to successfully implement the technology, and lower investment adoption costs.

Pawlina and Kort (2001a) consider the impact of investment cost asymmetry on the value and optimal real option exercise strategies of firms under imperfect competition. Both firms have an opportunity to invest in a project enhancing (ceteris paribus) the profit now. They show that three types of equilibrium exist and derive critical levels of cost asymmetry separating the regions in which they prevail. The presence of strategic interactions leads to counter-intuitive results. First, depending on the level of asymmetry, a marginal increase in the investment cost of the firm with the cost disadvantage can increase this firm's own value. Second, such a cost increase can result in a decrease in value of the competitor.

Pawlina and Kort (2001b) consider a firm's decision to replace an existing production technology with a new, more cost-efficient one. In a two-period model, increased product market uncertainty could encourage the firm to invest strategically in the new technology. Flexibility in timing introduces an option value of waiting which increases with uncertainty. In contrast with the two-period model, despite the existence of the strategic option of becoming a market leader due to a lower marginal cost, more uncertainty always increases the expected time to invest. Furthermore, it is shown that under increased uncertainty the probability that the firm finds it optimal to invest within a given time period always decreases for time periods longer than the optimal time to invest in a deterministic case. For smaller time periods there are contrary effects so that the overall impact of increased uncertainty on the probability of investing is in this case ambiguous.

Thijssen and Huisman (2001) develop a market model where two firms compete in investing in a risky project. The model incorporates a Stackelberg advantage for the first mover and information spillovers that may constitute a second mover advantage. At certain points in time the firms obtain information about the profitability of the project. The threshold beliefs in a profitable project for which investment is optimal are calculated. It is shown that both a preemption game as well as a war of attrition can arise for specific parameterizations of the model, depending on the levels of the first and second mover advantages. Furthermore, it is shown that more competition does not necessarily lead to higher social welfare.

Mason and Weeds (2001) examine irreversible investment in a project with uncertain returns, when there is an advantage to being the first to invest, and externalities to investing when others also do so. Preemption decreases and may even eliminate the option values created by irreversibility and uncertainty. Externalities introduce inefficiencies in investment decisions. Preemption and externalities combined can actually hasten, rather than delay, investment, contrary to the usual outcome. These facts demonstrate the importance of extending "real options" analysis to include strategic interactions.

Cottrell and Sick (2001) compare first mover advantages against the real option arising from delay and flexibility. The real options model recognizes the value of delaying projects until risk can be resolved. This value to delay is offset by the convenience value of possessing an operating project. Sometimes this convenience value is in the form of a first mover advantage. They claim that fear of losing first mover advantages has caused many managers to ignore real options analysis completely and simply go ahead with any project that they think has a positive net present value. The authors investigate first mover advantage to find that it usually isn't all that it is cracked up to be. By considering the merits of a delayed-entry follower strategy, they show that value enhancing managers will want to be suitably cautious before ignoring the real option analysis.

Paxson and Pinto (2002) consider in a duopoly environment the leader and follower value functions assuming that the leader's' market share evolves according to an immigration (birth) and death process. They derive explicit solutions for the follower's option to invest, and numerical solutions for the leader's option to invest. They calculate the partial derivatives of the leader and follower value functions to market share, birth/death parameters, volatility and market profitability. The model is possibly more realistic than that proposed by other authors studying the advantages of being first (and also being a follower).

Balmann and Mubhoff (2002) note that applications of the real options approach hardly consider investment returns to be the result of competitive markets. The reason is probably that Dixit and Pindyck (1994, ch. 8) find that the investment triggers of firms in competitive markets are equal to those of firms with exclusive options. It is shown that this finding is restricted to markets in which assets have infinite lifetime. If assets are subject to depreciation and subsequent reinvestment opportunities, competition leads to significantly lower investment triggers because depreciation dampens the potential decline in returns after negative demand shocks. The results are obtained by an agent-based simulation approach in which firms derive their investment triggers by a genetic algorithm.

Grenadier (2002) notes that under the standard real options approach to investment under uncertainty, agents formulate optimal exercise strategies in isolation and ignore competitive interactions. However, in many real-world asset markets, exercise strategies cannot be determined separately, but must be formed as part of a strategic equilibrium. This article provides a tractable approach for deriving equilibrium investment strategies in a continuous-time Cournot-Nash framework. The impact of competition on exercise strategies is dramatic. For example, while standard real options models emphasize that a valuable "option to wait" leads firms to invest only at large positive net present values, the impact of competition drastically erodes the value of the option to wait and leads to investment at very near the zero net present value threshold.

Weeds (2002) considers irreversible investment in competing research projects with uncertain returns under a winner-takes-all patent system. Uncertainty takes two distinct forms: the technological success of the project is probabilistic, while the economic value of the patent to be won evolves stochastically over time. According to the theory of real options uncertainty generates an option value of delay, but with two competing firms the fear of preemption would appear to undermine this approach. In non-cooperative equilibrium two patterns of investment emerge depending on parameter values. In a preemptive leader-follower equilibrium firms invest sequentially and option values are reduced by competition. A symmetric outcome may also occur, however, in which investment is more delayed than the single-firm counterpart. Comparing this with the optimal cooperative investment pattern, investment is found to be more delayed when firms act non-cooperatively as each holds back from investing in the fear of starting a patent race. Implications of the analysis for empirical and policy issues in R&D are considered.

Murto and Keppo (2002) develop a model where many firms compete for a single investment opportunity. When one of the firms triggers the investment the opportunity is completely lost for the other firms. The value of the project for the firms is assumed to follow a geometric Brownian motion. The model combines game theory and the theory of irreversible investment under uncertainty. They characterize the resulting Nash equilibrium under different assumptions on the information that the firms have about each other's valuations for the project. As an example, they present a case of building a telecommunications network.

Thijssen, Huisman and Kort (2002) consider the problem of investment timing under uncertainty in a duopoly framework. When both firms want to be the first investor a coordination problem arises. A method is proposed to deal with this coordination problem, involving the use of symmetric mixed strategies. The method is based on Fudenberg and Tirole (1985) developed in a deterministic framework. The authors extend the applicability of this method to a stochastic environment. They claim that several recent contributions in multiple firm real option models make unsatisfactory assumptions to solve the coordination problem mentioned above. They show that in many cases it is incorrect to claim that "the probability that both firms invest simultaneously, while it is only optimal for one firm to invest, is zero."

Sparla (2002) examines exercise policies for closure options in a duopolistic market that is subject to aggregate shocks. He shows that the equilibrium exercise policies in a symmetric duopoly differ significantly from the closure rules suggested by the standard real options theory, i.e., duopolists disinvest later than a monopolist and earlier than price-taking firms.

Huisman and Kort (2003) aim to determine the optimal timing of technology investment of a single firm in a duopoly framework. As time passes different technologies are invented which after some time become available for the firm to adopt. The question here is not only when a firm should invest but also which technology should be adopted. For different scenarios the optimal technology investment decision is determined. Outcomes range from preemption equilibria to equilibria with second mover advantages.

Lambrecht and Perraudin (2003) introduce incomplete information and preemption into an equilibrium model of firms facing real investment decisions. The optimal investment strategy may lie anywhere between the zero-NPV trigger level and the optimal strategy of a monopolist, depending on the distribution of competitors' costs and the implied fear of preemption. The model implies that the equity returns of firms which hold real options and are subject to preemption will contain jumps and positive skewness.

Paxson and Pinto (2003) present two different real options models, with two stochastic factors underlying strategic interactions. In the first model the profits per unit and the number of units follow two different stochastic paths and, in the second model the returns and the investment cost pursue different paths. For both models, the authors analyze dissimilar games considering that the roles of the players are pre-assigned and also exogenous to the models, always assuming that the first mover has a competitive advantage over the second mover. Closed form solutions are obtained for the value functions of the first and second mover and for its trigger functions, except for the trigger of the first mover in preemptive environments. The paper analyses the effect of returns, investment cost and uncertainty on the models. Uncertainty can delay the adoption of the first mover. Although preemption affects the leader's trigger it does not seem to influence the entry point of the follower.

Murto (2004) examines a declining duopoly, where the firms must choose when to exit from the market. The uncertainty is modeled by letting the revenue stream follow a geometric Brownian motion. He considers the Markov-perfect equilibrium in firms' exit strategies. With a low degree of uncertainty there is a unique equilibrium, where one of the firms always exits before the other. However, when uncertainty is increased, another equilibrium with the reversed order of exit may appear ruining the uniqueness. Whether this happens or not, depends on the degree of asymmetry in the firm specific parameters.

Botteron, Chesney and Gibson-Asner (2003) propose an approach which relies on barrier options to model production and/or sales delocalization flexibility for multinational enterprises making decisions under exchange rate uncertainty. They extend the model by introducing game theoretic considerations to show how the information set and the competitive structure of the market may lead firms to act strategically and exercise their delocalization options preemptively at an endogenously fixed exchange rate barrier.

Shackleton, Tsekrekos and Wojakowski (2004) analyze the entry decisions of competing firms in a two-player stochastic real option game, when rivals earn different but correlated uncertain profitabilities from operating. In the presence of entry costs, decision thresholds exhibit hysteresis, the range of which is decreasing in the correlation between competing firms. A measure of the expected time of each firm being active in the market and the probability of both rivals entering within a finite time are explicitly calculated. The former (latter) is found to decrease (increase) with the volatility of relative firm profitabilities implying that market leadership is shorter-lived the more uncertain the industry environment. In an application of the model to the aircraft industry, the authors find that Boeing's optimal response to Airbus' launch of the A380 super carrier is to accommodate entry and supplement its current product line, as opposed to the riskier alternative of committing to the development of a corresponding super jumbo.

III. The two stage duopoly competition models.

Smit and Trigeorgis (1997) use an integrated real options and game-theoretic framework for strategic R&D investments to analyze two-stage games where the growth option value of R&D depends on endogenous competitive reactions. In the model firms choose output levels endogenously and may have different (asymmetric) production costs as a result of R&D, investment timing differences or learning. The model illustrates the trade-off between the flexibility value and the strategic commitment value of R&D that interacts with market structure via altering the competitor's equilibrium quantity or changing the market structure altogether (e.g., from Cournot equilibrium to Stackelberg or monopoly). Comparative statics provide results for competitive R&D strategies depending on uncertainties in market demand and in the outcome of R&D, on whether R&D benefits are proprietary or shared, on imperfect or asymmetric information with signaling, on learning or experience cost effects, and on competition in R&D versus cooperation via a joint research venture.

Kulatilaka and Perotti (1998) provide a strategic rationale for growth options under uncertainty and imperfect competition. In a market with strategic competition, investment confers a greater capability to take advantage of future growth opportunities. This strategic advantage leads to the capture of a greater share of the market, either by dissuading entry or by inducing competitors to 'make room' for the stronger competitor. As a result of this strategic effect, payoffs are in a rough sense more convex than in the case of no investment in a growth option. When the strategic advantage is strong, increased uncertainty encourages investment in growth options: higher uncertainty means more opportunity rather than simply larger risk. If the strategic effect is weak the reverse is true. On the other hand an increase in systematic risk discourages the acquisition of growth options. Their results contradict the view that volatility is a strong disincentive for investment.

With a one period model, the authors analyze the impact of uncertainty on the decision to acquire a cost reducing technology in an duopolistic setting. The acquisition decision must be made at the beginning of the period and uncertainty surrounding demand is resolved at the end prior to production. In one case, the authors compare results under risk neutrality to those under risk aversion.

Three situations are discussed: 1) the firm has a monopoly on both the investment opportunity and the product market, 2) the product market is duopolistic, but only one firm has the growth opportunity and 3) the market is duopolistic and both firms share the growth option.

For the monopoly, the value of investing I at $t = 0$ to reduce production costs from K to k at $t = 1$ must be compared to that of not investing and producing at cost $K > k$. The expected net gain to investment is equal to

$$G = E_0\left[\pi_M^I\right] - I - E_0\left[\pi_M^N\right],$$

where π_M^I and π_M^N are monopoly profits with and without the growth opportunity, respectively. The authors show that a single $t = 0$ expected demand threshold triggers investment.

In a duopoly, the investment opportunity has a strategic value, expensing I deters entry and offers a greater market share. In the first case, only one firm possesses the growth option (firm 1). If firm 1 decides not to invest, the outcome at $t = 1$ is a symmetric Cournot equilibrium where each firm produces at cost K and both exercise their production option at the same level of demand. If firm 1 chooses to invest, firm 2 finds itself exercising its production option at a higher level of demand compared to the case where 1 does not invest. Consequently, firm 1 can act as a monopolist until demand is sufficient for the other to enter the market. Furthermore, when both firms are in the market, we have a non-symmetric

Cournot equilibrium with firm 1 producing more than firm 2 because of its cost advantage. The authors show that a single $t = 0$ expected demand threshold triggers investment. The payoff function after investment is a strictly convex function of demand, uncertainty thus increases the expected value of investing and reduces the optimal investment threshold. Spending I is like purchasing an option to produce at cost k at the end of the period.

However, when a net gain function similar to G is setup to compare the value of investing to that of not, it is hard to predict the effect of a mean preserving increase in variance on the optimal investment threshold. This ambiguity arises from the opposing effect an increase in uncertainty has on the value of the strategic advantage and on the value of waiting to invest.

The authors argue and show with an example that an increase in variance has a larger effect on the expected value of the strategic advantage when the spread $K - k$ increases. When $K - k$ increases, the region where firm 1 can act as a monopolist is larger along with the market share in the non-symmetric duopoly. This translates into a larger expected strategic advantage for firm 1.[4] If a mean preserving increase in uncertainty leads to larger systematic risk (risk aversion case), the relative value of the strategic advantage premium will be smaller. Consequently, it takes a higher strategic advantage than in the risk neutral case to reverse the waiting to invest effect.

When both firms have access to the investment opportunity, results are similar to those where only one firm has access. A higher cost advantage $K - k$ increases the expected strategic value of the investment which dominates the traditional waiting to invest effect that is also amplified by uncertainty (mean preserving).

Lambrecht (1999) derives the optimal investment thresholds for two symmetric investors who hold an option to invest in a two-stage sequential investment and who have incomplete information on each other's profits. In stage 1, the investors are competing to obtain a patent that gives its holder an option to proceed to the second stage. The latter stage consists of the commercialization of the invention. The optimal investment trigger for the first stage is stationary and implies a trade-off between the benefit of waiting to invest and the cost of being preempted. He determines the condition under which inventions are likely to be

[4]For the example, the authors suppose that demand is lognormally distributed.

patented without being put immediately to commercial use. Sleeping patents are more likely to occur when interest rates are low, profit volatility is high, or the first-stage cost is small relative to the second-stage cost. Interestingly, the strategic trigger is a decreasing function of profit volatility for the sleeping patent case.

Miltersen and Schwartz (2004) develop a model to analyze patent-protected R&D investment projects when there is imperfect competition in the development and marketing of the resulting product. The competitive interactions that occur substantially complicate the solution of the problem since the decision maker has to take into account not only the factors that affect her/his own decisions, but also the factors that affect the decisions of the other investors. The real options framework utilized to deal with investments under uncertainty is extended to incorporate the game-theoretic concepts required to deal with these interactions. Implementation of the model shows that competition in R&D, in general, not only increases production and reduces prices, but also shortens the time of developing the product and increases the probability of a successful development. These benefits to society are countered by increased total investment costs in R&D and lower aggregate value of the R&D investment projects.

Smit (2003) analyzes the optional and strategic features of infrastructure investment. Infrastructure investments generate other investment opportunities, and in so doing change the strategic position of the enterprise. A combination of real options theory and game theory can capture the elusive value of a strategic modification of a firm's position in its industry.

IV. The fully dynamic no-commitment framework.

Williams (1993) observes that options on real and financial assets can have very different properties. Typically, the good or service produced by a real asset has a finite elasticity of demand, and developers have finite capacities. Also, the supply of options can be limited, and developers can be less than perfectly competitive. In a subgame, perfect Nash equilibrium with these properties, the optimal exercise policy, and resulting values of developed and undeveloped assets are calculated explicitly.

Williams considers the decision to invest and develop an undeveloped asset under uncertain demand. The market for the good produced by the developed asset is perfectly competitive and before any investment is made, aggregate supply is superior to zero. In this setting, the author is able to study the impact on investment timing of situations other than perfectly elastic demand. That is, the value of the underlying asset is sensible to investment, there is feedback between investment (exercise of the option) and the value of the underlying asset (developed asset).

In addition, all of the holders of undeveloped assets are identical and their number ν is fixed with $\nu \in \{1, ..., \infty\}$. Each holds an equal amount of undeveloped assets from a limited supply. Here, $\nu = 1$ characterizes monopoly in the undeveloped assets, $v > 1$ with ν finite represents oligopolistic developers and $\nu \to \infty$ perfect competition. It is also important to note that development capacity is limited. With the characteristics described in the current paragraph, the author is able to asses the impact of development capacity, of the supply of undeveloped assets and the concentration of developers on the decision to invest.

Baldursson (1998) studies an oligopoly where firms facing a stochastic inverse demand curve use capacity as strategic variable. Capacity may be adjusted continuously over time with linear cost. The analysis uses the technique of a fictitious social planner and the theory of irreversible investment under uncertainty. Examples indicate that qualitatively the price process will be similar in oligopoly and competitive equilibrium. When firms are nonidentical, e.g., in initial size, and even if they are alike in other respects, substantial time may pass until they are all the same size. Much of that time, one firm may dominate the market.

Murto, Nasakkala and Keppo (2004) present a modeling framework for the analysis of investments in an oligopoly market for a homogenous commodity. The demand evolves stochastically and the firms carry out investment projects in order to adjust their production cost functions or production capacities. The model is formulated as a discrete time state-space game where the firms use feedback strategies. The firms are assumed to move sequentially to ensure a unique Markov-perfect Nash equilibrium. Once the equilibrium has been solved, Monte Carlo simulation is used to form probability distributions for the firms' cash flow patterns and accomplished investments. Such information can be used to value firms operating in an oligopoly market. An example of the model is given in a duopoly market. The example illustrates the trade-off between the value of flexibility and economies of scale under competitive interaction.

Pineau and Murto (2004) analyze the investment problem faced by producers in deregulated electricity markets with high uncertainties about the future. A dynamic stochastic oligopoly model to describe the production and investment in such a situation is developed and applied to the Finnish electricity market. The demand growth rate is modeled as a stochastic variable. The strategies of the firms consist of investments and production levels for base and peak load periods. The firms have nuclear, hydro and thermal capacities, but are only allowed to invest in new thermal capacity. Using a so-called sample-path adapted open-loop information structure, the model contributes to the understanding of the dynamics of production, investment and market power in a medium time horizon. The solution method uses recent developments in variational inequality and mixed complementarity problem formulations.

Aguerrevere (2003) looks at the effects of competitive interactions on investment decisions and on the dynamics of the price of a non-storable commodity in a model of incremental investment with time to build and operating flexibility. He finds that an increase in uncertainty may encourage firms to increase their capacity. He shows that it may be optimal to invest in additional capacity during periods in which part of the operational capacity is not being utilized. The impact of competition on the properties of the endogenous output price is dramatic. For example, price volatility may be increasing in the number of competitors in the industry.

Boyer, Lasserre, Mariotti and Moreaux (2003) study a simple duopoly model of preemption with multiple investments and instantaneous price competition on a market of finite size driven by stochastic taste shocks. Different patterns of equilibria may arise, depending on the importance of the real option effect. If the average growth rate of the market is close to the risk-free rate, or if the volatility of demand shocks is high, no dissipation of rents occurs in equilibrium, despite instantaneous price competition. If these conditions do not hold, the equilibrium investment timing is suboptimal, and the firms' long-run capacities may depend on the initial market conditions. Their conclusions contrast sharply with standard rent dissipation results.

Boyer, Lasserre, Mariotti and Moreaux (2004) develop a methodology that allows the study of real-options investment decisions in a strategic duopoly setup, with the formulation of appropriate payoff functions and the generalization to a stochastic context of Fudenberg and Tirole (1985)'s formalism for defining strategies in a continuous-time environment.

Applying this methodology to specific special cases allows to identify some properties and stylized characteristics of industries developing under duopoly, when the investment required are indivisible, irreversible, and big relative to the market. While many other considerations affect industry development, the authors claim that the magnitude and irreversibility of outlays relative to market size are important considerations not only in young sectors, especially those involving scale economies, but also in more conventional and older ones such as the aircraft industry. The speed of market development and the uncertainty regarding its future evolution are also important considerations that the real options approach is well equipped to handle.

In the model, the indivisible capacity unit is costly and never becomes small relative to the market despite unbounded market development. Nonetheless it is shown that one firm cannot durably keep its opponent at bay by holding as many capacity units as the market can bear.

Boyer, Lasserre, Mariotti and Moreaux (2004) have found that the early phase of such an industry is characterized by strong competition in the sense that one firm preempts the other. This competition causes the first industry investment to occur earlier than would be socially optimal, a distortion which implies riskier entry, lower expected returns, and more bankruptcies. This waste of resources is inevitable and allows the equalization of the rents of the leader and the follower. It occurs irrespective of the volatility or the speed of market development.

At later stages of development, when both firms hold capacity, competition may be weaker in the sense that tacit-collusion equilibria may exist. Tacit collusion to restrict production takes the form of postponed simultaneous investment by both firms. In fact tacit-collusion equilibria are sure to exist in high volatility markets or fast growth markets. Here the conventional real options result that high volatility postpones investments is reinforced by the fact that higher volatility may allow a switch from the preemption equilibrium, which always exist, to a tacit-collusion equilibrium involving later investment and higher profits.

When it exists at all, the possibility of collusion is more attractive to firms of equal size than to unequal ones. This is because a tacit-collusion equilibrium requires simultaneous investment by both firms. When firms are of equal size, this is compatible with joint profit maximization; when firms differ in size the joint-profit joint-investment threshold is beyond the level that maximizes the expected profits of the smaller firm: the latter would defect at that level of market development. This suggests that tacit collusion is less efficient as a way to raise profits the more the firms differ in size. If other forms of collusion, such as acquisitions or mergers, are possible, one would expect them to become relatively more attractive the more unequal the firm sizes.

Thus competition definitely works, but collusion is possible, and appearances may be deceiving. The stylized properties outlined in this paper suggest that competition is more likely to be at work when only one firm operates and that collusion is more likely when the industry is made up of two active firms of equal size and when market develops quickly and/or with much volatility.

References

[1] Aguerrevere, Felipe L.. 2003. "Equilibrium Investment Strategies and Output Price Behavior: A Real Options Approach," *Review of Financial Studies* 16(4): 1239-1272.

[2] Ankum, L.-A. and Han T.-J. Smit. 1993. "A Real Options and Game-Theoretic Approach to Corporate Investment Strategy Under Competition," *Financial Management* 22(3): 241-250.

[3] Athey, S. and A. Schmutzler. 2001. "Investment and Market Dominance," *Rand Journal of Economics* 32(1): 1-26.

[4] Baldursson, F.M. 1998. "Irreversible Investment Under Uncertainty in Oligopoly," *Journal of Economic Dynamics and Control* 22(4): 627-644.

[5] Balmann, A. and O. Mubhoff. 2002. "Real Options and Competition: The Impact of Depreciation and Reinvestment," Paper presented at the 6^{th} annual conference on Real Options Theory Meets Practice, Paphos, Cyprus.

[6] Botteron, Pascal, Marc Chesney and Rajna Gibson-Asner. 2003. "Analyzing Firms' Strategic Investment Decisions in a Real Options Framework," *Journal of International Financial Markets, Institutions and Money* 13(5): 451-479.

[7] Boyer, M. and S. Clamens. 2001. "Strategic Adoption of a New Technology under Uncertain Implementation", mimeo, CIRANO.

[8] Boyer, Marcel, Pierre Lasserre, Thomas Mariotti and Michel Moreaux. 2003. "Preemption and Rent Dissipation under Bertrand Competition," *International Journal of Industrial Organization* (to appear).

[9] Boyer, Marcel, Pierre Lasserre, Thomas Mariotti and Michel Moreaux. 2004. "Real Options, Preemption, and the Dynamics of Industry Investments," mimeo, CIRANO.

[10] Cottrel, Thomas J. and Gordon A. Sick. 2001. "First Mover (Dis)advantage and Real Options," *Journal of Applied Corporate Finance* 14(2): 41-51.

[11] Cottrel, Thomas J. and Gordon A. Sick. 2002. "Real Options and Follower Strategies: the Loss of Real Option Value to First-mover Advantage," *The Engineering Economist* 47(2).

[12] Décamps, J.-P. and T. Mariotti. 2000. "Irreversible Investment and Learning Externalities," mimeo, GREMAQ, Université de Toulouse I.

[13] Dixit, A.K. and R.S. Pindyck. 1994. *Investment Under Uncertainty*, Princeton, Princeton University Press.

[14] Fudenberg, D. and J. Tirole. 1985. "Preemption and Rent Equalization in the Adoption of New Technology," *Review of Economic Studies* 52: 383-401.

[15] Gilbert, R.J. and R.G. Harris. 1984. "Competition with Lumpy Investment," *Rand Journal of Economics* 15(2): 197-212.

[16] Grenadier, Steven R. 1996. "The Strategic Exercise of Options: Development Cascades and Overbuilding in Real Estate Markets," *Journal of Finance* 51(5): 1653-1679.

[17] Grenadier, Steven R. 1999. "Information Revelation Through Option Exercise," *Review of Financial Studies* 12(1): 95-130.

[18] Grenadier, Steven R. 2002. "Option Exercise Games: An Application to the Equilibrium Investment Strategies of Firms," *Review of Financial Studies* 15(3):691-721.

[19] Huisman, K.J.M. and P.M. Kort. 1998. "A Further Analysis on Strategic Timing of Adoption of New Technologies Under Uncertainty," CentER Discussion Paper 9803, Tilburg University, Tilburg, The Netherlands.

[20] Huisman, K.J.M. and P.M. Kort. 1999. "Effects of Strategic Interactions on the Option Value of Waiting," CentER Discussion Paper 9992, Tilburg University, Tilburg, The Netherlands.

[21] Huisman, K.J.M.. 2000. "Strategic Technology Adoption Taking into Account Future Technological Improvements: a Real Options Approach," CentER Discussion Paper 2000-52, Tilburg University, Tilburg, The Netherlands.

[22] Huisman, K.J.M.. 2001. *Technology Investment: A Game Theoretic Real Option Approach*, Kluwer Academic Publishers, Norwell.

[23] Huisman, K.J.M. and P.M. Kort. 2003. "Strategic Investment in Technological Innovations," *European Journal of Operational Research* 144(1): 209-223.

[24] Joaquin, Domingo Castelo and Kirt C. Butler. 1999. "Competitive Investment Decisions: A Synthesis," in Project Flexibility, Agency and Competition, eds. Michael J. Brennan and Lenos Trigeorgis.

[25] Kulatilaka, Nalin and Enrico C. Perotti. 1998. "Strategic Growth Options," *Management Science* 44(8): 1021-1031.

[26] Lambrecht, Bart and William Perraudin. 1997. "Real Options and Preemption," JIMS working paper, University of Cambridge.

[27] Lambrecht, Bart. 1999. "Strategic Sequential Investments and Sleeping Patents," in Project Flexibility, Agency and Competition, eds. Michael J. Brennan and Lenos Trigeorgis.

[28] Lambrecht, Bart and William Perraudin. 2003. "Real Options and Preemption Under Incomplete Information," *Journal of Economic Dynamics and Control* 27(4): 619-643.

[29] Mason, Robin and Helen Weeds. 2000. "Networks, Options and Preemption," University of Southampton, Discussion Papers in Economics and Econometrics 41.

[30] Mason, Robin and Helen Weeds. 2001. "Irreversible Investment with Strategic Interactions," CEPR Discussion Paper 3013.

[31] Miltersen, K.R. and E.S. Schwartz. 2004. "R&D Investments with Competitive Interactions," NBER Working Paper no. w10258.

[32] Mills, D. 1988. "Preemptive Investment Timing," *Rand Journal of Economics* 19(1): 114-122.

[33] Murto, Pauli and Jussi Keppo. 2002. "A Game model of Irreversible Investment Under Uncertainty," *International Game Theory Review* 4(2): 127-140.

[34] Murto, P. 2004. "Exit in Duopoly Under Uncertainty" *RAND Journal of Economics* 35(1): 111-127.

[35] Murto, P., E. Näsäkkälä and J. Keppo. 2004. "Timing of Investments in Oligopoly Under Uncertainty: a Framework for Numerical Analysis," *European Journal of Operational Research* 157(2): 486-500.

[36] Pawlina, G. and P.M. Kort. 2001a. "Strategic Capital Budgeting: Asset Replacement under Uncertainty," CentER Discussion Paper 2001-04, Tilburg University, Tilburg, The Netherlands.

[37] Pawlina, G. and P.M. Kort. 2001b. "Real Options in an Asymmetric Duopoly: Who Benefits from your Competitive Disadvantage?" CentER Discussion Paper 2001-95, Tilburg University, Tilburg, The Netherlands.

[38] Paxson, D. and Helena Pinto. 2002. "Timing Advantage: Leader/Follower Value Function if the Market Share Follows a Birth and Death Process," Paper presented at the 6^{th} annual conference on Real Options Theory Meets Practice, Paphos, Cyprus.

[39] Paxson, Dean and Helena Pinto. 2003. "Competition Games in Duopoly Settings with Two Stochastic Factors," Working Paper.

[40] Perotti, Enrico C. and Silvia Rossetto. 2001. "Strategic Advantage and the Optimal Exercise of Entry Options," CEPR Discussion Paper 3061.

[41] Pineau, P.-O. and P. Murto. "An Oligopolistic Investment Model of the Finnish Electricity Market," *Annals of Operations Research* (to appear).

[42] Shackleton, Mark B., Andrianos E. Tsekrekos and Rafal Wojakowski. 2004. "Strategic Entry and Market Leadership in a Two-Player Real Option Game," *Journal of Banking and Finance* 28(1): 179-201.

[43] Smets, F. 1995. "Exporting Versus Foreign Direct Investment: The Effect of Uncertainty, Irreversibilities, and Strategic Interaction," Bank for International Settlements Working Paper, Basel, Switzerland.

[44] Smit H.-T.-J. and L. Trigeorgis. *Strategic Investment: Real Options and Games*, Princeton University Press, forthcoming.

[45] Smit H.-T.-J. and L. Trigeorgis. 1997. "R&D Option Strategies," Working Paper.

[46] Smit, Han T.-J.. 2003. "Infrastructure Investment as a Real Options Game: The Case of European Airport Expansion," *Financial Management* 32(4): 27-57.

[47] Sparla, T. 2002. "Closure Options in Duopoly: the Case of Second Mover Advantage," Working Paper, University of Dortmund, Dortmund, Germany.

[48] Thijssen, J.J.J. and K.J.M. Huisman. 2001. "Strategic Investment under Uncertainty and Information Spillovers," CentER Discussion Paper 2001-91, Tilburg University, Tilburg, The Netherlands.

[49] Thijssen, J.J.J., K.J.M. Huisman and P.M. Kort. 2002. "Symmetric Equilibrium Strategies in Game Theoretic Real Options Models," CentER Discussion Paper 2002-81, Tilburg University, Tilburg, The Netherlands.

[50] Trigeorgis, L. 1991. "Anticipated Competitive Entry and Early Preemptive Investment in Deferrable Projects," *Journal of Economics and Business* 2(5): 143-156.

[51] Weeds, Helen. 2002. "Strategic Delay in a Real Options Model of R&D Competition," *Review of Economic Studies* 69(3):729-747.

[52] Williams, Joseph T. 1993. "Equilibrium and Options on Real Assets," *Review of Financial Studies* 6(4): 826-850.