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A multi-criteria game theory and real-options model for irreversible ICT investment decisions

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A R T I C L E   I N F O

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A B S T R A C T

The information and communication technology (ICT) industry is one of the most capital intensive among the high-technology industries. ICT business analysis, especially after the industry deregulation, has become a difficult task. Traditional quantitative cost–benefit analysis concerning investment decisions is by no means sufficient for capturing the complexity of the problem in its entirety. This work combines quantitative and qualitative analyses for modeling competitive interactions between players in the ICT business field. The proposed decision analysis model combines real options, game theory, and analytic hierarchy process for analyzing ICT business alternatives under the threat of competition. The proposed model is applied to a real broadband technology business case, showing how it can be formulated and solved.

1. Introduction

After the deregulation of information and communication technology (ICT) markets, their related business activities are not possessed exclusively by a single firm but rather are shared by many competitors. Examples of ICT markets with a limited number of players are manufactures in operating systems such as Microsoft, Apple, Sun, and Linux, in CPUs such as Intel, Sun, and in mobile phones such as Nokia, Siemens, Motorola, and Ericsson. Furthermore, most countries issued a limited number of licenses for mobile telecommunication operators; so in every country, there are only a few mobile telecommunication operators.

The main challenge for a potential provider (investor) is to roll out its business activity at the right time and the right scale taking into account the threat from competition that the potential competitor can eliminate. Although it is useful to take into account the traditional quantitative cost–benefit analysis, it is by no means sufficient for capturing the depth of complexity of the problem in its entirety. Actually, traditional methods do not properly account for the flexibility inherent in most ICT investment decisions to launch them at the right time and the right scale. Real-option (RO) analysis presents an alternative method since it takes into account the managerial flexibility of responding to a change or new situation in business conditions (Trigeorgis, 1996). However, RO models are strictly quantitative, while ICT investments experience tangible and intangible factors and the latter can be mainly treated by qualitative analysis. In addition, RO analysis in itself brings to the "surface" a number of factors that cannot be quantified, at least easily, by existing RO models and methodologies. Particularly, even though it may be difficult to precisely calculate the value of ROs, it is plausible that managers ascribe a higher value to a project with one or more embedded options than they would to the same project

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without any embedded options. In an exploratory survey of managerial practice surrounding ROs, Busby and Pitts (1997) found that "very few decision makers seemed to be aware of RO research but, mostly, their intuitions agreed with the qualitative prescriptions of such work". Kogut and Kulatilaka (2004) indicated that interviews with managers have shown that RO valuation is rarely used, but, even when this is the case, managers may still be engaging in RO thinking. Fichman, Keil, and Tiwans (2005) presented several case examples in which information technology managers took actions and/or gave rationales consistent with option thinking, even though ROs were not a formal part of the project assessment. Formally or not, RO application in business decisions analysis requires a basic assumption, which is to defer investment until more information is available before deciding to proceed to the implementation of the investment. However, this delay is under high criticism since during waiting a possible competitor may preempt the firm of interest (decision maker) and decrease or eliminate business value.

Two directions have been followed to integrate the ROs and competition modeling in the ICT business field: exogenous and endogenous competition modeling (Angelou & Economides, 2008b; Smit & Trigeorgis, 2004; Zhu, 1999). However, in real telecommunication markets, especially after their liberalization, the situation is more efficiently characterized as an oligopoly and not as a perfect competition. Specifically, the deregulation of telecommunications did not result in a many-player "wild race" but rather in an oligopoly market. In such a market there are only a few companies present, who know about each other's activities and take into account the other competitors actions (Fekete & Konkoly, 2004). Situations like that can be more efficiently modeled by game theory (GT) under endogenous competition modeling (Smit & Trigeorgis, 2004; Zhu, 1999).

The business problem to solve is an ICT business opportunity, which is shared by the "competitors" (potential investors—players) in the market. The players have to decide, if they proceed in the implementation of investment opportunity, when and how much to produce (offer in the market, capture of the market share—MS). Under the threat of competition, the decision to exercise options strategically depends on the trade-off between overall quantitative and qualitative benefits and costs of going ahead with an investment against waiting for more information. Waiting can have an informational benefit (Trigeorgis, 1996). However, if a firm chooses to defer exercising its option until better information is received (thus resolving the uncertainty), it runs the risk that another firm may preempt it by exercising first (Zhu, 1999). Such an early exercise by a competitor can erode the profits or even force the option to expire prematurely. Despite its importance, competition has been typically ignored in most of the RO literature. Only a few recent papers have started to address this issue. Among others, Trigeorgis (1996), Grenadier (1996, 2002), Smit and Trigeorgis (2004), Joaquin and Butler (2000), Kulatilaka and Perotti (1998), and Zhu and Weyant (2003a, 2003b) provided various treatments of the intersection between ROs and GT.

In addition, in a wider perspective concerning integration efforts in GT itself between the preemption motive and the RO motive, McGahan (1993) studied uncertainty in a game-theoretic context where a first mover (FM) may commit in order to deter entry by a newcomer. He showed the effects of incomplete information about demand on preemption and explored the tension between competitive pressure to invest and the RO value in an entry opportunity under uncertainty about demand. Particularly, if the competitors' expectation about customers' demand makes the investment (entry in the market) less attractive and if a player (e.g. an incumbent) can keep proprietary its updated information about demand, then it may be able to secure its possible advantage and partially deter competitors' entry without a substantial initial investment entry.

Also, Spencer and Brander (1992) looked at waiting with a decision as a response to uncertainty in an oligopoly game, while Choi (1996) examined the fact that uncertainty can also lead a firm to experiment rather than to standardize too early, where standardization is also a form of commitment. These cases were treated using quantitative analysis. They focused on revenues, or cost of investment modeling, and found the equilibrium strategies between usually two competitors. However, investment decision in the deregulated ICT business field is a very difficult task that requires complex modeling of a large number of criteria. Hence, a holistic methodology should be developed in order to assist executives and decision makers in formulating problem's parameters, understanding their interactions, estimating their contributions to the overall business value, and so valuating effectively new ICT business activities.

The goal of this paper is to show how RO and GT theories can be merged to enrich the theory of ICT investment valuation under a multi-criteria perspective. These theories are applied to analyze oligopoly competition and to highlight possible further applications and research topics.

Angelou and Economides (2008a) provided a decision analysis model called ROAHP, which combines quantitative and qualitative analysis of ROs. This paper extents this work, by adopting GT and combining ROs and analytic hierarchy process (AHP) in a multi-criteria decision analysis framework for ICT investments in the liberalized market. It analyzes joint effects of the flexibility offered by ROs and the competitive interaction between players offered by GT. A multi-criteria model is developed to evaluate investment decisions based on an AHP structure.

AHP is a multi-criteria decision analysis technique. It aims at choosing from a number of alternatives based on how well these alternatives rate against a chosen set of qualitative as well as quantitative criteria (Saaty & Vargas, 1994; Schniederjans, Hamaker, & Schniederjans, 2005). The main advantage of the AHP approach is that different criteria with different measures can be easily transformed into a single utility measure. For a review of AHP applications to ICT the reader is referred to Angelou and Economides (2008a).

It is the first time in the literature where ROs, GT, and AHP are integrated into a common decision analysis model, called ROGT–AHP. The model is expressed by a mathematical equation and a multi-criteria hierarchical structure. Finally, the proposed model is applied to a real case study, showing how it can be formulated and solved.

The paper is organized as follows. Section 2 presents the problem (business situation) to be solved. Section 3 reviews ROs, AHP, and GT in the ICT field. Section 4 integrates ROs, AHP, and GT into a common decision analysis framework, providing a new model. Section 5 provides the proposed methodology. Section 6 applies the proposed models and methodology in a real business study. In Section 7, managerial implications and future research paths are discussed. Finally, Section 8 concludes.

2. The business problem—game formulation

In order to keep the game simple and focus on the key issues identified above, a duopoly case is considered where two rival firms face an ICT investment opportunity, which is treated as a RO. It is assumed that the investment opportunity is available to the players for one period, up to T_1. In addition, each player is not able to observe its competitors' state before T_1. It is also assumed that T_1 is the time moment where each firm analyzes the market status and recognizes the state (situation) of its competitor.

The game ends when either both players invest or loose their opportunity. If none of the players invests at T_1 the opportunity is lost for both players. Also, if one player enters the market then the other will follow too (simultaneously or sequentially). There may be two possible types of equilibrium: a leader–follower equilibrium and simultaneous investment equilibrium. Fig. 1 illustrates these possible combinations. The leader is alternatively called as the first mover, while the follower as the second mover (SM). Specifically, the game is defined as follows:

Players: Firm *A* and Firm *B*.
Sequence of events: (1) Decide to invest and (2) decide how much to produce.
Strategies: Each firm decides either to invest (I) or defer (D) ICT business activity that requires a lumpy investment outlay. If a firm decides to invest, it also needs to decide, at the second stage, how much to produce (i.e. a quantity q_i, $i = A, B$), maximizing its expected pay-off.
Pay-offs: The pay-off of firm *i* (i.e. its expected utility) is a function of the strategies chosen by it and its competitor. In this work, an expected utility function is developed that contains both quantitative and qualitative factors. Each of these factors depends on the strategies of both firms.

The competitors do not exercise their options randomly. Rather they do this based on certain rational decisions. The competitors' decisions are endogenous. It is also assumed that: (1) the competitors make rational decisions in determining when to exercise their options, thus exhibiting optimizing behavior; (2) each player makes decisions by monitoring its overall internal and external business environment and anticipating competitor's moves; and (3) the pay-offs depend on the resulting equilibrium.

Under quantitative analysis, if both firms A and B invest without observing each other's decisions, they will split the market according to a Nash–Cournot equilibrium. If one firm invests first and the other does it later, their pay-offs will be determined through a Stackelberg leader–follower equilibrium (Smit & Trigeorgis, 2004). If one firm invests first, but the other never does, then it will enjoy a monopoly position. The proposed analysis considers that finally both firms will invest.

3. Research methodology

The research goal is to model, in a multi-criteria perspective, the managerial flexibility of deferring an ICT business opportunity and the threat from competition to eliminate the overall business value and find the optimum implementation time. Fig. 2 describes the proposed methodology.

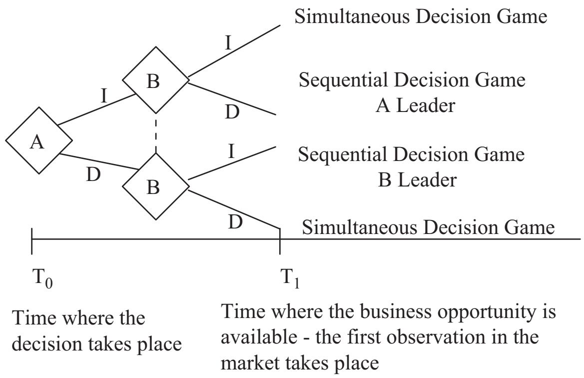

Fig. 1. The game tree.

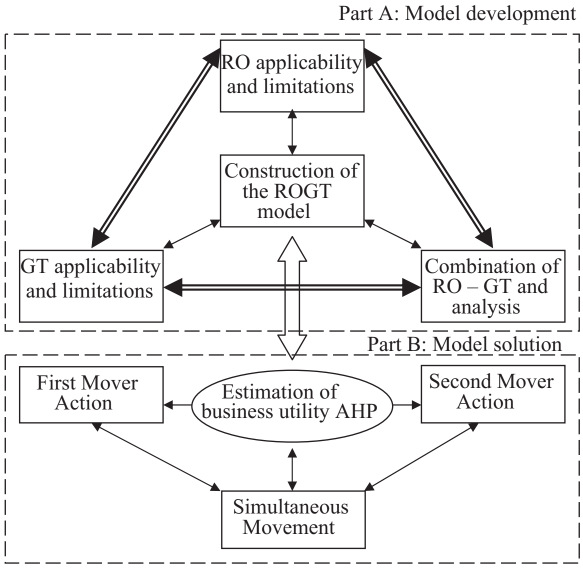

Fig. 2. Structure of the research methodology.

Part A is based on the theories used to build our model as well as the assumptions required for their applicability to the ICT business field. It also takes into consideration their limitations and the need for combining each other under quantitative and qualitative analysis. Furthermore, the model is developed by combining all the aforementioned issues and constructing a hierarchical structure using AHP. Finally, in part B, the business utility of the player is estimated.

3.1. ROs

3.1.1. RO applicability to the ICT business field

An option gives its holder the right, but not the obligation, to buy (call option) or sell (put option) an underlying asset in the future. Financial options are options on financial assets (e.g. an option to buy 100 shares of Motorola at 200€ per share in January 2010). The RO approach is the extension of the options' concept to real assets. An investment embeds a RO when it offers to the management the opportunity to take some future action (such as abandoning, deferring, or expanding the project) in response to events occurring within the firm and its business environment (Trigeorgis, 1996).

Alleman (2002) showed how ROs can be helpful to the telecommunication industry for issues related to strategic evaluation, estimation, and cost modeling. Examples of RO applications in telecommunication investments and particularly mobile networks and broadband technology are given by Harmantzis and Tanguturi (2007) and Iatropoulos, Economides, and Angelou (2004).

For a general overview of ROs, Trigeorgis (1996) provided an in-depth review and examples on different ROs, while Angelou and Economides (2005) presented a literature survey of RO applications in the ICT field. For more practical issues the reader is referred to Mun (2002).

This study focuses on the option to delay investment, called option to defer. RO valuation can be used when the future is uncertain, the (investment) decision is, at least in part, irreversible, and the firm holding the (investment) option has the ability to delay. The first two conditions are usually met (as it happens generally in most investment opportunities): the return to investment is not certain, and the investment cost cannot be recouped in full if the project is subsequently abandoned. But what happens when the firm has the ability to hold the option? This condition forms the basis of our problem. In most ICT industry settings, the ability of a firm to delay its investment (and other) decisions is crucially affected by the actions of *other firms*. When several firms compete in a market, delay by one firm is liable to result in its being preempted by a rival. After its rival's investment, the first firm's investment opportunity is likely to be reduced in value, and may even be forfeited entirely. Thus, to judge whether a firm has the ability to delay investment, it is necessary to understand strategic interactions between firms in the market and so predict the behavior of one's rivals.

3.1.2. RO limitations and need for qualitative perspective

Several conceptual and practical issues emerge when one tries to apply options theory in ICT business practice as proposed in the current literature. It is accepted that all RO models provide approximate valuations of RO values (Amran and Kulatilaka, 1999). Even the so-called accurate RO models, such as the Black–Scholes formula, require some assumptions whose validity is still under criticism in the field of ICT investments (Tallon, Kauffman, Lucas, Whinston, & Zhu, 2002). Particularly, while ROs are widely proposed for evaluating ICT investments, it is still accepted that RO applicability is limited by the fact that ICT investments assets are not traded. The non-tradability of ICT assets cannot reveal the investor's risk attitudes in order to estimate the correct discount factor of ICT investments.

In addition, accurate estimation of parameters of a statistical distribution of outcomes and mainly volatility depends on the senior managers' ability. Dai, Kauffman, and March (2007) stated that many managers do not really have a "gut feeling" for the estimation of volatility though they understand its technical definition as a statistic. Hence, the estimation of revenues and cost volatility, which are used as input parameters in typical ICT option values, can be a very difficult task (Taudes, Feurstein, & Mild, 2000). Also, the existing RO models cannot support, in parallel, many sources of uncertainties. In practice, no more than two or three sources of uncertainties, which are usually revenue and cost, can be modeled by existing RO models (Trigeorgis, 1996). However, ICT investments experience a variety of risks arising from competition, technology, firm, customer demand, and environmental issues. In a detailed quantitative RO analysis the aforementioned issues should be modeled as specific parameters that follow stochastic processes.

From another perspective, one can consider that the various sources of uncertainties contribute to the overall volatility of investment revenue and cost and hence they are efficiently modeled. However, estimation of contribution of various risk factors to the overall uncertainty (volatility) level (technology, competition, demand uncertainties, etc.) may not be possible. For example, customer demand uncertainty may be quantified by estimating its contribution in the overall investment volatility, while contribution of the technology and firm's capability uncertainties may not. By adopting qualitative analysis we can model some of the uncertainty "clearness" inherent in the investment opportunity that cannot be quantitatively estimated and included in the overall volatility. Benaroch (2002) provided a method for estimating the overall investment uncertainty (volatility), which can be broken down into its components (e.g. customer demand uncertainty, competition uncertainty, technology uncertainty). However, estimation of each component of the uncertainty may not be possible. We extend this thinking by considering that some of the overall uncertainties components may be more efficiently treated in a qualitative way. On the other hand, sources of uncertainties that can be quantified and included in the estimation of the overall investment volatility can be integrated in typical RO models.

An important barrier to the successful implementation is a general inability to reliably estimate cash flows that are enabled by ICT investments. Existing models for option valuation assume a certain distribution of the resulting cash flows, based on an efficient market. However, this is only rarely the case in the context of investments in ICT business field, which is known for its uncertain and unpredictable business conditions. It has been further recognized that finance-oriented option valuation models are too complex for managerial decision-making practice when real business conditions are taken into account. Especially after the ICT market liberalization, the required competition modeling has increased the complexity of existing options models. Options theory in its present state does provide a conceptual decision framework to evaluate the pro and con of ICT investments but in many cases it cannot be considered as a fully operation tool for management. Overall, these issues suggest that even quantified RO analysis could produce only approximate valuations, which in some cases can cause serious mistakes in ICT investment decisions (Benaroch, Shah, & Jeffery, 2006).

We consider that in many cases it is much more feasible, simpler, and faster to apply what could be called "option thinking" in the context of risk control that an option can provide. This means that alternative options can be designed, categorized, and examined for finding their optimum combination that management's intuition will recognize as the most promising in terms of risk mitigation. Of course, this qualitative thinking may increase the inaccuracy of option's understanding and quantification. In practice the increase of inaccuracy should be compared with the computational simplicity that quantified RO models are not able to provide. Hence the accuracy versus computational simplicity trade-off can be seriously investigated, especially concerning complex ICT investments (Benaroch et al., 2006).

3.2. GT

3.2.1. GT applicability to the ICT business field

Since the initial formulation of the routing load balancing (load sharing) problem among different traffic classes or telecommunication operators as in Nash games (Economides, 1990; Economides & Silvester, 1990a, 1991), as well as Stackelberg games (Economides, 1990, 1994; Economides & Silvester, 1990b), many researchers modeled resource-sharing problems in computer and communication networks as games (Altman, Boulognea, El-Azouzi, Jiménez, & Wynter, 2006).

GT is suitable for analyzing different players' behavior and interactions among them. The players can be telecommunication companies that decide to enter a new ICT market by selling products in a given market segment. To formulate a practical model (game of perfect information) it is necessary that the market players know – or at least assume – what the competitors will do or will not do. In the telecom market, the possible intention of competitors to invest, services provided by the other players, or even more their quality of service, tariffs, network platform costs, and number of subscribers have to be known. Actually, companies do not coordinate their activities as they are generally not allowed to do so. Particularly, after the telecommunication markets' deregulation, related telecommunication companies (providers) are not allowed to collude against their customers in order to achieve benefits only for them and usually not for their customers. This rule in most of the cases is controlled by governmental regulatory authorities. However, there can be cases where players can cooperate not only for their own benefits but also for the whole market's benefit. An example could be the basic infrastructure (platform) investment, which could be implemented cooperatively by a group of players in order to reduce cost. Then in the next stage of the commercial exploitation of the infrastructure (platform), these players may compete among themselves at a higher business level such as telecommunication services and application provision.

In most countries the incumbent operator owns, at least initially, the strongest competitive position, especially concerning the infrastructure exploitation and the last-mile broadband access. One of the regulatory purposes is to ensure that the incumbent's commitment to offer access level to new "comer" operators is of suitable quality and price in order to achieve the required level of competition in the market.

In our analysis we assume that the game does not contain a direct coordination of the players. However, simultaneous movements may concern some type of coordination. Our model and methodology permits such kind of coordination.

The GT analysis provides information on how players can determine their optimal strategies taking into account the expected behavior of the competitors.

3.2.2. GT limitations and need for qualitative analysis

A key assumption underlying GT is that players (competitors) are rational and their primary objective is to maximize their own utility; that is their value gained from the business activity. Specifically, the expected utility is expressed in a quantitative perspective, mainly containing business revenues and profit. However, in a complicated business environment, such as the ICT market, it is useful that the expected utility function contains both quantitative and qualitative factors. Hence, the main limitation of the typical GT analysis is the inability to accurately estimate players' expected utility based only on quantitative factors' estimation. We suggest that it is more efficient to take into consideration both quantitative and qualitative factors.

3.3. Merging ROs with GT

Although several papers were written during the last 10–15 years regarding the combination of ROs and GT, this field of research is still in its infancy (Lindinger, 2006). GT introduces strategic competition into RO thinking and thereby emphasizes flexibility versus commitment trade-off, which is often neglected by RO models. On the other hand, creation of new opportunities relative to competition from investment projects via ROs enhances GT by introducing dissimilar characteristics of competitors. So, option games enable the "quantification" of qualitative strategic thinking and merge the internal (resources, capabilities) and external (industry, competition) views of the firm (Smit & Trigeorgis, 2004).

Nevertheless, it is not always advisable, from a strategic (game) perspective, to defer investment because the firm could lose early cash flows or miss out a competitive first mover advantage. The fist mover advantage may be generally related to the possibility for the FM to dominate the market and capture higher MS than its competitor, who acts second. Therefore, it is necessary to weigh the strategic benefits of early investment commitment against the lost flexibility value when exercising the option. For the integration of GT and ROs in a multi-criteria model the AHP technique is adopted. The aim is to choose from a number of alternatives the best one taking into account a set of qualitative and quantitative criteria. This is exactly the main advantage of the AHP approach; different criteria with different measures can be easily integrated into a single utility function.

4. The model

In a generic perspective each of the investment alternatives provides an overall value for each player (firm), which is called the overall business utility (*OBU*). Table A1 (in Appendix A) provides the notations used in the proposed model. The *OBU* of a player is given as follows:

$$OBU_{i_{(S_A,S_B)}} = \sum_{l=1}^{L} w_{QL_{l,i}} QL_{l,i_{(S_A,S_B)}} + \sum_{n=1}^{N} w_{QN_{n,i}} QN_{n,i_{(S_A,S_B)}} \tag{1}$$

It contains qualitative and quantitative factors or criteria. Particularly, we define for each factor the respective criterion. Each player assigns specific values to each criterion for each alternative taking into account the overall investment alternatives. The value of each criterion for player *i* depends on its decision strategy (investment alternative) and the strategy of its competitor. Each player determines its optimum investment strategy so as to maximize its *OBU*.

The following problem has to be solved:

$$\max_{QL_{l,i_{(S_A,S_B)}},QN_{n,i_{(S_A,S_B)}}} OBU_i(QL_{l,A_{(S_A,S_B)}}, QN_{n,A_{(S_A,S_B)}} QL_{l,B_{(S_A,S_B)}}, QN_{n,B_{(S_A,S_B)}})$$

where $OBU_i(i = A, B)$ is firm *i*'s *OBU*; $QL_{l,A_{(S_A,S_B)}}, QN_{n,A_{(S_A,S_B)}}$, and $QL_{l,B_{(S_A,S_B)}}, QN_{n,B_{(S_A,S_B)}}$ are business factors of players A and B, respectively. In the following, the specific factors/criteria included in the *OBU* are discussed. The proposed criteria are related to the ICT business field and enable the use of RO thinking for decision making.

4.1. Qualitative criteria analysis

RO thinking may provide value when the investment is irreversible; it contains risks and uncertainties and the management is capable of delaying investments.

4.1.1. Irreversibility (IRR)

The measure of irreversibility (IRR) is based on the value of the second choice solution compared to the first one when the first is not at the expected level. The irreversibility of investments is a fundamental attribute of many technology projects (Fichman, 2004). Particularly, the presence of an existing option to investments (e.g. the option to switch the use of some of the resources of the project) creates valuable opportunities to recoup part of the sunk costs by reconsidering the project. Particularly, the *option to switch use* refers to the option to put a project to a different application than that for which it was originally intended. Also, the irreversibility is related to the presence of the abandon option. An *abandon option* is associated with a project if the managers have the discretion to discontinue it prior to completion and re-deploy the remaining project resources. While in principle any project can be terminated, not every project has an abandon option of nontrivial value. For example, if there is no useful way to reallocate the project's resources, then there would not be an abandon option. The nonexistence of an abandon option may also happen when a contract does not include a termination clause and so the developer must be paid in full anyway. Another case is when the company will go out of business or be subject to severe regulatory sanctions if the project is not completed. Even when potentially valuable abandonment options do exist, they are often difficult to exercise for two reasons: (i) ambiguity about timing and (ii) reputational consequences. Especially for the second reason, managers' desire not to appear wasteful, the political implications of cancellation, and the possible detrimental effect of abandonment on staff morale and reputation can keep even a deeply troubled project alive (Keil, Mann, & Rai, 2000). Therefore, the amount of irreversibility contained in an investment opportunity is its crucial part. It requires both quantitative and qualitative analyses. Hence, the type and amount of irreversibility depends on the timing when the investment takes place and the competition status.

4.1.2. Risk control

Risks in the ICT business field can be classified into firm-, market-, technology-, and competition-specific risks (Benaroch, 2002). Firm risks may include business complexity and firm's financial exposure capability to afford business. Further, market risks to low customer demand may involve regulatory and environmental issues. Technology risks may involve new technologies that would be immature for the investment under investigation. Finally, competition risks may involve competitors' preemption and elimination of business value. ROs can provide risk mitigation in ICT investments (Angelou & Economides, 2007; Benaroch, 2002). Option thinking can support the control of different sources of risks present at various stages of the investment life cycle (Benaroch, 2002; Bräutigam, Esche, & Mehle-Bicher, 2003).

Risk control achieved by the ROs is quantified by the volatility of stochastic parameters such as investment revenues and cost. The higher the value of volatility, the higher the value of risks achieved by deferring investment.

Benaroch (2002) provided a method for estimating the overall investment's volatility, which can be broken down into its components (e.g. customers' demand uncertainty, competition's uncertainty, technology's uncertainty). However, the estimation of each component of the volatility may be impossible. This paper extends this work by considering that some of the overall components of the volatility may be treated in a qualitative way. Hence, qualitative modeling would help on this by providing a more flexible (for the management decision makers) way to deal with uncertainty "clearness" and risk control.

4.1.3. Capability of delay

By deferring the firm may loose some investments' benefits. The cost of delay in RO literature was modeled as a divided yield (Trigeorgis, 1996). Instead, this study proposes a qualitative modeling of this factor taking into account more generic issues for the cost of delay. The specific option factor is called the "*option cost of delay*" (*OCD*). *OCD* may be also related to business loss due to regulatory issues and firm's commitment to proceed in the implementation of ICT activities in possibly not so profitable cases. However, the management's capability of delay is strongly related to competition conditions and the possibility that a competitor will preempt the firm of interest and destroy its business value.

4.1.4. Competition factors

The possible investment decisions can involve sequential or simultaneous moves in the market. Under sequential decision analysis, strategic interactions between firms can be classified into two broad types: first mover action and second mover action. In the first type, the player acts first by investing before its competitor, expecting a higher pay-off than its competitor. In the second type, a player acts second, trying to achieve a higher pay-off than its competitor.

Under simultaneous (SIM) decisions, both players decide to invest simultaneously at the same time. Normally, FM and SM actions are enough to express the competition situations, especially in the relatively new ICT market industry. However, both players should know that if both decide to act as FM their final business utility would be different since there will be a SIM decision mode (Smit & Trigeorgis, 2004; Zhu, 1999). Hence, the simultaneous decisions case is also examined. In the following the attributes/criteria that are included in our model and related to the FM, SM, and SIM decision modes are discussed.

4.1.5. FM attributes

When strategic interactions give rise to FM's advantages each firm has an incentive to act just before its rival does so, thus gaining the advantage for itself.

The following attributes (criteria) are considered:

- *Network effects*: In a market where "tipping" effects are strong (e.g. computer software market, satellite broadcasting market) the first firm to establish a base tends to dominate the whole market in due course.
- *Limited demand for two players (LD)*: Consider a market that is initially unprofitable but it is growing over time. The first firm to enter the market enjoys a period of monopoly profits before the market becomes sufficiently large to sustain a duopoly, while the second firm earns no profit during this initial period.
- *Cost of switching (COS)*: If there are significant costs of switching between suppliers, there is an even stronger advantage to enter the market first and get customers signed up. The FM continues to enjoy a strong position even after the entry of the second firm.
- *Influence and severity of follower's action (SFA)*: In a competitive situation it is likely that, in addition to the existence of FM's advantage, subsequent action of the SM harms the leader.

A main question is whether the FM's advantage is temporary or persistent. Temporary FM's advantage is lost when the SM invests; thus the follower's investment is harmful to the leader. On the other hand, persistent FM's advantage implies that the FM is insulated from the SM's actions in some way, at least in part, and the effect of the SM's reaction is of smaller magnitude. If the FM's action deters investment by the rival, this gives added advantage to preempt. However, a rapid (and harmful) reaction by the SM quickly undermines the FM's advantage and reduces the incentive to preempt.

In conclusion, if the FM's advantage persists despite investment by the SM, a firm has less to fear from its rival's reaction and is likely to act preemptively to seize the FM's advantage. On the other hand, if the FM's advantages are temporary and the rival reacts rapidly to the leader's action, the fear of the competitive reaction may induce a firm to delay investment and capture the RO value.

4.1.6. SM attributes

The SM's decision may provide an additional motivation for investment to be delayed. In contrast with the FM's action, the SM's action increases the value of delay for players, tending to reinforce the effect of ROs. The main criteria concerning the SM's decision are the following:

- *Information spillovers (risk control mitigation for market, technology risks)*: Information spillovers are a major source of the SM's advantage. Suppose that the demand in a market is uncertain (e.g. entry may be profitable or unprofitable with equal probability). The first entrant reveals the true state of demand to subsequent entrants, who learn from this and enter if and only if the market is profitable.
- *Complementary investments by the competitor (network effects)*: In some instances a firm's investment project has higher value if another firm also invests; in this case the investments of the two firms are said to be complementary. For example, as long as competitive effects are not too strong, a firm may benefit from the advertising expenditure of other firms to the extent that this creates demand for the product class as a whole, not just the output of the particular producer.

Similarly to the temporary and permanent FM's advantages, a distinction can be drawn between two forms of SM's advantages. The complementarity of investment underlying the SM's advantage may either be *one-way*, benefiting the follower alone, or it may be *two-way*, such that the leader also benefits when the follower invests. Informational spillovers tend to benefit the SM alone, though in a setting with on-going research it is possible that the activity of the SM may benefit the FM. However, network effects may be two-way if the FM benefits from the subsequent increase in demand generated by the SM. If the complementarity of investment is one-way the advantage to the SM is permanent—the FM never benefits from the other firm's investment. On the other hand, two-way complementarity gives rise to a temporary SM's advantage.

4.1.7. General comments on FM and SM actions

In some settings, SM's advantages co-exist with FM's advantages. An example is the following: two competing telephone companies where each one of them benefits from the other's customer base since their customers could communicate with many people and thus increase both companies' profits. Such a situation becomes complicated since there is an incentive to preempt but the position of the follower may also have advantages. If the complementarity of investment is two-way, a firm may wish to preempt its rival but also to ensure that the other firm does not delay its investment too long.

Also, under asymmetric information between the two players, the order of sequential moves may reveal private information. Firms can infer information by observing the other firms' actions. The sequencing of moves becomes subtler, as it reflects each firm's calculated trade-off between the early mover advantage and the information benefit of waiting to learn the rival's private information (i.e. information revelation).

4.1.8. Simultaneous decisions

Simultaneous investment decisions can occur when both players decide to act as FMs, or there is a cooperative game where simultaneous entry can capture higher business value by choosing all players to defer investment.

There can be cases where some form of coordination may be required to overcome the tendency of each firm to wait for the other to act first. Joint research and investment efforts may be an example. It may involve the development of a common infrastructure such as an optical fiber backbone network. Also, a common infrastructure may be the case among ICT providers, local utilities, and municipalities. The joint venture of utilities that own physical resources offered to the interested telecommunication providers may lead to more profitable condition for all existing and potential future players.

Simultaneous investment may involve strategic alliances benefits. Strategic benefits from this alliance may include the following: (1) risk reduction, (2) economies of scale, (3) complementary resources (network effects), (4) learning, and (5) aggressive market entry—network effects. Especially for the last, if both players act (invest) simultaneously they can achieve an aggressive market entry. Finally, the complementary follow-on investment opportunities concern the case where both players plan to build future investment opportunities that are complementary between each other.

Another factor that can be considered in all FM, SM, and SIM actions has to do with emotional issues of the management's perspective. Actually, there can be some cases where the management may act at least partially emotionally. It is called *no clarified reasons to emotionally decide (EMD) to act as first or second mover.* This is the case where the management feeling drives the firm to act for reasons mainly related to emotional issues. It is true that the EMD factor violates our assumption for rationality; however, we include in our model an attribute that is related to emotional (not rational partially or fully) decisions. We do this in order to consider at least partially some deviation from rational behavior.

4.2. Quantitative criteria analysis

In order to consider quantitative criteria, the standard GT analysis for both simultaneous and sequential decisions is adopted (Smit & Trigeorgis, 2004; Trigeorgis, 1996). It considers the profit (P) of the investment, which is described by operational revenues related to the quantity produced, the operational cost, as well as the one-time investment cost (OC). It is the cost of exercising the ROs and implementing the investment. Especially for large infrastructure investments (e.g. optical fiber installation), the installation cost (e.g. fiber to the building, fiber to the home) is a very significant factor, presenting serious asymmetries between players in the market. Finally, interested investors that own installation rights and even more resources to install fibers (e.g. water and sewerage companies) experience significant infrastructure cost advantages. Appendix B presents the investment profits and quantities offered by competitors for the various equilibria of the investment game. Finally, the proposed model incorporates the market share. Under quantity competition the MS is defined as the percentage of the service offered by each player, in this case the quantity offered.

The *OBU* for each player, concerning the aforementioned criteria, is given by expression (2). The value of each criterion, for each player, is strongly related to the decision of its competitor.

$$\begin{aligned} OBU_i = {} & w_{IRR_i} IRR_i + w_{FRC_i} FRC_i + w_{MRC_i} MRC_i + w_{TRC_i} TRC_i \\ & + w_{OCD_i} OCD_i + w_{NE_i} NE_i + w_{LD_i} LD_i + w_{CoS_i} CoS_i \\ & + w_{SF/CA_i} SF/CA_i + w_{EMD_i} EMD_i + w_{P_i} P_i + w_{OC_i} OC_i \\ & + w_{MS_i} MS_i \end{aligned} \tag{2}$$

The target of each player is to select the strategy that maximizes its *OBU* with respect to the competitors' selection.

5. The methodology

The proposed dynamic ROGT–AHP hierarchy for the aforementioned criteria is illustrated in Fig. 3. Each player constructs its hierarchy and runs pair-wise comparisons for each investment alternative (here, invest or defer and how much).

The proposed analysis provides the framework for a series of iterations between player A and player B hierarchies. It involves role-playing the competitors(s)' likely actions and reactions concerning the sequential decision mode or simultaneous actions concerning the simultaneous decisions.

Analytically, there is a parallel hierarchy for competitors. Each player constructs its ROGT–AHP hierarchy. Without loss of generality the proposed methodology is presented from the player A point of view. Player A performs pair-wise comparisons for each of the available entry points (here at $t = T_0$, $t = T_1$), with respect to the aforementioned criteria. The quantitative criteria for each alternative are normalized with respect to their maximum value (Angelou & Economides, 2008a). Afterwards, it estimates the relative importance of the criteria included in the model. Hence, player A estimates its

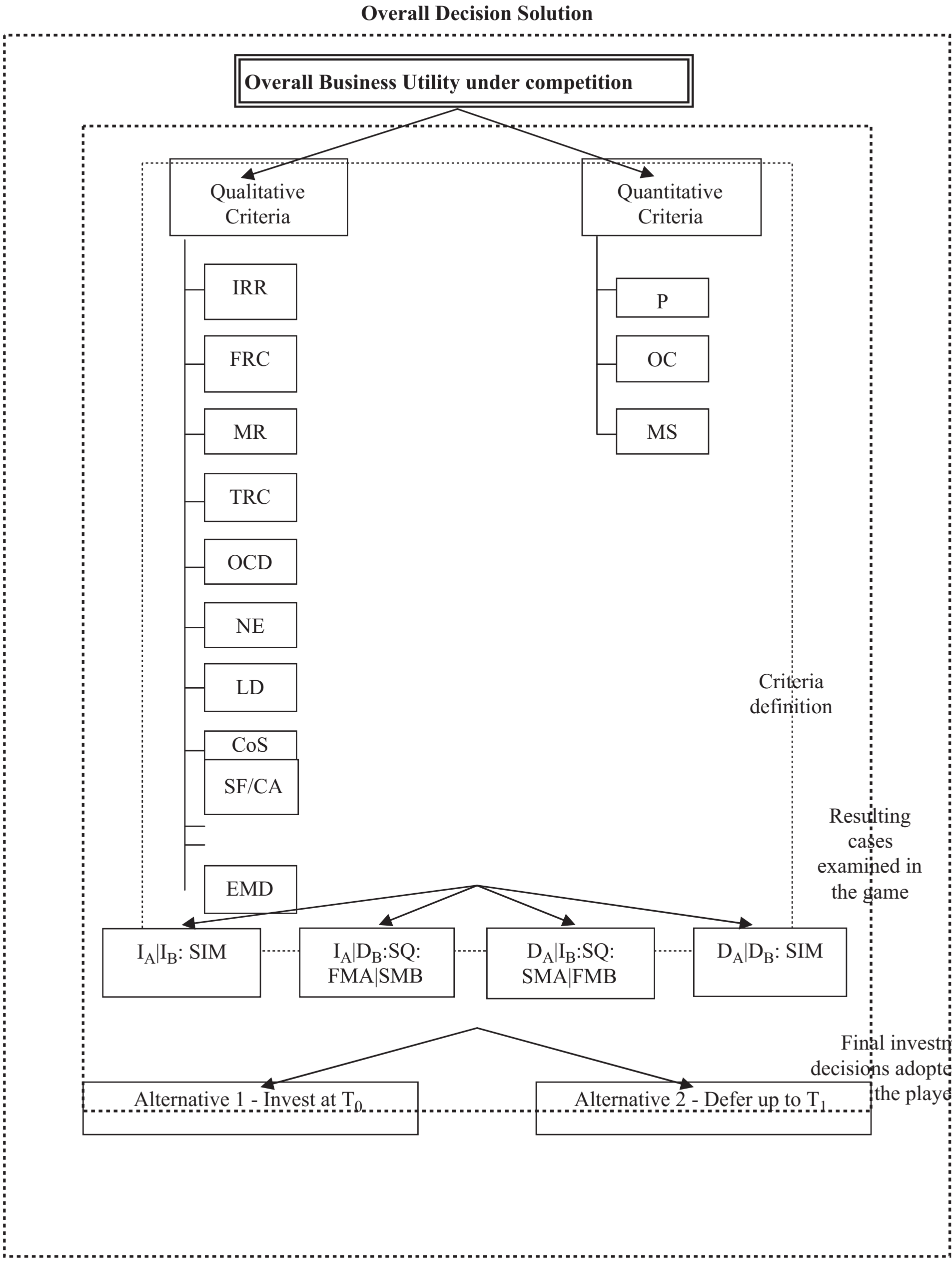

Fig. 3. A dynamic ROGT–AHP hierarchy for competitive strategy analysis.

OBU for each entry point ($t = T_0$, $t = T_1$) and for each decision mode (FM, SM, and SIM). Since, symmetry between players is assumed the same values are considered by player B too.

The resulting cases are presented in the following pay-off matrix (Table 1). There are four decision cases:

- Case 1: a simultaneous investment will take place at $t = T_0$.
- Case 2, 3: a sequential investment will take place.
- Case 4: one or both players will finally invest at the latest possible entry time or loose business investment) opportunity. The proposed analysis considers that both players will finally enter into the market; hence a simultaneous investment will take place at $t = T_1$.

The question to be examined is: "at what time instance the aforementioned competitors' decisions should take place?". RO thinking recognizes the value of waiting for risks mitigation, while the introduction of the threat from competition

Table 1
Pay-off matrix of the investment game for the available strategies.

A \ B	S_{B1}: I_{BT0}	S_{B2}: D_{BT1}
S_{A1}: I_{AT0}	SIM $SIMA_B$ $SIMA_A$	SQ SMA_B FMA_A
S_{A2}: D_{AT1}	SQ FMA_B SMA_A	SIM $SIMA_B$ $SIMA_A$

Strategy 1 (Si1)—Invest immediately: the player *i* invests immediately without waiting.*Strategy 2 (Si2)*—Defer up to T_1: during the first period the player is able to observe the market demand; however, he is not able to recognize the strategy of the competitor.

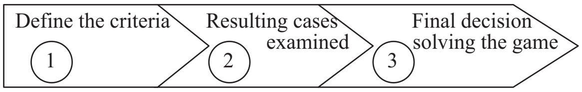

Fig. 4. Overall methodology for choosing the best investment strategy.

defines the value of competitor's preemption. Overall, there is a balance between investing to preempt competitor or waiting for collecting more business-related information.

In particular, the decision maker has to decide whether to invest now or wait until the moment when the business value is higher than its expected value in the future up to the time moment when the investment is still available to the decision maker.

During the waiting period, some of the decision factors may change and even if some of them could be accurately estimated the decision maker has to estimate the pro and con of an early or late decision. Our analysis takes into account the FM and the SM attributes. Our model considers the specific business conditions in order to find the optimum decision between "invest" or "wait" despite competition threat. In one case the FM could have advantage, while in another case the SM could have advantage.

Focusing particularly only on investment cost, waiting and investing is more promising as seen in Fig. 5. The network infrastructure cost decreases over time due to technological progress (Fig. 5). A predictable change occurs, perhaps with some uncertainty, but quite predictable overall. The game tilts from a preemption advantage to wait and see before acting advantage. The delay to invest and probably being SM undercuts the immediate action and probably the FM by buying lower cost equipment.

The game may now change to one where the established firm waits in ambush. Once the newcomer moves, the established firm will react. If the newcomer does not act, nobody moves. In this situation, the FM is not the established firm that would use its timing benefit, but the entrant that cannot become active unless it acts, which automatically brings it in the undesirable situation of a FM. This seems to be the situation of the real case study examined later. The supposed FM is not the established incumbent operator but the potential new entrant. The typical FM advantage study cannot account for this outcome, while the SM advantage account based on predictable decreasing input prices (technological advantage) can. Our analysis can easily incorporate the aforementioned case since we consider both FM and SM attributes.

In the general case where during waiting–deferring period there are many decision nodes (many stages) the game for the sequential case process starts by identifying the "best" strategy for the firm (say, A). This strategy is then introduced as part of the scenario facing the key competitor, and the competitor's best strategy firm B, reflecting firm's A strategy as part of its environment, is assessed by the former. This strategy is then considered as part of the scenario of firm A, and the previous strategy and other strategic options are examined against it to assure that the selected strategy is the best one. The series of iterations can continue in each decision node (time instance at which the model is executed) up to the moment when the investment opportunity is still available.

Hence, the equilibrium point is estimated as the combination of strategies that maximize the *OBU* of each player taking also into account the corresponding *OBU* of its competitor.

The steps of the proposed methodology are presented in Fig. 4. In the first step, the criteria strongly related to the decision problem are defined. The analysis focuses on the ICT business field, which is characterized by oligopoly market conditions and high level of uncertainty and risks. Afterwards, the decision combinations of players in the game are recognized and each player estimates for each final resulting case its utility function. Particularly, each player runs the model and calculates its utility function as well as its competitor's utility function for each of the decision combinations. Finally, in order to estimate the final solution that maximizes the business utility in combination for both players, the pay-off matrix is constructed.

Each player runs the model in each decision node (time instance at which new information is collected and the model is executed).

5.1. Asymmetries between players (competitors)

As mentioned before, it is initially assumed that there is full symmetry between competitors. However, incorporating asymmetries between players will add greater realism to the model. Asymmetries may involve different values for various criteria of the model or just information about business issues. These asymmetries may be common knowledge or may not be between players. This work assumes that asymmetries are common knowledge for players. In practice, even if there is full symmetry about quantified factors, it is almost certain that qualitative factors cannot take the same values by the two competitors. Information asymmetry does exist among competing firms in technology markets (Zhu & Weyant, 2003a, 2003b). For example, Amazon.com may have better information about the cost (profitability) of selling books on-line than a traditional book retailer who wants to do the same. Also, the incumbent telecommunication operators may have better information about the cost and the overall difficulties of the last-mile connections with optical fibers compared to new potential operators.

6. A real case study

The firm under investigation is the Greek company Egnatia Odos S.A. (EO). Its core business activity is the management of design and construction, operation, maintenance, and exploitation of the 680 km long ''Egnatia Odos'' motorway (EOM). The strategic goal of EO is to enter into the telecommunication market. To fulfil this goal EO is examining the exploitation of competitive advantage of its physical resources. Iatropoulos et al. (2004) applied ROs and examined the case of installing optical fiber backbone network and offering it afterwards to possible operators and big organizations. The current work examines the business activity of going a step ahead, taking also into account the threat from competition in addition to offering these bandwidth services. The installation, operation, management, and maintenance of active equipments are required for offering bandwidth services.

6.1. Market status

The area under consideration includes the eastern part of Northern Greece (Region of Eastern Macedonia and Thrace). Potential customers are other telecommunication providers, big organizations, and various authorities. After the deregulation of Greek telecommunication market in 2001, an increasing number of new players has entered the market and started competing with the incumbent OTE and between each other in the value-added services (ITI, 2005; Kantor, 2005).

The main interest of the telecom providers is focused on the areas of Athens and Thessaloniki, where 59% of the small- and medium-size companies are located. In addition to the topology constraints other factors that prohibit the deployment of fiber networks by telecommunication investors other than OTE to remote areas like Eastern Macedonia and Thrace are the difficulty in getting rights of way, the complicated local loop unbundling (LLU) processes, and the restricted access to leased lines (Iatropoulos et al., 2004).

Although OTE holds a dominant position in the region of interest, it is mainly focused on the provision of ADSL services in high-competition areas (with dense population). Interviews with broadband experts in Greece lead to the conclusion that the main competitor OTE will delay the broadband service provision in sub-urban and rural areas beyond the year 2006 (Iatropoulos et al., 2004).

The ''Egnatia Odos'' motorway, along which an optical fiber backbone network will be installed, is located outside dense urban areas, the prime focus of the other broadband network investors. In particular, it passes through areas with low level of business activities except Thessaloniki. In addition, the duct construction corresponds to more than 40% of the overall cost of an optical fiber network. In this sense, EO has a strong competitive advantage against other possible telecom investors in the area, facing for the moment no or little competition by the incumbent and other network operators (Iatropoulos et al., 2004). Hence, by waiting EO will not lose significant MS, at least until OTE or some other competitors (e.g. Vodafone, Tellas) decide to enter that market. Naturally, by waiting EO will lose some revenues. However, waiting too long could lead to MS gains by competitors who had no prior presence in the market. Iatropoulos et al. (2004) compiled the information received by interviewing company executives and broadband experts in Greece, and concluded that the waiting period to achieve the best timing for market entry cannot exceed 3 years. This conclusion is still valid according to EO ICT management since broadband service penetration in the area of interest is still low.

Thus, from EO's perspective the decision to enter broadband business can be a matter of timing. Whether EO can afford to wait since there are no credible threats in the markets (regions) of interest or whether it should move early in order not to loose its competitive advantage and even more the overall business value is examined. By waiting, EO expects that uncertainties, related to the acceptance of broadband services in the regions along Egnatia's track and the sustainability of additional irreversible network infrastructure investments would be resolved. In turn, EO could learn more about the potential returns on such investments. For example, the acceptance rate for such services might increase as customers become more aware of these services. In parallel, EO could take actions to lower its market entry risk (e.g. by seeking corporate alliances for common exploitation of the specific North Greek regional market).

With these concerns in mind EO is addressed to the question—how long should EO wait to enter the broadband market? A two-player game is considered where one player is EO and the other player is the incumbent operator, OTE. The numbers are fictitious in order to protect EO business activity. However, the content and business characteristics of the specific case study are real and are results of extensive discussions between the authors and EO's ICT management. Next, the proposed analysis is applied to this case.

6.2. Application of the proposed model

6.2.1. Define the criteria

We consider all criteria as presented before; however, there might be cases where only some of them should be considered. Particularly, in cases where some of the criteria are not applied or are not related to the specific investment alternatives they should be excluded (e.g. network effects, limited demand).

6.2.2. Resulting cases to be examined and pay-off matrix estimation

We examine the cases for simultaneous and sequential investment decisions. We also consider that finally at least one player will invest at the end of the game.

For the estimation of the utility function, each player applies the AHP and pair-wise comparisons are performed for each of the decision combinations. In order to find the optimum solution and solve the game, a pay-off matrix is estimated where both players' utility functions are included.

This case study is for intuition purpose only and hence we make the pair-wise comparisons by ourselves. Roper-Lowe and Sharp (1990) commented that since it is sometimes difficult to find technical people who can compare options, it is necessary for the analyst to learn in detail about each option and do the scoring himself. We play the role of the analyst here and select the consistency ratio level according to AHP to be less than 0.10 (Saaty, 1980).

The quantitative criteria, as derived in Appendix B, are normalized with respect to their maximum value in order to include them in the *OBU*. Particularly, for the OC it seems that due to economies of scale it is more useful for the competitors (EO and OTE) to coordinate and proceed in the common implementation of dark fiber installation along northern Greece.

Of course since the investment cost is significantly decreasing with time the delay to invest is more preferable. Implementation cost (OC) or capital expenses (CAPEX) has been decreasing along time in the last years as seen in Fig. 5. CAPEX contains the costs of purchase and installation of the passive and active equipment. As seen the CAPEX has decreased over 40% from 2001 to 2006 (http://ru6.cti.gr/broadband/download/P93_P3.1_EAITY_FINAL.pdf).

The specific analysis considers a 10% yearly reduction of OC. Also, the OC may differ for simultaneous or sequential investment decisions. Particularly, simultaneous decisions may concern cooperation of the competitors for the duct construction and so partial sharing of the OC. An interesting extension could be the case where EO acts first, due to infrastructure advantage and afterwards OTE buys infrastructure rights from EO, instead of investing itself.

6.3. Result presentation

After making all paired comparisons for all alternatives, according to the principles of AHP with respect to all criteria defined in the proposed model, the total priorities for the alternatives are computed using the Expert Choice (1995) tool. The prioritization results are given in Fig. 6.

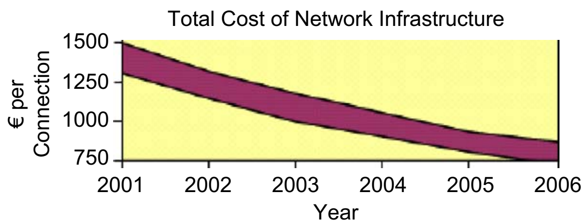

Fig. 5. The ratio of decrease of broadband technology cost.

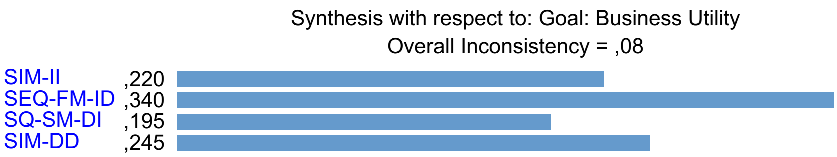

Fig. 6. Prioritization of game-decision alternatives.

As can be seen here, sequential investment decisions and FM action provides the highest business value. The second best alternative is simultaneous investment decisions at $t = T_1$.

Table 2 describes the pay-offs in the four decision-timing scenarios: (a) both invest now; (b) one firm preempts its competitor investing now; (c) one firm acts as SM; and (d) both firms decide to wait up to $t = T_1$. Similar to quantitative analysis, both firms have a dominant strategy to invest, resulting in a Nash equilibrium outcome under no collaboration. This corresponds to a prisoner's dilemma where both firms would have been better off to collaborate or coordinate and fully appropriate the option value of waiting (Zhu, 1999).

In particular, firms tend to move early in an effort to preempt competitors (act as FMs). Such an effort may lead to simultaneous early investment. Actually, this is a phenomenon that has been often observed in the real ICT markets.

It seems that FM action provides the highest value of 0.345. However, if both players proceed in this decision, it will finally guide to simultaneous investments at $t = T_0$, leading to 0.220, since this "rush equilibrium" falls in the classic Prisoner's Dilemma.

Quantitative analysis is in accordance with the work of Zhu (1999). Of course, the equilibrium results may not be the same when qualitative analysis is further performed. In the following we focus on the qualitative influence factors, and particularly risk factors, in the final result of the decision game. We examine the influence of the importance of these criteria to the priorities of alternatives. Fig. 7 shows the sensitivity analysis of the results with respect to the risk control factors (FR, MR, TR) and NE. The left vertical axis shows the utility values (priorities) of the four investment alternatives, while the horizontal axis shows the FR, MR, TR, and NE importance (i.e. weight factor of their significance).

Table 2
Pay-off matrix for the investment game for the available strategies of EO and OTE (prisoner's dilemma).

B / A	S_{B1}: I_{BT0}	S_{B2}: D_{BT1}
S_{A1}: I_{AT0}	SIM 0.220 / 0.220	SQ 0.195 / 0.340
S_{A2}: D_{AT1}	SQ 0.340 / 0.195	SIM 0.245 / 0.245

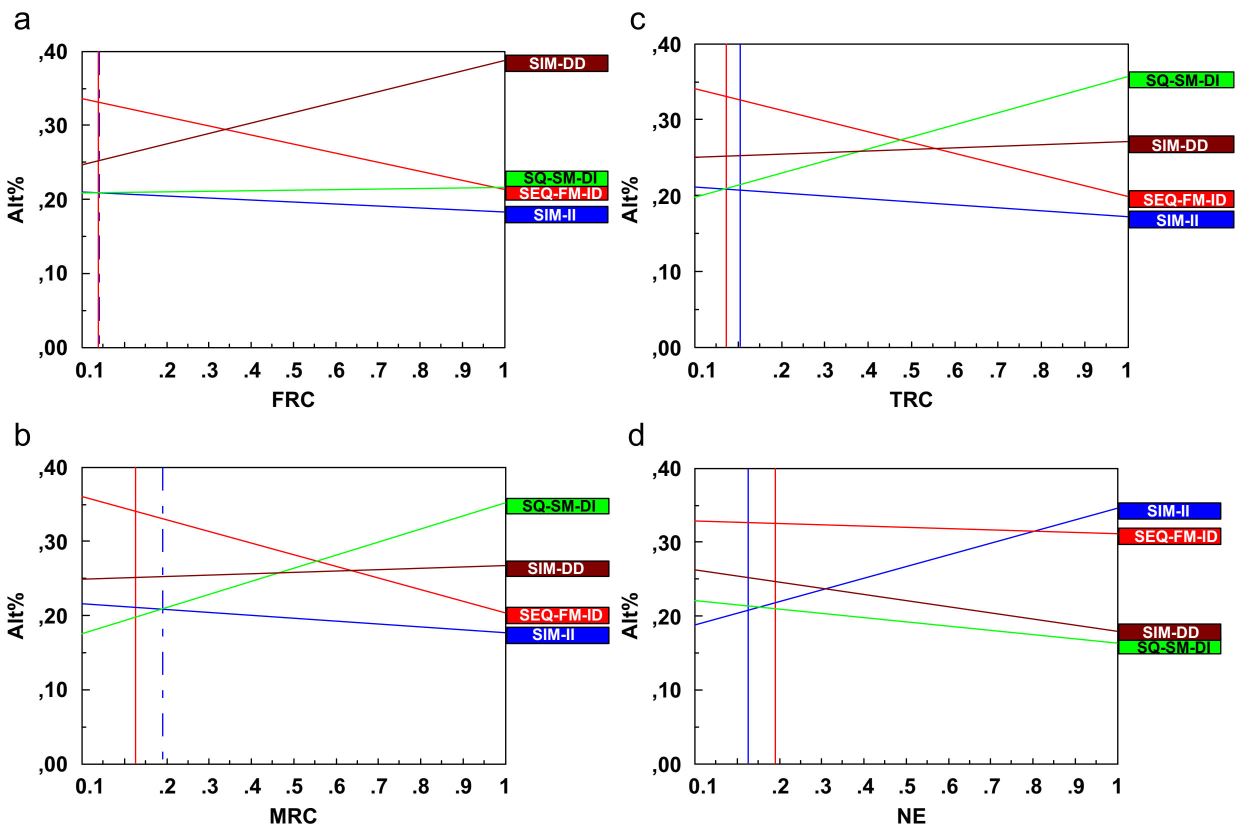

Fig. 7. Sensitivity analysis for FR, MR, TR, and NE.

As can be seen, the priority list of the investment alternatives changes with weight factor for the risk criteria. Particularly, the optimal solution is the SM action and not FM, as given by the single quantitative analysis, for MR and TR weight values higher than 0.50–0.55 with respect to all qualitative criteria.

Similarly, when the weight of the NE criterion is higher than 0.8 with respect to all qualitative criteria then the optimum decision is simultaneous investment without waiting. The weight of each criterion is given by the decision makers who run the model and quantify the significance of each of it according to the existing business conditions at the time when the decision process takes place.

Finally, for FR weight higher than 0.35, the delay to invest for both players seems to be the best decision.

The conclusion of the specific sensitivity analysis is that when qualitative criteria are included in the analysis the optimum decision may be different than the one given by the single quantitative analysis. Our model provides to the decision maker the capability to model more business attributes by including more criteria and considering specific values of importance for each of them.

6.4. Asymmetries between players

As mentioned before, asymmetry between players is a more realistic phenomenon. This paper examines asymmetries concerning FR. Fig. 8 provides the importance of the criteria for EO, where FR takes higher value than the previous symmetrical case. Particularly, EO is a new potential business player in the area of the ICT field and its organizational structure experiences significant internal risks, which require time to be mitigated.

Finally, Table 3 provides the pay-offs for the two players, where the resulting equilibrium is for OTE to act as FM and for EO as a SM. As can be seen in this case the best strategy for EO is to defer investment while for OTE it is to act immediately as FM.

In conclusion, quantitative analysis and typical GT modeling may mislead decision makers as seen in our example. Particularly, we see that the best strategy for both players is to act as FM. However, if qualitative analysis is also incorporated then the SM attributes may appear higher than the FM ones. Hence, while competition may change investment behaviors of a firm, causing aggressive attack in the market, in the case where more factors or criteria are considered this may change, guiding to more collaborating situations. Specifically, for the broadband technology business

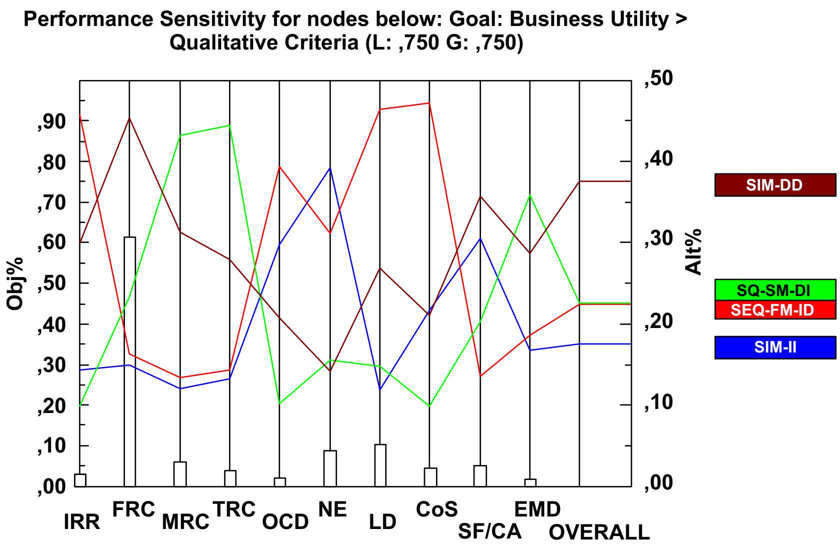

Fig. 8. Importance of qualitative criteria for player A (EO).

Table 3
Pay-off matrix of the investment game for the available strategies of EO and OTE firms with risk asymmetries between players.

A \ B	S_{B1}: I_{BT0}	S_{B2}: D_{BT1}
S_{A1}: I_{AT0}	SIM 0.220 / 0.175	SQ 0.195 / 0.215
S_{A2}: D_{AT1}	SQ 0.340 / 0.225	SIM 0.245 / 0.37

field, SIM decision may be more profitable for investors since higher level of network effects and risk control can be achieved.

7. Discussion and future work

ROs have been already applied in the literature for evaluating ICT investments. However, the option analysis faces criticism concerning the need for the quantification of RO model parameters. The issue becomes even more complicated in ICT markets. Particularly after the deregulation of the ICT markets the competition intensity has increased dramatically and the players (competitors) are usually so many that oligopoly models are becoming very complicated to be used in practice. This situation demands the adoption of GT. Quantitative analysis of the competition in ICT investment opportunities is a very difficult task that requires high level of mathematical modeling, while managers and experts do not prefer to adopt this modeling.

This paper extends the quantitative analysis of ROs and GT, introducing further qualitative option and GT thinking. It suggests that management and business analysts should recognize qualitatively the factors affecting the investment value. The ability to hold the option and delay investment depends on the balance between a large number of criteria, of which some of them can be treated qualitatively while some others quantitatively.

A preemptive outcome is more likely not only when the option's benefits from risk control are relatively small and FM advantages are significant, but also when the SM's reaction is deterred by the FM's action and/or has little effect on the FM. The evaluation of a real-world industry situation requires a judgment to be made regarding the relative magnitude of these factors and the likely outcome of the strategic game between the players.

This paper focuses on a two-player game in order to make the presentation of the proposed model clear and simple. The more the players included in the game the more complicated the model and each one of the players has to define a larger number of business alternatives to be considered in the decision game. However, the model and the methodology are similarly applied. Particularly in telecommunication markets there are normally two–three strong players and a number of weaker players that normally follow the strong ones. A possible extension of the model could be the case where the game concerns two parties; one is the firm of interest and the other is the rest of competition as one entity.

In addition, the paper considers that both firms will finally invest no later than T_1. It can be easily extended to consider the case where none of the firms invests if conditions finally are not favorable up to the time T_1, where investments are available, or only one player invests, having monopoly conditions. In this case for two players more investment alternatives should be added to the alternatives presented in this work. Particularly, each player may abandon (or lose) investment opportunity, while the competitor either enters experiencing monopoly conditions or abandons too. In the last case, no business activity takes place in the market. For example, there might be the case where none of the players invests, replacing this opportunity for another one with alternative technology, such as abandoning optical fiber investment for future wireless technology installation. The model should be run by decision makers for the players every time when new information arrives. Each time the FM and SM attributes are examined for finding the optimal decision.

Hence, there might be the case where FM is more promising than SM, as it is in this paper. However, in the next time when the game is still open and the model is run again the SM action might be more profitable.

Further to the aforementioned assumptions, as main limitations of our analysis we first consider the linear relationship between the various factors/criteria, while as mentioned before some of the criteria may present an amount of overlapping between each other. Also, when the number of players is large then the number of investment alternative to be analyzed by each player becomes large, increasing the complexity of the analysis process.

In addition, the proposed model should be further tested in real cases for recognizing its suitability in the ICT business field. We consider that players make their decisions either one after another having first observed the earlier player's action in a sequential or simultaneous move game. Of course, real-life games might involve a combination of simultaneous and sequential games. Specifically, there are cases where an initial investment decision for capacity implementation could form a sequential game, while, once capacity is installed competition might shift the prices and the game changes to simultaneous decision mode.

The model may also include the qualitative analysis concerning building (deployment) mode of the business activity. In this case each of the players, in addition to the deferral strategy, has to decide about the building mode. The available building modes are the following:

- Full mode (F): Invest at once.
- Partial mode (P): Invest a part and afterwards if business conditions are favorable invest the rest (F−P). Adopt initially a pilot phase.

In addition, the deferring period may be composed of many periods in which each player collects specific business information, analyzes it, and runs the model for selecting the most suitable strategy for him, taking also into account the parallel hierarchy of the model for its competitor.

Finally, the proposed model can be also applied in a multi-player environment. In this case, each player (competitor) can view itself as opposing the rest of the industry (i.e. them versus us). Particularly, in the case of MS, what one company gains, the rest of the companies in the industry may lose.

8. Conclusions

This work extends the RO and GT analysis by combining quantitative and qualitative factors in a single business utility function. In the literature, RO and GT models have so far employed only a quantitative analysis under competition. However, the problem under investigation also has a number of qualitative factors that should be also taken into account along with the quantitative ones. In addition, RO analysis produces a number of factors that cannot be quantified, at least not easily, by the existing RO models and methodologies. For this reason, the proposed analysis combines ROs, GT, and AHP into a common decision analysis framework, providing a new multi-criteria model called ROGT–AHP.

Under quantitative analysis the FM advantages tend to conflict with ROs by eroding the flexibility to delay, whereas SM advantages tend to complement ROs by enhancing the motivation for delay. However, under a multi-criteria perspective the problem is more efficiently treated since the SM has to examine whether investment by another firm is beneficial to him and whether it is worthwhile to delay investment to benefit from the other firms' actions.

Finally, the proposed model is applied to a specific case showing how it can be formulated and solved. In this case, it is shown that the ranking of the decision alternatives may change when quantitative and qualitative factors are integrated, in comparison to the purely quantitative analysis performed by the typical RO and GT models.

Appendix A

See Table A1

Table A1
Notation, $i = $ A, B.

Notation	***Definition***
S_i	Investment strategy of player i, $S_i = I_i$: player i invests, $S_i = D_i$ player i defers
$OBU_{i_{(S_A,S_B)}}$	Overall business utility for player i considering strategies S_A and S_B of players A and B
$QL_{l,i_{(S_A,S_B)}}$	Qualitative criterion l ($l = 1,\ldots,L$) for player i considering strategies S_A and S_B of players A and B
$w_{QL_{l,i}}$	The weight of importance of criterion QL_l for player i
$QN_{n,i_{(S_A,S_B)}}$	Quantitative criterion n ($n = 1,\ldots,N$) for player i considering strategies S_A and S_B of players A and B
$w_{QN_{n,i}}$	The weight of importance of criterion QN_k for player i
IRR_i	Irreversibility measure of business opportunity for player i
FRC_i	Firm risk control for player i
MRC_i	Market risk control for player i
TRC_i	Technology risk control for player i
OCD_i	Option cost of delay for player i
NE_i	Network effects of business opportunity for player i
LD_i	Limited demand for business opportunity for player i
CoS_i	Cost of switching of the customers between players for business opportunity for player i
SF/CA_i	Severity of followers' or competitors' action for player i
EMD_i	Emotional decision for player i
P_i	Profit of business opportunity for player i
OC_i	One-time cost (exercise cost of RO) of business opportunity for player I
MS_i	Market share of business opportunity for player i
W_{IRR_i}	The weight of importance of *IRR* criterion for player i
W_{FRC_i}	The weight of importance of *FRC* criterion for player i
W_{MRC_i}	The weight of importance of *MRC* criterion for player i
W_{TRC_i}	The weight of importance of *TRC* criterion for player i
W_{OCD_i}	The weight of importance of *OCD* criterion for player i
W_{NE_i}	The weight of importance of *NE* criterion for player i
W_{LD_i}	The weight of importance of *LD* criterion for player i
W_{CoS_i}	The weight of importance of *CoS* criterion for player i
W_{SF/CA_i}	The weight of importance of *SF/CA* criterion for player i
W_{EMD_i}	The weight of importance of *EMD* criterion for player i

Appendix B

B.1. Quantitative analysis for sub-game-equilibrium outcomes

The quantitative analysis is based on a typical GT analysis under quantity competition, while the investment game is expressed in Section 2. There are two possible decision modes: (1) simultaneous investments and (2) sequential investments. First, the equilibrium quantities and pay-offs are derived.

Suppose $P(\Theta, Q)$ is the inverse demand function, i.e.

$$P(D, Q) = D - b(q_A + q_A) \quad \text{(B.1)}$$

where D is the demand parameter. Parameter b measures the elasticity of demand, which is inversely related to the quality of the product. $Q = q_A$+q_B is the aggregate quantity in the market, where q_A and q_B are the quantities offered by firms A and B. Let the cost function be $C_i(q_i) = c_i q_i$, where c_i is the marginal cost of the provided service.

The following quantities and profits are derived:

B.2. Simultaneous investments

If firms A and B make their decision without observing each other, this is equivalent to the situation in which they decide simultaneously.

Each firm determines its optimal quantity so as to maximize its profit:

$$\max_{q_i} P_i(q_A, q_B) = \max_{q_i}[P(\Theta, (q_A + q_B))q_i - c_i q_i] \quad \text{(B.2)}$$

where $P_i(i = A, B)$ is firm i's profit, and q_A, q_B are quantities of firms A and B, respectively. Solving the optimization problem, the equilibrium quantities and profits for firms A and B are given by

$$q_A^{SIM} = q_B^{SIM} = \frac{1}{3b}(D - 2c_A + c_B) \quad \text{(B.3)}$$

$$\pi_A^{SIM} = \pi_B^{SIM} = \frac{1}{9b}(D - 3c_B + 2c_A)^2 \quad \text{(B.4)}$$

B.3. Sequential investments

If two firms move sequentially, the game would proceed in an information structure where one firm can observe the other's move. Supposing that firm A invests first and firm B follows, the backward induction method to solve the problem is adopted.

Assuming that the FM is already in the market, the SM's decision is

$$\max_{q_B} P_B(q_A^*, q_B) = \max_{q_B}[P(\Theta, (q_A^* + q_B)) - c_B]q_B \quad \text{(B.5)}$$

Anticipating the SM's move, the FM's decision is

$$\max_{q_A} P_A(q_A, q_B^*(q_A)) = \max_{qA}[P(\Theta, (q_A + q_B^*(q_A))) - c_A]q_A \quad \text{(B.6)}$$

Similarly, solving the optimization problem the equilibrium quantities and profits for firms A and B are given by

$$q_{A,B}^{FM} = \frac{1}{2b}(D - 2c_A - c_B) \quad \text{(B.7)}$$

$$q_{A,B}^{SM} = \frac{1}{4b}(D - 3c_A - 2c_B) \quad \text{(B.8)}$$

$$\pi_{A,B}^{FM} = \frac{1}{8b}(D - 2c_A + c_B)^2 \quad \text{(B.9)}$$

$$\pi_{A,B}^{SM} = \frac{1}{16b}(D - 3c_A + 2c_B)^2 \quad \text{(B.10)}$$

where D is the demand parameter, c_A and c_B are the marginal costs for players A and B, respectively.

The analysis considers no asymmetries between players ($c_A = c_B$). From the quantified factors the analysis adopts the investment profit. In order to include it in the ROGT–AHP model we normalize it with respect to the maximum values, which are

$$\overline{\pi_{A,B}^{FM}} = \frac{\pi_{A,B}^{FM}}{\sum \pi_{A,B}^{FM} + \pi_{A,B}^{SM} + \pi_{A,B}^{SIM}} = 0.418$$

$$\overline{\pi_{A,B}^{SM}} = \frac{\pi_{A,B}^{SM}}{\sum \pi_{A,B}^{FM} + \pi_{A,B}^{SM} + \pi_{A,B}^{SIM}} = 0.209$$

$$\overline{\pi_{A,B}^{SIM}} = \frac{\pi_{A,B}^{SIM}}{\sum \pi_{A,B}^{FM} + \pi_{A,B}^{SM} + \pi_{A,B}^{SIM}} = 0.372$$

Also, concerning the MS or quantity offered, the normalized values are

$$\overline{q_{A,B}^{FM}} = \frac{q_{A,B}^{FM}}{\sum q_{A,B}^{FM} + q_{A,B}^{SM} + q_{A,B}^{SIM}} = 0.461$$

$$\overline{q_{A,B}^{SM}} = \frac{q_{A,B}^{SM}}{\sum q_{A,B}^{FM} + q_{A,B}^{SM} + q_{A,B}^{SIM}} = 0.230$$

$$\overline{q_{A,B}^{SIM}} = \frac{q_{A,B}^{SIM}}{\sum q_{A,B}^{FM} + q_{A,B}^{SM} + q_{A,B}^{SIM}} = 0.307$$

Finally, the normalized values for the OC are

$$\overline{OC_{t=0}} = \frac{1OC}{1.9OC} = 0.526$$

$$\overline{OC_{t=T}} = \frac{0.9OC}{1.9OC} = 0.473$$

References

Alleman, J. (2002). A new view of telecommunications economics. *Telecommunication Policy*, *26*, 87–92.

Altman, E., Boulognea, T., El-Azouzi, R., Jiménez, T., & Wynter, L. (2006). A survey on networking games in telecommunications. *Computers and Operations Research*, *33*(2), 286–311.

Amran, M., & Kulatilaka, N., (1999). *Real options, managing strategic investment in an uncertain world*. Boston, MA: Harvard Business School Press.

Angelou, G. N., & Economides, A. A. (2005). Flexible ICT investments analysis using real options. *International Journal of Technology, Policy and Management*, *5*(2), 146–166.

Angelou, G. N., & Economides, A. A. (2007). E-learning investment risk management. *Information Resource Management Journal*, *20*(4), 80–104 (October–December).

Angelou, G. N., & Economides, A. A. (2008a). A decision analysis framework for prioritizing a portfolio of ICT infrastructure projects. *IEEE Transactions on Engineering Management*, *55*(3), 479–495 (August).

Angelou, G. N., & Economides, A. A. (2008b). A real options approach for prioritizing ICT business alternatives: A case study from broadband technology business field. *Journal of the Operational Research Society*, *59*(10), 1340–1351 (October).

Benaroch, M. (2002). Managing information technology investment risk: A real options perspective. *Journal of Management Information Systems*, *19*(2), 43–84.

Benaroch, M., Shah, S., & Jeffery, M. (2006). On the valuation of multistage information technology investments embedding nested real options. *Journal of Management Information Systems*, *23*(1), 239–261.

Bouras, C., Gamas, A., Kapoulas, E., & Tsiatsos, T. Proposed business plans for region of West Greece. Retrieved on 20/11/2007 from 〈http://ru6.cti.gr/broadband/download/P93_P3.1_EAITY_FINAL.pdf〉, Research Academic Institute of Computers Technology, Patra, Greece, 2007.

Bräutigam, J., Esche, C., & Mehle-Bicher, A. (2003). Uncertainty as a key value driver of real options. In Proceedings of the fifth conference of real options on theory meets practice. Retrieved on 20/1/2008 from: 〈www.realoptions.org/papers2003/BraeutigamUncertainty.pdf〉.

Busby, J. S., & Pitts, C. G. C. (1997). Real options in practice: An exploratory survey of how finance officers deal with flexibility in capital appraisal. *Management Accounting Research*, *8*, 169–186.

Choi, J. P. (1996). Standardization and experimentation: Ex ante vs. ex post standardization. *European Journal of Political Economy*, *12*(2), 273–290.

Dai, Q., Kauffman, R. J., & March, S. T. (2007). Valuing information technology infrastructures: A growth options approach. *Information Technology and Management*, *8*(1), 1–17.

Economides, A. A. (1990). *A unified game-theoretic methodology for the joint load sharing, routing and congestion control problem*. Ph.D. thesis, University of Southern California, CA, pp. 1–538.

Economides, A. A. (1994). Hierarchical resource sharing: NCP and VIP formulation. *Information and Decision Technologies*, *19*, 379–392.

Economides, A. A., & Silvester, J. A. (1990a). A game theory approach to cooperative and noncooperative routing problems. In *Proceedings of the IEEE international telecommunications symposium* (pp. 597–601). IEEE.

Economides, A. A., & Silvester, J. A. (1990b). Priority load sharing: An approach using Stackelberg games. In *Proceedings of the 28th annual Allerton conference on communications, control and computing*.

Economides, A. A., & Silvester, J. A. (1991). Multi-objective routing in integrated services networks. In *Proceedings of IEEE Infocom 1991, the conference on computer communications* (pp. 1220–1227). IEEE.

Expert Choice (1995). *Expert Choice for windows based on analytic hierarchy process*, version 9, user manual. Pittsburgh, PA.

Fekete, I., & Konkoly, R. (2004). Price optimization by using business risk analysis and game theory. In *Proceedings of the 2004 Crystal Ball User conference*. Retrieved on 20/7/2007 from: 〈http://www.cbpredictor.com/cbuc/2004/papers/CBUC04-Fekete.pdf〉.

Fichman, R. G. (2004). Real options and IT platform adoption: Implications for theory and practice. *Information Systems Research*, *15*(2), 132–154.

Fichman, R., Keil, M., & Tiwans, A. (2005). Beyond valuation: "Option thinking" in IT project management. *California Management Review*, *47*(2), 74–95.

Grenadier, S. R. (1996). The strategic exercise of options: Development cascades and overbuilding in real estate markets. *Journal of Finance*, *51*, 1653–1679.

Grenadier, S. R. (2002). Option exercise games: An application to the equilibrium investment strategies of firms. *Review of Financial Studies*, *15*, 691–721.

Harmantzis, F., & Tanguturi, V. (2007). Investment decisions in the wireless industry applying real options. *Telecommunications Policy*, *31*, 107–123.

Iatropoulos, A. D., Economides, A. A., & Angelou, G. N. (2004). Broadband investments analysis using real options methodology: A case study for Egnatia Odos S.A. *Communications and Strategies*, *55*(3–4), 45–76.

International Telecoms Intelligence (ITI) Company (2005). Available reports: Market Intelligence Report. Retrieved on March 15, 2007 from 〈http://www.espicom.com/web3.nsf/structure/tel_bksmgreece?OpenDocument〉.

Joaquin, D. C., & Butler, K. C. (2000). Competitive investment decisions: A synthesis. In M. J. Brennan, & L. Trigeorgis (Eds.), *Project flexibility, agency and competition: New developments in the theory and application of real options analysis* (pp. 324–339). London: Oxford University Press.

Kantor Capital, 2005. *Overview of status of the telecommunication market in Greece*. Retrieved on April 22, 2007 from 〈http://www.kantor.gr/files/surveys/ExecSummary_Telecoms12_9_05.pdf〉.

Keil, M., Mann, J., & Rai, A. (2000). Why software projects escalate: An empirical analysis and test of four theoretical models. *MIS Quarterly*, *24*, 631–664.

Kogut, B., & Kulatilaka, N. (2004). Real options pricing and organizations: The contingent risks of extended theoretical domains. *The Academy of Management Review*, *29*(1), 102–110.

Kulatilaka, N., & Perotti, E. C. (1998). Strategic growth options. *Management Science*, *44*, 1021–1031.

Lindinger, A. (2006). Real options and game theory. Working paper, University of Wien. Retrieved on 20/11/2008 from 〈http://www.andreaslindinger.net/downloads/methwiwis-lindinger.pdf〉.

McGahan, A. M. (1993). The effect of incomplete information about demand on preemption. *International Journal of Industrial Organization*, *11*(3), 327–346.

Mun, J. (2002). *Real options analysis: Tools and techniques for valuing strategic investments and decisions*. New York: Wiley Finance.

Roper-Lowe, G., & Sharp, J. (1990). Analytic hierarchy process and its application to an information technology decision. *Journal of Operational Research Society*, *42*(1), 49–59.

Saaty, T. L. (1980). *The analytic hierarchy process*. New York: McGraw-Hill.

Saaty, T. L., & Vargas, L. G. (1994). *Decision making in economic, political, social, and technological environments with the analytic hierarchy process*. Pittsburgh: RWS Publications.

Schniederjans, M., Hamaker, J., & Schniederjans, A. (2005). *Information technology investment—Decision-making methodology*. Singapore: World Scientific Publishing.

Smit, J. T. J., & Trigeorgis, L. (2004). Quantifying the strategic option value of technology investments. Working Paper, Erasmus University Rotterdam and University of Cyprus. Retrieved on 20/5/2007 from 〈http://www.realoptions.org/papers2004/SmitTrigeorgisAMR.pdf〉.

Spencer, B. J., & Brander, J. A. (1992). Pre-commitment and flexibility: Applications to oligopoly theory. *European Economic Review*, *36*(8), 1601–1626.

Tallon, P. P., Kauffman, R. J., Lucas, H. C., Whinston, A. B., & Zhu, K. (2002). Using real options analysis for evaluating uncertain investments in information technology: Insights from the ICIS 2001 debate. *Communications of Association for Information Systems (CAIS)*, *9*, 136–167.

Taudes, A., Feurstein, M., & Mild, A. (2000). Options analysis of software platform decisions: A case study. *MIS Quarterly*, *24*(2), 227–243.

Trigeorgis, L. (1996). *Real options: Managerial flexibility and strategy in resource allocation*. Cambridge, MA: MIT Press.

Zhu, K. X. (1999). *Strategic investment in information technologies: A real options and game theoretic approach*. Doctoral dissertation, Stanford University, CA.

Zhu, K., & Weyant, J. P. (2003a). Strategic decisions of new technology adoption under asymmetric information: A game-theoretic model. *Decision Sciences*, *34*(4), 643–675.

Zhu, K., & Weyant, J. P. (2003b). Strategic exercise of real options: Investment decisions in technology systems. *Journal of Systems Science and Systems Engineering*, *12*(3), 257–278.