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Flexible ICT investments analysis using real options

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Abstract: Information-communication technology (ICT) investments analysis using real options (ROs) has been a subject of active research during the last decade. It is a flexible method to value investment opportunities and to derive optimal timing of investments deployment taking into account uncertainties in future benefits and costs. We develop a framework for classifying the research on real ICT projects' evaluation using ROs. We analyse these projects with respect to three issues:

- the complexity of the ICT project
- the ROs calculation method
- the assumptions made.

The ROs applicability on ICT projects has been successfully tested in a dozen real cases. The focus so far is on the evaluation of ICT investments that embed a single, apriori known option. Finally, we conclude and suggest directions for future research taking into account more complicated scenarios containing a number of ROs as well as the real competitive environment.

Keywords: information-communication technology (ICT); broadband networks; investment analysis; real options; net present value (NPV).

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1 Introduction

The basic inadequacy of traditional quantitative cost-benefit analysis methods, like Net Present Value (NPV) and other Discounted Cash Flow (DCF), is that they ignore or cannot properly capture the management's flexibility to adapt and revise later decisions (Trigeorgis, 2000).

Real Options (ROs) address this inadequacy of traditional capital budgeting methods and offer to the management the flexibility to take actions, which can change traits of the project over time (Dixit and Pindyck, 1994). The term 'flexibility' refers to the capability of responding to a change or new situation.

Traditionally, there have been three approaches to dealing with uncertainty and complexity in capital budgeting: sensitivity analysis, simulation and decision tree analysis (Bhagat, 1999).

Sensitivity analysis, performed by changing one variable at a time, while it is easy to be implemented and understood, it is not a perfect method since it ignores interdependencies among variables.

Simulation, while it takes into account interdependencies among variables, makes it difficult for the decision maker to interpret a distribution of Net Present Values since there is no rule for translating that profile into a clear-cut decision for action. Also, it cannot handle well asymmetries in the distributions, which are introduced by the management's flexibility to revise its prior operating strategy as more information about project cash flows becomes available over time.

Finally, decision tree analysis is able to accommodate the flexibility, for example to abandon an investment plan at certain discrete pre-specified points in time, based on the expectation of cash flows and their probabilistic estimates that can be quantified at the time of the initial decision. However, its main problem is that while the risk of the project may change over time and so the discount rate, it assumes a constant value for the latter for the whole period of the investment. In addition, decision tree analysis can easily become unmanageable when actually applied in most realistic investment settings, as the number of different paths through the tree expands geometrically (Trigeorgis, 2000).

The real options (ROs) approach is a new method, which tries to apply methods of financial planning on investment valuation problems. An investment project embeds an RO when it offers to the management the opportunity to take some future action (such as *abandoning*, *deferring* or *scaling up* the project) in response to events occurring within the firm and its business environment (Trigeorgis, 2000).

This management's flexibility (called active management) to adapt its future actions in response to altered future business conditions expands an investment opportunity's value by improving upside potential and limiting downside losses (Trigeorgis, 1999). The business condition either refers to market conditions or firm conditions depending on where the investment is focusing. For example, an investment of a telecommunication network inside the premises of a firm refers to the later case while a broadband network investment of a network operator to the former one.

By adopting active management philosophy, we decrease the possibility of experiencing losses while increasing the possibility of gaining. This is achieved by waiting and learning about the changing business conditions and generally resolving over time part of the overall investment's risk level.

Although the ROs theory is increasingly used in other industries, such as Research and Development and Pharmaceuticals, it has not widely been applied to the Telecommunications industry (Alleman, 2002). In this paper, we review and taxonomise real cases of information-communication technology (ICT) business evaluation using ROs. Also, we explain why the ROs have not been used in the ICT industry to the same extent as in other industries.

The remainder of the paper is organised as follows. In Section 2, we provide a brief review of the ROs theory as well as its relation to the economic characteristics of an investment's scenario. In Section 3, we develop a framework for classifying the research and we review and taxonomise real ICT investments' scenarios. We follow a specific classification according to the investment's nature in terms of its deployment plan, the RO's type as well as the method used for the option's value calculation. In Section 4, we discuss concerns and assumption about the ROs applicability in such investments scenarios and their validity checking. In Section 5, we evaluate the state of the current research in the topic. Finally, in Section 6, we conclude suggesting directions for future work.

2 An overview of ROs

A financial option is the right, but not the obligation, to buy (call option) or sell (put option) an asset at some point within a predetermined period of time for a predetermined price.

The opportunity to invest in a project, called *real option*, is analogous to a call option to acquire a claim to the cash flow value of a completed and operating project by paying a specified cost as the exercise price.

Spending money to exploit a business opportunity is analogous to exercising an option on, for example, a share of stock. It gives the right to make an investment's expenditure and receive an investment's asset, the value of which fluctuates stochastically. The amount of money spent for investment corresponds to the option's exercise price (X). The present value of the project's asset (total gain of investment) corresponds to the stock price (V). The length of time the company can defer the investment decision without losing the opportunity corresponds to the option's time to expiration (T). The uncertainty about the future value of the project's cash flows (the risk of the project) corresponds to the standard deviation of returns on the stock (σ). Finally, the time value of money is given in both cases by the risk-free rate of return, (r_f). The project's value calculated using ROs is the same to that calculated using the NPV method when a final decision on the project can no longer be deferred (expiration date of the option) (Trigeorgis, 2000).

Table 1 summarises the parameters' analogy between a call option and an investment project.

Table 1 Parameters' analogy between a call option and an investment opportunity

Investment opportunity	*Variable*	*Call option*
Present value of a project's assets or Present value of cash flows from investment	V	Stock price
The amount of money spent for the investment, investment expenditure required to exercise the option (cost of converting the investment opportunity into the option's underlying asset, i.e., the operational project)	X	Agreed exercise price of the option
Length of time where the investment's decision may be deferred	T	Option's time to expiration (i.e., the maximum length of the deferral period)
Time value of money	r_f	Risk-free rate of return
Variance (Riskiness or Uncertainty) of the investment's project assets	σ^2	Variance of returns on stock

The total value of a project that owns one or more options is given by (Trigeorgis, 1999):

Expanded (Strategic) NPV = Static (Passive) NPV + Value of Options from Active Management

The value of managerial flexibility, which is also named option premium, is the difference between the NPV value of the project as estimated by the Static or Passive NPV method (PNPV) and the Strategic or Expanded NPV (ENPV) value estimated by the ROs method.

For more background information on ROs, the reader is referred to Dixit and Pindyck (1994) and Trigeorgis (2000).

Table 2 is adapted from Bhagat (1999) and Lassila (2001) to include the real ICT projects reviewed in this paper. It describes various types of ROs and the corresponding ICT projects.

Table 2 Taxonomy of real options in ict investments

Real option	*Description*	*ICT projects*
Defer	To wait before taking an action until more is known or timing is expected to be more favourable	When to introduce a new product or service or replace an existing piece of equipment, e.g., Investments in new point to point connections in capacity markets Benaroch and Kauffman (1999, 2000), Schwartz and Zozaya-Gorostiza (2003), Kalgegen and Elnegaard (2002), Elnegaard (2002), Elnegaard and Stordahl (2002), Eurescome P-901 (2000) and Kim and Alleman (2000)
Time-to-build (staged investment)	To commit investment in stages, giving rise to a series of valuation and abandonment options if new information is unfavourable	Large-scale telecom investments projects with long time horizon. Also, IT investment is realised (implemented) as a series of m development stages. Jeffery et al. (2003)
Expand or contract	To increase or decrease the scale of an operation in response to demand	Adding to or subtracting from a service offering, adding memory to a computer or upgrading the transmission technology and thus increasing the capacity of existing connections. Panagyi and Trigeorgis (1998), d'Halluin Y et al. (2002) and d'Halluin Y et al. (2003)
Abandon	To discontinue an operation and liquidate the assets, in case market conditions decline severely	Discontinuation of a service line; or broadband access infrastructure
Switch inputs or outputs	To alter the mix of inputs or outputs of a production process in response to market prices	The output mix of telephony/internet/cellular services for a telecommunications company
Compound/Strategic, Growth	To expand the scope of activities to capitalise on perceived new opportunities	Wide telecommunication infrastructure provides a possibility to offer ISP services When IT investment involves two or more of the above options, where the value of an earlier option can be affected by the value of later options or vice-versa. Also, when IT investment yields capabilities that open up future investment opportunities Jeffery et al. (2003) and Taudes et al. (2000)

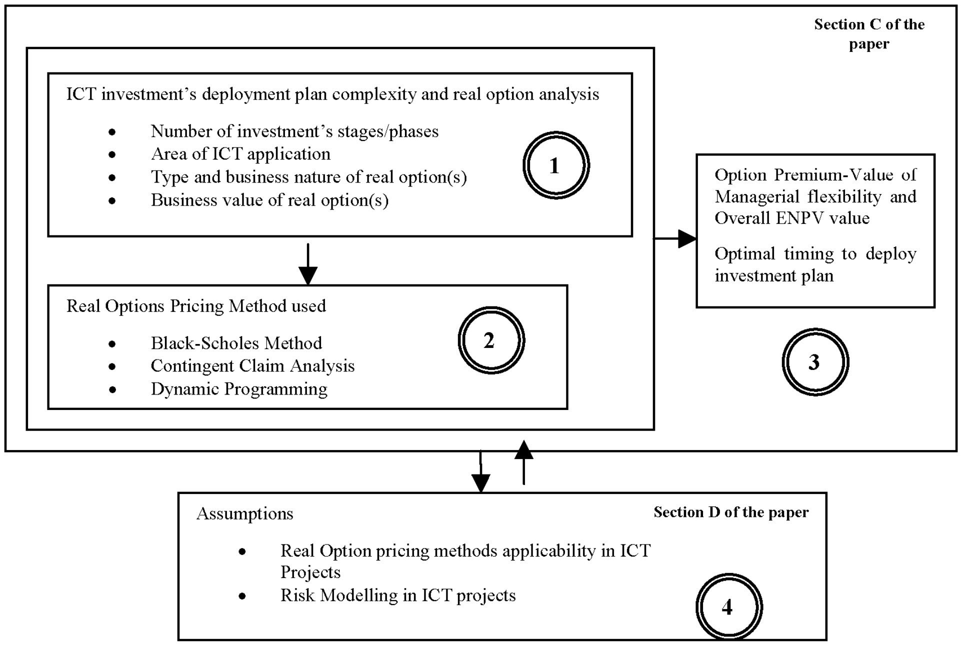
3 Classification of real ICT investments using ROs

In order to analyse the prior research and to identify gaps for future efforts, we develop a four-step conceptual framework (Figure 1).

- We distinguish between one-stage, two-stage and multi-stage ICT investment scenarios concerning their deployment complexity. We further identify the RO types used in the investment, as well as the qualitative business value that they may represent.
- We examine the method used for the option estimation.
- We calculate the RO premium or quantified value of managerial flexibility. We use a common indicator to measure the contribution of the ROs methodology to the overall economic figure of the investments scenarios. This is ether the ratio of the ENPV that includes the option premium over the PNPV value or the percentage increase in the latter. Alternatively, it can be the optimal timing of the investment's deployment that maximises its overall value.
- We review the assumptions underlying the Options Pricing Models (OPM) and in general the overall ROs applicability and risk modelling in ICT investments and we discuss their validity.

Hence, the emphasis is mainly on three issues.

Figure 1 Framework of ICT investments evaluation using ROs



ICT investment deployment plan complexity and RO analysis

Previous scenarios on ICT investments using ROs include IT, Broadband Networks and Voice over IP telephony investment's justification.

The first level of our classification is the business scenario that contains one or more ROs. We classify the cases according to the investment evolution path or the number of their deployment stages.

We start with single-stage deployment plan and single-option presence. Afterwards, we examine the two-stage investment scenario where the first stage is considered as the acquisition of strategic options for further investment expansion or growth at a later time. The reviewed cases have mainly focused on evaluating ICT investments that embed a single a priori known option.

Three-stage and more investments' plans may concern multi-option analysis since for each stage of investment there could be a single option to be analysed and quantified in terms of the business value that it brings.

Real options (ROs) pricing methods

The two most commonly used models for calculating the value of ROs are the Binomial and the Blach-Scholes models. The Binomial approach is a simple technique to value options in discrete time using a binomial lattice. The Black-Scholes model is used for the RO calculation in continuous time (Trigeorgis, 2000). There is also the asset-for-asset exchange model (Margrabe, 1978) used in an IT project by Kumar (1999). However, this method requires the analyst to develop an understanding of how the underlying asset, V, and the exercise price, X, are correlated, which could be quite difficult in practice. For this reason, Benaroch and Kauffman (1999) suggest B&S and Binomial methods as more attractive for ICT investments analysis.

ROs applicability assumptions and their validity check

In order to apply the ROs methodology to the ICT investments analysis, some assumptions are made. We check the validity of these assumptions.

The key concerns and assumptions about option-pricing models are:

- Investors are risk-neutral and the discount factor is risk-free interest rate. A risk-neutral investor is indifferent between an investment with a certain rate of return (risk-free is assumed, r_f) and an investment with an uncertain rate of return whose expected value matches that of the investment with a certain rate of return.
- An ICT asset acquired through an option can be traded in the open market.
- The variance of the returns (or cash flows) from the ICT investment opportunity is known.

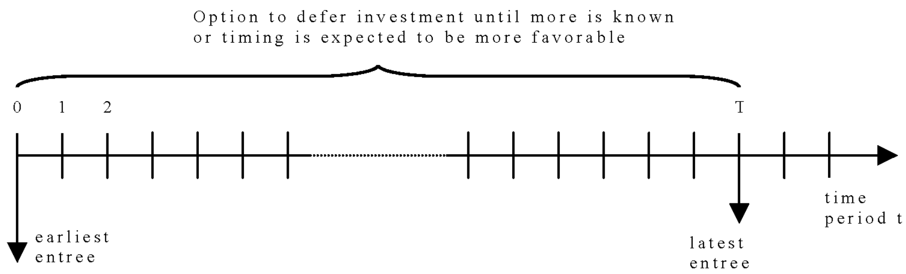
Next, we further discuss these three issues.

3.1 One-stage investment deployment plan with option to defer

The simplest case is the option to wait or defer to invest. In a one-stage investment scenario that contains an RO to defer, there is the possibility but not an obligation to perform a large discretionary and irreversible investment in a new product or service at time $t \leq T$. T is the upper limit of the time period where the investment's decision may be deferred (Figure 2). This possibility of deferral gives rise to two sources of values.

- paying later than sooner we can earn the time value of money of the investment cost
- while waiting the world changes and the present value of the operating cash flows may change, indicating finally the non-profitability of the investment.

Figure 2 One stage investment possessing option to defer



In such situations, the question is not whether the investment should be undertaken or which one out of several alternatives should be chosen, but when to exercise the option held, meaning when to implement it.

Benaroch and Kauffman (1999, 2000) present the first application of ROs to IT investments. They analyse the timing of the deployment of point-of-sale (POS) debit services by the Yankee 24 shared electronic banking network of New England.

By waiting, Yankee 24 resolved uncertainties concerning the acceptance of POS debit services in Yankee's markets and the viability of additional irreversible network infrastructure investment.

They view Yankee's ability to flexibly defer this roll out as an American call option that matures at time T. *American options* are those which can be exercised on or before their expiration date, unlike *European options* which can be exercised only on their expiration date. To find whether an early exercise at time t is more profitable, they approximate the American investment option with a portfolio of European options in order to apply the B&S model. Actually, this model is applied for European options only. They calculate the prices of European options that mature at T and t, C_T and C_t, by using the B&S model and then set the American price to be the higher of these two. T is the maximum deferral upper limit time while t is any possible moment where the option can be exercised (investment performed). Hence, early exercise at time $t = t'$ would be more profitable if $C_{t'} > C_T$.

They consider the riskiness of the expected revenues to be 50% based on a series of interviews with decision makers of the company. At the optimum, time to defer the option value contributes to the increase in the PNPV up to six times more. A sensitivity analysis took place for σ values varying from 10% to 100% indicating a significant change of option value up to 270% for the same optimum deferral time.

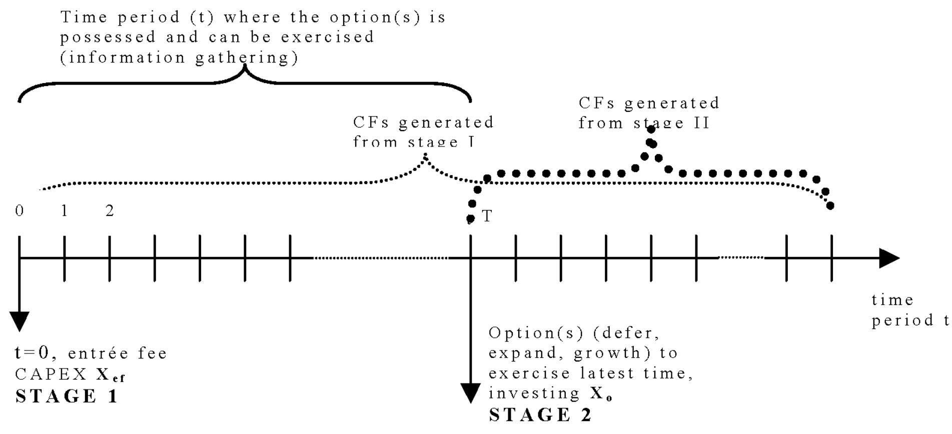
Kalhagen and Elnegaard (2002) apply ROs to analyse an incumbent's investment decisions for deploying broadband services in rural areas. They focus on Digital Terrestrial Television provision as an alternative technology for rural areas, locating an option to defer investment, which is supposed to start with a pilot launch. By deferring, incumbent resolved uncertainties related to penetration, willingness to pay, service and application development as well as uncertainties about the cost of equipment. They use the B&S model for the option to defer calculation. For investments riskiness, 60% the option premium contributes to PNPV increase up to 1.5 times more.

Similarly, Kim and Alleman (2000) examine an option to defer investment in order to estimate the value of Voice over the Internet Protocol (VoIP), also known as IP Telephony. They show that the traditional NPV approach has underestimated the value of VoIP investment opportunity since IP telephony has many uncertainties such as uncertain service demands by subscribers, devaluating equipment and service by the short IP technology transition cycle, a fiercely competitive landscape by technology substitution and innovations. They use both B&S and Binomial option-pricing models to calculate the existing option. They estimate an investment' riskiness of about 60% for IP telephony investment, by using historical data of the Internet stock index (ISDEX). Whereas the traditional NPV to IP Telephony produced a negative NPV, the RO analysis provides an overall NPV improvement of more than two times, concluding to positive value.

3.2 Two-stage investment deployment plan

In these cases, the investments' projects are in two phases/stages. In the first stage, there is an entree fee capital expense, which gives the opportunity to grow, expand, upgrade the investment in a second stage or even to defer this stage up to a time *T*. Hence, the initial stage is considered as paying an entrée fee for acquiring the right of possessing one or more options to be exercised at a later stage spending on a large discretionary investment (Figure 3).

Figure 3 Two-stage investment scenario with option presence in the second stage



Option to defer

Project 901 (EURESCOM P-901, 2000) analyses such a case of a two-stage investment scenario concerning Broadband Access networks upgrade from copper ISDN to xDSL technology in a suburban areas.

An incumbent operator offering existing services over twisted copper pairs such as POTS, ISDN and dial-up based Internet service starts offering wideband and broadband services in $t = 0$ using his existing copper plant and adopting ADSL technology. At some future date (T), the operator may decide to install fibre closer to the customers, offering more advanced services over VDSL.

The RO to defer concerns the second stage of the project where the operator has a possibility but not an obligation to invest in an advanced upgrade at time T. By waiting, uncertainty will be resolved and the management can use this achieved knowledge to either proceed with an aggressive strategy or defer the investment if market conditions are not favourable, technology is not available, etc.

The B&S formula and the methodology suggested by Luehrman (1998) are used for calculating the option value. An investment's variant or riskiness of the expected returns is selected to be 40%. The overall ENPV value (including both stages) is about seven times more than the PNPV one. Actually, in case of variance change to 60%, the ENPV increases by 100%.

Elnegaard and Stordahl (2002), Elnegaard (2002) and Kalhagen and Elnegaard (2002) examine investment's evaluation in upgrading from ADSL to VDSL services in suburban areas. They capture the value of flexibility in future VDSL rollout investments in a suburban area concluding with similar results as those of the P-901 project (EURESCOM P-901, 2000).

Option to expand

Panayi and Trigeorgis (1998) also use a two-stage ROs pricing model to value the IT infrastructure investment for the state telecommunications authority of Cyprus (CYTA). They consider in the first stage an entry fee for acquiring a right or option to expand the IS network later. The initial investment X_{ef} would position CYTA such that if future development turned out favourably, it would be able to pay for the second-stage investment cost X_0 for the network expansion (exercise the option) and receive the value of cash flows from the expansion phase.

The overall investments value taking into account the embedded option value of the second stage (expansion stage if things go favourably) is given by

Expanded NPV = NPV of stage I + Option to expand value of the stage II

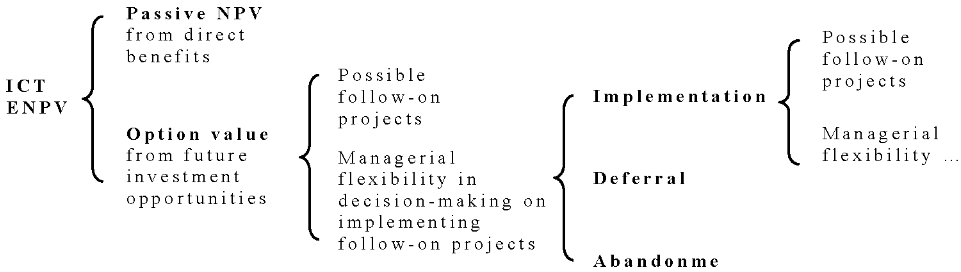
They use the B&S formula and assume a quite small investment's riskiness value of 15% to model the uncertainty surrounding the project. They find that the overall NPV improvement is more than two times of its respective passive value. We have performed a sensitivity analysis for the project's stage 2 variance vs. option premium in order to handle the scepticism for the small variance value of the expected returns. Among others, the option premium increases four times for 55% riskiness compared to the 15% case, while the lower threshold for stage 2 uncertainty that it is still keeping the overall investment's profitability positive is 12%.

The cases reviewed so far were up to two-stage investments. We consider stage 1 as an entree action investment being evaluated by the classical capital budgeting method while stage 2 contains the option value.

In general, under uncertainty, staged investments can offer valuable flexibility to management. This fact is reflected explicitly in ICT justification models that incorporate ROs. Investment in an earlier project is similar to buying one or more options at later projects, giving to the management the flexibility to engage or not engage in those later projects (i.e., whether to exercise the acquired options). As more information becomes available and some of the uncertainties are resolved, the management can change a future project – from any of its details (e.g., timing, vendors, build rate, rollout, etc.) to its overall strategic purpose in the business. Future projects can be deferred, abandoned, expanded, contracted or otherwise modified, to meet the management's requirements. Without loss of generality, we can conceptualise the stages of a project as a *sequence of related projects* Benaroch and knuff man (1999).

A large portion of the value of ICT projects comes from the potential value of future projects that are enabled by them (option value). That is, ICT projects enable follow-on projects that would be impossible or much more expensive irrespective of whether the current project was completed. Thus, the investment in an ICT project is analogous to buying an option(s) on those follow-on projects (Figure 4).

Figure 4 Option-inclusive value of an ICT Project



Option to grow

Growth options refer to a situation where early investment is a "prerequisite or a link in a chain of interrelated projects, opening up future growth opportunities" (Trigeorgis, 1993).

Taudes (1998) investigates the options methodology for evaluating 'software growth options'. This work lays the foundation of valuing software platforms. Taudes et al. (2000) present a real case.

They use the options theory to decide whether to continue employing SAP R/2 or to switch to SAP R/3. The most important type of flexibility offered by the software platform is the ability to decide whether or not to implement an application in the future based on this platform. In this case, the initial investment on this platform is considered as an entry fee that gives the right for further investment on new applications based on it (option to growth). They examine some applications, such as EDI-based purchasing, EDI-based invoicing, workflow for sales, electronic document handling and web based e-commerce systems applications, that could be implemented after a stabilisation period.

They consider the overall investment opportunity for the software platform upgrade as:

> Value of a software platform = NPV of fixed application portfolio (entree fee, stage 1: platform upgrade) + option value of future implementation opportunities.

The uncertainty of the project's assets is considered to take different values for the different future applications of stage 2, varying from 35% to 80%. These values are estimated by a team consisting of the corporate planning, accounting, IT personnel and consultants.

Using the B&S model, the authors estimated that the option value of follow-on projects exceeded the conventional NPV estimates by a factor of 4. The ENPV value of the overall investments plan is more than 2.5 times that of the respective PNPV one.

However, Benaroch (2002) provides a criticism concerning the applicability of growth option(s) in practice. First of all, it is difficult to identify upfront all the investment opportunities that a growth option spawns. Even if all these opportunities could be identified, it is hard to estimate their payoffs or even determine whether they are likely to materialise, depending on internal and external conditions. Second, a growth option is like an operating option to expand, except that its underlying asset – the payoffs expected from future investment opportunities – is not the asset that creates it in the first place. When an option involves multiple underlying assets, standard option valuation models cannot directly measure the value of synergetic effects among interdependent investments. Taudes et al. (2000) assume that all spawned investment opportunities and their respective valuation parameters can be identified upfront and that these opportunities are independent of each other (i.e., no cross-investment synergies exist).

3.3 Multi-stage (more than two stages) investment deployment plan

In the previous cases, the emphasis is on the initial investment's decision that contains a single RO to be evaluated. The management has the flexibility for risk handling by controlling only the time period where this option is present and valuable. They do not consider more complicated strategies for firm/industry and market risk handling for large-scale and multi-staged investments' projects.

A common strategy to mitigate risk in large-scale projects is to divide the project into smaller components, or stages. However, there may be loss of possible benefits in case of full project development from the beginning. Therefore, in this case, we should examine the trade off of risk mitigation and revenues losses.

Each project's stage is often executed sequentially with a stage gate at the end of the stage. This stage-gate approach gives the opportunity to the management to review the project at the end of each stage; if the completed stages of the project are not demonstrating business value then the management may decide not to continue. Therefore, each stage incorporates the RO value; at the end of each stage, the management actively decides whether to continue the project, and works to leverage learning to improve results at later stages.

Time-to-build option

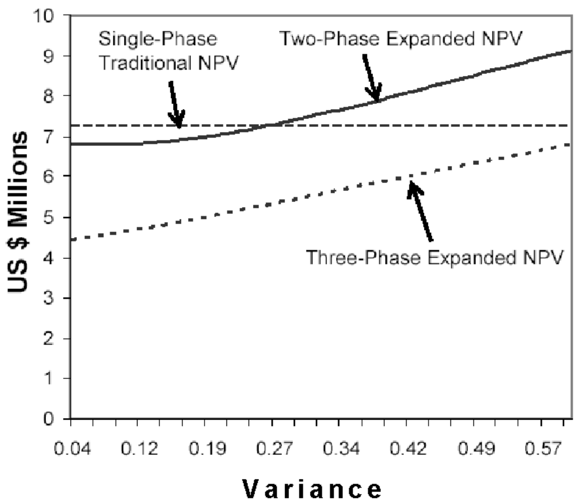
Jeffery et al. (2003) examine different stage-wise deployment strategies for large enterprise technology investments and incorporate ROs into the decision-making framework. They focus on multi-stage options, embedded in large enterprise data warehousing projects (EDW), using the framework of Herath and Park (2002) for compound options pricing. The target is to find the optimal timing of investment deployment strategy in order to maximise benefits and mitigate risks.

They use ROs to answer the question: "What is the optimal stage-wise deployment strategy that balances risk and return in a data mart consolidation project?". They show that the answer depends upon the risk, or variance of the project and the PNPV of each stage. They examine single-, two- and three-stage deployment strategies for a 15 data mart consolidation. They calculate the ENPV and PNPV values for two- and three-stage data mart consolidation.

The target is to find in which case the ENPV is higher. Both B&S and Binomial models are used for the two-stage case. Option premium is calculated to be about 12% of the traditional NPV for the whole project, while the variance value, which is estimated by using Monte Carlo Simulations for the second stage of the project, is about 10%. Since the three-stage strategy incorporates a multi-stage compound growth option, the B&S model is not applicable. Instead they use the Binomial method as in the two-staged deployment scenario. The option premium is even bigger, about 17%, than the respective PNPV value, assuming the one-step Binomial method and the variance for the second and third stage to be about 11%.

Figure 5 is a plot of the expanded NPVs of the two-stage and the three-stage deployment strategies as a function of the variance for this project. For the variance used in this analysis, the expanded NPVs of the two- and three-stage strategies are both less than the traditional NPV of the single-stage strategy. This is because breaking the EDW project into stages delays the realisation of cash reduction benefits from the project. This delay, due to the time value of money, reduces the traditional NPV of the stage-wise deployment compared to the single-stage deployment. Hence, in this case, the value of the RO is not large enough to compensate for the loss in NPV due to the delayed realised benefits in the stage-wise deployment. Based on these numbers, the management should select the single-stage strategy, since this has the highest total NPV compared to the stage-wise strategies.

Figure 5 Optimal deployment strategy: trade off between the risk of the project and the deployment strategy



Source: Jeffery et al. (2003)

When the variance of the project is such that the expanded NPVs of the multi-stage strategies are greater than the traditional NPV of the single-stage deployment strategy, the management should select the appropriate multi-stage deployment strategy. Jeffery et al. (2003) state that for a high variance or risk project, the management decision to execute in two, three, or n stages depends upon how the stage-wise deployment reduces the traditional NPV of the project by deferring net benefits.

A major limitation of the application of the standard option models to value ROs is that an analyst can only consider a single source of uncertainty, corresponding to a single RO. The model developed by Herath and Park (2002) and used by Jeffery et al. (2003) allows an analyst to consider multiple underlying variables and thus multiple sources of uncertainty. This model recognises that multi-stage ROs are nested within one another and thus values them accordingly. However, its limitation is that it is assumed that the gross project values are un-correlated, which does not happen for many cases.

Option to expand in a multi-staged investment scenario

Modern financial option-pricing methods have also been applied to the problem of network investment decision timing. In particular, d'Halluin et al. (2002) examine the optimal decision problem of building new network capacity in case of stochastic demand (Q) for services. Demand is modelled as a stochastic process $\mathrm{d}Q = \mu Q\mathrm{d}t + \sigma Q\mathrm{d}z$, where μ is the drift rate of the growth rate of the demand, σ the standard deviation and $\mathrm{d}z$ is the increment of a Wiener process that indicates the stochastic part.

They apply the dynamic programming ROs approach for optimal investment timing of broadband network capacity expansion. They consider the utilisation of the lines to be the indicator of the optimal time to upgrade. If it reaches a specific threshold, an upgrade to a higher capacity line should be initiated.

The goal is to determine the optimal action so as to maximise the value of the investment, $V(t, Q)$, given that the actual usage of the network in the future is uncertain.

They conclude that it may be optimal to wait until the maximum capacity for a line is reached before upgrading. Essentially, this is because an increase in usage may be a random event and may not be sustained. Then, the investment value, $V(Q, t)$, is maximised.

d'Halluin et al. (2003) apply modern financial option valuation methods to the problem of the optimal timing of new wireless network capacity investment. They extend the algorithm of d'Halluin et al. (2002) to handle arbitrary decision date intervals. In particular, given a cluster of base stations (with a certain traffic capacity per base station), they determine when it is optimal to increase the capacity for each of the base stations contained in the cluster.

4 Concerns and assumptions about the ROs applicability in ICT investments

The applicability of the ROs methodology in ICT investments evaluation is not free from concerns about the assumptions made. In the following paragraphs, we discuss these assumptions.

Non-tradability of the ICT investment asset

In both the Binomial and the Black-Scholes models, the main idea is to form a risk-free portfolio of traded assets that will exactly replicate the pattern of returns from our investment project containing the RO, at every future date. The composition of this portfolio need not be fixed; it could change as the prices of the component assets change.

Then, the value of the investment project must equal the total value of that portfolio. Deriving option values by constructing portfolios, which replicate the return and the risks of the option through existing and tradable assets, is often referred to as contingent claims analysis.

In case the underlying project's asset to be evaluated is not traded, one assumes that a 'twin security' exists as a continuous adjusted portfolio of traded securities that perfectly replicates the present value of the project's asset. However, this assumption is questionable since such projects often also show idiosyncratic risks such as technology risks regarding the feasibility of the enabling technology or organisational risks, e.g., resistance by the staff. It is implausible that such risks are priced by the financial market for a traded asset.

This naturally raises a concern whether the option models can be applied to IT investment. This is still a controversial issue with no clear answer yet, although Zhu et al. (1999) suggests a favourable answer. He states that the no tradability of technology can be handled if all assets are priced, in a risk-neutral world, so as to yield an expected rate of return equal to the risk-free rate, with the drift adjusted by a risk premium.

Benaroch and Kaufman (1999) examine the theoretical foundation of ROs and their relevance to IT investments. They examine the impact of adjusting the risk-neutral option value calculated by this model to the case of risk-averse investors. They address the claim that because most decision makers are risk-averse, risk-neutral valuation overvalues options embedded in non-traded investments. Trigeorgis (2000) explains this claim as follows: Managers evaluating an investment that is subject to a firm- and/or industry-specific risk not shared by all market investors must discount the option value by a factor corresponding to the investment's unique risk. Analogously, if the asset underlying an option is not traded in limited supply by a large number of investors (so that the demand for the asset exceeds the supply), the asset's return rate, α, may fall below the equilibrium expected rate of return that the investors require from an equivalent risk traded, a^*. The rate of return shortfall, $\delta = \alpha^* - a$, necessitates an adjustment in the option valuation.

Concluding, they state that even for a non-traded underlying asset, we can apply risk-neutral valuation using the B&S model adjusted by an appropriate rate of return shortfall, δ. Parameter δ is difficult to be estimated in practice. However, they suggest that if you don't subscribe to risk-neutral valuation, and thus have to estimate the rate of return shortfall, δ; first calculate a risk-neutral option value using the Black-Scholes model; finally, use sensitivity analysis with the adjusted B&S model to see how robust the option value is with respect to δ. In their case, it is shown that the optimal timing does not depend on the particular value chosen for this parameter.

Nevertheless, Talon et al. (2002) argue that while the ROs approach is appropriate for evaluating IT investment, particularly in recognising the value of timing, we must still accept that the ROs applicability is limited by the fact that IT projects are not traded.

In addition, Dixit and Pindyck (1994) suggest an alternative approach to handle this. They model investment decisions that involve options for the firm using a dynamic programming approach to identify critical points at which it would be optimal to exercise an option (i.e., undertake a project). d'Halluin et al. (2002, 2003) applied this approach in a couple of cases as mentioned above.

Uncertainty modelling

In the ROs analysis and the B&S model, the uncertainty is considered to be in the assets value (benefits) only, while the investment cost (options exercise price) is known and constant. Moreover, exercising the option is instantaneous. However, this may not be the case for many real investment scenarios.

Schwartz and Zozaya-Gorostiza (2003) describe a methodology for evaluating IT investments using a couple of models that account for uncertainty both in the costs and benefits associated with the investment opportunity. Furthermore, in contrast to other models in the ROs literature in which benefits are summarised in the underlying asset value, they model these benefits as a stream of stochastic cash flows. Rather than determining in advance when the option should be exercised, their model provides information for making a decision once the manager observes what are the current cash flows and costs at any point in time. Finally, they apply their model in the real business case presented by Benaroch and Kauffman (1999, 2000).

Riskiness of the expected revenues

The option-pricing methodology requires the variance or riskiness of the returns to be known in advance. The project's variance of the expected returns is the most crucial parameter in the ROs analysis. The challenge in any option-pricing model is to accurately calculate the variance of the expected returns of the part of the project, which contains the RO. However, this is quite difficult in many cases since market data are rarely available.

In some of the reviewed cases, the variance or riskiness of the expected revenues is extracted by a series of interviews with decision makers of the company, (Benaroch and Kauffman, 1999, 2000). Another way to estimate the project's variance is by analysing historical data, (EURESCOM P-901, 2000; d'Halluin et al., 2002, 2003).

In some other cases, variance is calculated through the Monte Carlo Simulation, (Jeffery et al., 2003). By knowing the probability distribution of the expected project revenues, we can specify mathematically the functional relationships between the input and output variables. Hence, we can use a Monte Carlo Simulation to estimate the variance associated with the present value of expected cash flows.

Furthermore, when there is a 'twin traded security' price S that has the same risk characteristics as the project under consideration, σ can be estimated as the variability of the rate of return on S. This scheme is readily applicable when the primary risk in the target project is strongly related to a risky IT product that is sold by a traded firm (e.g., CASE tools, multimedia tools). Kim and Alleman (2000) estimate the variance for IP telephony, by using historical data of the Internet stock index (ISDEX).

In the majority of the cases, the scepticism, about the selection of riskiness value of the investment's project, is handled through sensitivity analysis of the σ value vs. the RO one. In this way, the importance and influence of σ to the overall investment's value is verified.

5 Evaluation of the state of research

In general, ROs can be seen as the opportunity to invest in a currently available innovative project, taking into consideration the strategic value associated with the possibility of future and follow-up investments due to emergence of another related innovation in future. In addition, the ROs approach helps to structure the project as a sequence of managerial decisions over time and clarifies the role of uncertainty in investments evaluation.

As mentioned earlier, ROs have not been used in the ICT industry to the same extent as in other industries. The concerns and assumptions discussed in the previous section have certainly contributed to the limitation of the ROs applicability in the ICT industry. Furthermore, the ROs applicability in the ICT industry is also limited by the following characteristics.

The ROs applications are focusing on valuing, operational or strategic flexibility and identifying trigger points where the direction of the business plan may be amended. The challenge is how to implement the mechanics of the ROs analysis. In the ICT industry, there are no standard natural trigger/decision points where hard-stop reviews are required as it happens in the pharmaceutical industry or in the oil and gas industry (Mun, 2002).

These decision points can be based on fixed time line reviews (monthly/quarterly/yearly) or can occur when a technology reaches a natural review stage such as the completion of product design, product development, market analysis or pricing. Other milestones include when financial and operational thresholds are realised (project overspent/competing technology introduced/growth targets exceeded).

For ICT companies, these trigger points are not implicit. Instead, they need to be actively defined by the management and built into a structured analysis. ROs are providing high assistance to achieve active risk management and investment evaluation for cases where several uncertainties can be controlled and resolved, at least partially, in these points.

Benaroch (2002) states that in practice, real options are not inherent in any IT investment. Rather, they usually must be planned and intentionally embedded in a target IT investment so as to enable a beneficial configuring of the investment.

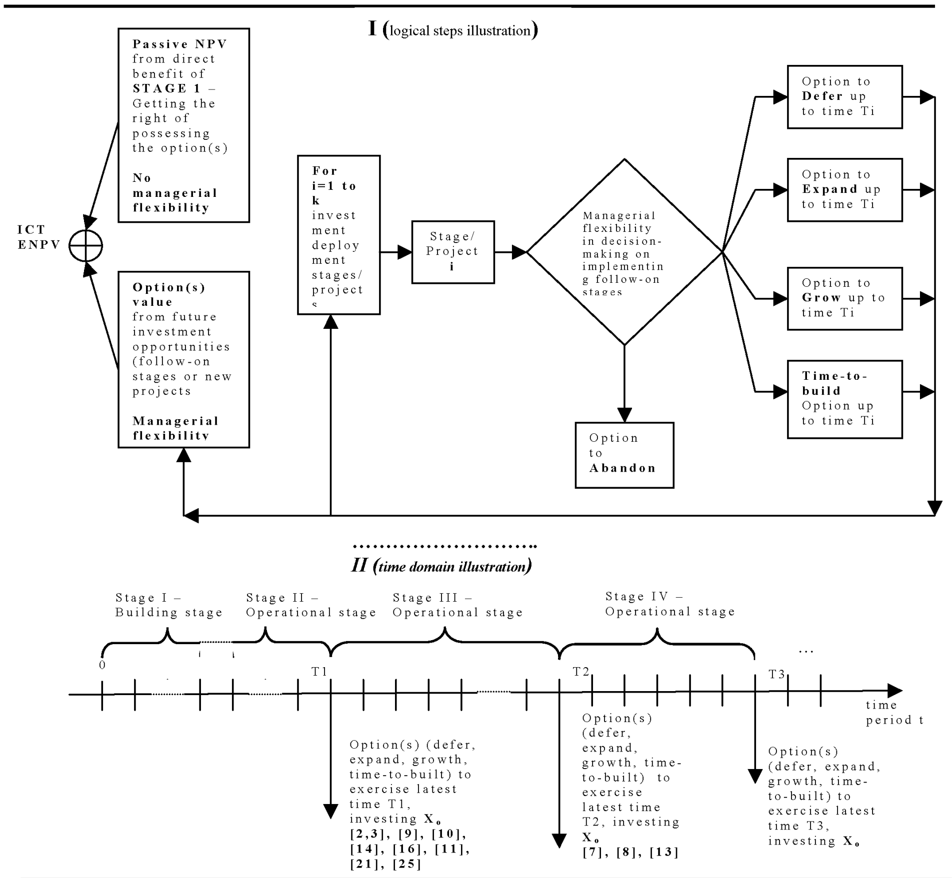
Hence, the appropriate application of ROs in the ICT industry is something that requires more effort from decision makers than in other industries. This is another reason for the immatureness of the ROs application in the ICT industry.

The main results of this paper are:

- One-, two- and three-stage investments deployment plans have been reviewed and taxonomised. Past ICT systems research on ROs has focused mainly on evaluating information technology (IT) investments that embed a single, apriori known option. Multi-option applications such as compound ROs or growth options that spawn investments opportunities in the future have taken place in quite a simple way.

In Figure 6, we review the ICT staged investments scenarios that contain one or more ROs. First, we give a logical illustration of one or more options' contribution to the overall Expanded NPV value of the multi-stage (up to k stages or interrelated new projects) investments scenarios. Second, we provide the classification of the reviewed cases in time domain.

Figure 6 Real options applications in ICT projects-scenarios review and cases classification



The majority of the cases reviewed here is from the IT literature. They use ROs to find the overall investments value as well as the optimum timing to invest. There are also some cases from telecommunications network industry and more specifically Broadband networks and IP telephony investments that use ROs to analyse their performance. However, only the single option to defer capacity and technology upgrade has been applied so far.

- The option values come from the belief that some of the investments uncertainties could be resolved during the deployment process of all stages. This will give extra value to the overall investments profitability since in case of ‘bad news’ we can stop or scale down the project. In addition, dividing investments in stages we mitigate risk and make it easier to be handled. The more stages we divide the investment into, the higher the value of ENPV vs. PNPV that is achieved. The optimum number of stages is strongly related to the uncertainty level or the variance of the project’s asset. The optimum number of deployment stages increases as uncertainty takes higher values.

- Contingent claim analysis and dynamic programming methodology have been used to price the options. The following models have been used:
  - single option analysis using the Black-Scholes and Binomial models
  - single option analysis in nested options phenomenon (option in option or compound option) using the Binomial model.

The dynamic programming approach handles more efficiently the non-tradability issue of the project's underlying asset.

- Uncertainty modelling is based on:
  - the benefits summarised in the ICT project's cash flows (underlying asset value)
  - the benefits that represent a stream of stochastic cash flows during the operational stage
  - the investment cost.
- The theoretical foundation of the ROs analysis and its relevance to IT investments has been discussed and applied in practice by Benaroch and Kauffman (1999) as far as the real asset non-tradability issue is concerned. Introducing a convenience yield into the B&S formula can capture the effect of an underline asset that is not traded. The convenience yield decreases the option value of an investment opportunity due to a project's idiosyncratic risk. This factor is hard to be measured but its impact to options value is very limited. The non-tradability issue is still under investigation.
- The option to defer was taken in a non-competitive environment. The cost of the option to defer is not high. Generally, a firm could obtain a deferral option at no cost if it faces no credible competitive threat of losing the deferred investment opportunity (Dixit and Pindyck, 1994). However in a competitive environment, this is not true (Talon et al., 2002).

6 Conclusions

In this paper, we have reviewed and classified real cases of ICT investment analysis using ROs. The ROs approach provides flexibility to the management decisions. The ROs applicability on ICT projects has been successfully tested in a dozen of real cases. The value of managerial flexibility expressed with the options' presence is clearly positive. We classified the cases according to the number of the investment's stages and according to the option to defer, to expand or to grow. The ROs models usually used are the Black-Scholes, Contingent Claim Analysis and the Dynamic Programming. The focus so far is on the evaluation of ICT investments that embed a single, apriori known option. More complicated scenarios containing a 'bunch' of ROs in a simultaneous or/and compound mode remain to be applied.

Assumptions about the independence of investment opportunities, about knowing upfront the valuation parameters, the tradability and liquidation of options and the risk neutrality of the investor remain to be attacked. Finally, the real competitive environment should be considered to have reliable investment decisions.

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