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A Decision Analysis Framework for Prioritizing a Portfolio of ICT Infrastructure Projects

Abstract

The inadequacy of traditional quantitative cost-benefit analysis for evaluating Information and Communications Technologies (ICT) infrastructure investments have led researchers to suggest real options (ROs) analysis for valuating ICT projects. However, ROs models are strictly quantitative and often, ICT investments may contain qualitative factors that cannot be quantified in monetary terms. In addition, ROs analysis results in some factors that can be treated more efficiently when taken qualitatively. This paper combines ROs and the Analytic Hierarchy Process (AHP) into a common decision analysis framework, providing an integrated multi-objective, multi-criteria model called ROAHP for prioritizing a portfolio of interdependent ICT investments. The proposed model is applied to an ICT case study showing how it can be formulated and solved.

***Keywords*:** Decision analysis, Information and Telecommunication Technologies (ITT), ITT-s strategic fit in the organization-s mission, Economic evaluation of ITT, Decisions Under Risk and Uncertainty, AHP, Cost Benefit Analysis, Information and Communication Technologies (ICT), Multi-criteria Decision Making.

1. INTRODUCTION

The valuation of Information and Communication Technologies (ICT) investments is a challenging task. It is characterized by rapidly changing business and technology conditions, as well as intangible benefits, cost and risk factors and other attributes that cannot be quantified in monetary terms. Traditional finance theory suggests that firms should use a Discounted Cash Flow (DCF) methodology to analyze capital allocation requests. However, this approach does not properly account for the flexibility inherent in most ICT investment decisions. For example, an ICT infrastructure project may have a negative Net Present Value (NPV) when evaluated on a stand-alone basis, but may also provide the option to launch future value-added services if business conditions are favorable. Real Options (ROs) analysis presents an alternative method since it considers the managerial flexibility of responding to a change or new situation in business conditions [1].

Although the use of ROs for the valuation of ICT investments has been documented, little research has been conducted to examine its relevance for valuing and prioritizing a portfolio of projects [2]. Complexities of ICT projects, along with the effect of project interdependencies, raise several challenges in applying ROs to prioritization of ICT investments. In addition, ROs models are strictly quantitative. ICT investments, however, experience intangible factors that can be mainly treated by qualitative analysis [3]. For this reason, we provide a nested ROs model considering both positive and negative dependencies among projects in a portfolio. The ROAHP model that we introduce here considers tangible and intangible financial factors and quantifies managerial flexibility in the portfolio's deployment strategy. This is the first time in ICT literature that ROs and AHP are integrated into a common decision analysis framework. The ROAHP model provides a better understanding of interdependencies and various intangible factors of projects extracted by the ROs analysis, enabling these projects to be valued and prioritized with higher accuracy.

Problem Definition

We consider a portfolio of M ICT investment opportunities. They are grouped into i=1, …, n phases (Figure 1). In phase 1, there are K infrastructure projects $P_{1,k}$ (k=1, 2, …, K). Infrastructure projects do not have any prerequisites. Each one of them provides a platform for launching other applications by enabling follow-on investments during future periods. Projects from phases 2 to n depend on capabilities deployed from projects during the previous phases. We treat the launching of these applications as ROs. Typical infrastructure projects include telecommunication networks, ICT platforms, management of shared customer databases and ICT expertise development. Our aim is to prioritize the phase 1 infrastructure projects in terms of the overall utility value that they bring to the investor. Table 1 provides definitions of the variables used in our analysis.

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The first challenge is to estimate the value of phase 1 infrastructure projects, which create future growth options. These options can be exercised if and when management decides that business conditions are favorable. The quantification of this managerial flexibility is achieved by using ROs. The first challenge arises from the modeling of the dependencies among projects. The second challenge is to combine tangible factors given by the ROs analysis with intangible ones coming from ROs perception, such as ill-defined growth option opportunities, and threats from competition.

--------------------------------Figure 1------------------------------------

This paper is organized as follows. In Section 2, we present a nested ROs model for portfolio prioritization. In Section 3, we integrate ROs and AHP into a common decision analysis framework providing the proposed model called ROAHP. In Section 4, we apply the ROAHP to an ICT case study. Finally, in Section 5, we conclude and propose possible future research.

2. A MULTI OPTIONS MODEL FOR PORTFOLIO ANALYSIS

A. Real Options for ICT Investment Valuation

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 Nokia at $90 per share in January 2008). The approach of ROs is the extension of the options concept to real assets. For example, an ICT investment can be viewed as an option to exchange the cost of the specific investment for the benefits resulting from this investment. An investment embeds an 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 [1]. This flexibility (called active management) expands the value of an investment opportunity by improving upside potential and limiting downside losses [4].

The business condition may refer either to market conditions or to firm conditions, depending on where the investment is focused. For example, investment in an e-learning infrastructure for providing educational services within a big organization mainly refers to firm conditions. On the other hand, a broadband network investment, which focuses on providing services in the market, mainly refers to market conditions.

ICT investments provide the capability to expand or launch other applications across different platforms. Prior research has shown that software platforms may not generate value directly, but may enable other value-added applications [5],[6],[7]. ICT infrastructure projects may involve a “wait-and-see” component that gives ICT managers the option to defer decisions for future investment opportunities until some uncertainties are resolved [8],[9],[10].

The total value of a project that owns one or more options is called Expanded (Strategic) Net Present Value (ENPV) and is given by Trigeorgis [1]:

$$\textit{Expanded}\ \text{(Strategic) NPV} = \text{Static (Passive) NPV} + \text{Value of future Options}_{\text{Active Management}} \quad (1)$$

The flexibility value named “option premium” is the difference between the NPV value of the project, estimated by the Static or Passive NPV method (PNPV), and the ENPV value, estimated by the ROs method. The higher the level of project uncertainty is, the bigger the value of the RO will be due to gains in upside potential and minimization of downside potential.

ROs are usually defined as either operating or strategic options. Operating options are found mainly in operational investments, whose value follows from direct cash flows and/or cost savings that they generate. Strategic (growth) options are usually found in infrastructure investments, whose value is derived mainly from new investment opportunities that they create. ROs thinking emphasizes the sources of uncertainty inherent in IT investments. These risks include firm-specific risks, competition risks, market risks, and environmental and technological risks [11]. Kim and Sanders [12] addressed the relationship between ICT investments and ROs theory. So far, research on ROs for justifying IT investments has mainly focused on valuation decisions for a single project. For instance, Taudes et al. [7] used an options model to quantify the benefits of switching from SAP R/2 to SAP R/3. Similarly, Schwartz and Zozaya-Gorostiza [13] developed options that consider the effect of uncertainty in costs and benefits associated with ICT investment opportunities, using data on the deployment of point-of-sale debit services as reported by Benaroch and Kauffman [8]. Iatropoulos et al. [14] examined the ROs applicability in a real-life broadband investment case study. Kauffman and Xiatong [15] developed a decision analysis model based on ROs theory for analyzing the optimum investment timing strategy of a firm that has to decide between two incompatible and competing technologies. Santiago and Bifano [16] also introduced an ROs model that uses multidimensional decision trees to assess the development process of a high-technology product. For a general overview, Trigeorgis [1] provided an in-depth review and examples on different ROs. For more practical issues, the reader is referred to Mun [17]. Angelou and Economides [18] provided a literature review of ROs applications in real life ICT investment analysis. However, little research has been conducted to examine the relevance of ROs for valuing and prioritizing a portfolio of ICT projects that are typically characterized by interdependencies and sequencing constraints [2].

B. A Nested Options Model

For simplicity, we consider a portfolio implemented in two phases, i=1, 2. We can easily extend our analysis to more complicated interactions of compound options in a portfolio of more than two phases. For example, in the case of a three-phase scenario, the total value of an infrastructure project $P_{1,1}$, implemented in phase 1 that embeds one future investment opportunity $P_{2,1}$ in phase 2, which in turn embeds a future investment, $P_{3,1}$, can be represented by a nested options model. The total value of the cluster of projects is given by:

$$ENPV\ (\mathrm{P}_{1,1}) = \mathrm{NPV}(\mathrm{P}_{1,1}) + \text{Option Value}\left[\mathrm{P}_{2,1} + \text{Option Value}\left[\mathrm{P}_{3,1}\right]\right] \qquad (2)$$

We work on compound options analysis similar to that found in the works of Benaroch [11],[19] and Panayi and Trigeorgis [10].

Option valuation models can be classified in both continuous time and discrete time domains. The Black-Scholes formula is the most popular continuous time model. In the discrete time domain, the Binomial model is the most widely applied especially in cases of multi-options analysis. However, continuous time models are not readily applicable for practical valuation purposes [20]. Since our portfolio of projects involves ICT infrastructure investments that may embed a number of options, we adopt a discrete time domain analysis.

Dependencies level analysis

Bardhan et al. [2] modeled dependencies among subsequent projects for a portfolio of 31 real-life projects. They recognized two kinds of dependencies: hard dependencies and soft ones. Hard dependencies between two projects exist when a capability developed for one project is also required by another project. Alternatively, it means that a project is a prerequisite for the next phase of projects. Soft dependencies exist when a capability from one project supports or enhances capabilities required by other projects. In our analysis, we extend this model by also adopting negative dependencies among projects. This can happen in cases where two projects cause cannibalization of each other's products or services. For example, in the case of a dark fiber provider who also offers bandwidth (light fiber) and network services, the business activity of dark fiber provision could cannibalize the network services of the specific dark fiber provider, since other network providers may offer similar and competitive network services [14]. There might also be cases where parallel ICT investments inside an organization could provide parts of similar modules and functions, resulting in a low utilization of some of the modules/functions against a high utilization of others. For example, some benefits that can come from a specific ICT application are not credited to it because the application's software is not utilized. On the contrary, they are credited to another application where the respective software is operating. Thus, the implementation of one project may result in the value reduction of another. We represent these types of soft positive dependencies as $s_{k,j}$, which is defined as the percentage reduction in benefit of project $P_{2,j}$ if it is not preceded by project $P_{1,k}$. In other words, if project $P_{1,k}$ is implemented first, it enhances the economic performance of project $P_{2,j.}$ Similarly, we define as $g_{k,j}$ the negative dependency factor, which indicates the percentage reduction in benefit of project $P_{2,j}$ if it is preceded by project $P_{1,k}$ (product/project cannibalization, partially substitutes projects/options). In particular, our exploration includes interactions between projects, where implementation of one project may result in a reduction in the value of another project (negative soft dependencies).

Positive (or negative) dependencies may also address the issue of complementarity (or substitutability) of relationships among projects. The projects in a portfolio may be partial or full strategic substitutes or complements of each other. Among others, if two projects are full (or partial) substitutes of each other, then the implementation of one results in full (or partial) performance degradation of the other. For complementary relationships, the implementation of one project results in a partial performance increase of another in case of a soft positive dependency, and in the performance existence of another in case of a hard dependency.

However, since the implementation of a project may result in the increase or decrease in the value of another project, we estimate the maximum or minimum potential ENPV value, defined as ENPV', for the initial infrastructure projects. In addition, we estimate the potential ENPV value for all combinations of projects that experience positive and negative dependencies. Hence, for each project in phase 1, we estimate the potential ENPVs for all the implementation combinations of the projects in the portfolio that can affect the specific infrastructure project.

Next, we present a compound ROs model taking into account interdependencies of projects. In compound multi-options analysis, the degree of interactions among options may take place in substitutive, in additive or in a synergetic fashion [1].

In particular, we estimate the attribute of the option value of a future investment opportunity $P_{2,j}$ that an initial infrastructure project $P_{1,k}$ has. Our aim is to estimate how much of the option value embedded in project $P_{2,j}$ should be allocated as a nested option to the initial infrastructure project $P_{1,k}$. This depends on the nature of the dependencies between two projects.

Hard dependencies between projects

As mentioned earlier, we work on a portfolio implemented in two phases. There is an initial ICT infrastructure investment project $P_{1,k}$ at phase 1 that has an option to expand or growth investment opportunity called project $P_{2,j}$ at phase 2. In addition, we consider hard dependencies among projects $P_{1,k}$, and $P_{2,j}$. Since project $P_{2,j}$ cannot exist at all if project $P_{1,k}$ is not implemented, we allocate the overall value of option $OV_{2,j}$ as a nested option to the ENPV of project $P_{1,k}$. Even if other projects also contribute to benefits of project $P_{2,j}$, the contribution of project $P_{2,j}$ to $P_{1,k}$ should still be the overall option value, since without $P_{1,k}$, no option value can exist at all.

Hence the maximum potential Expanded NPV is given by:

$$ENPV'_{1,k} = \mathrm{NPV}_{1,k} + \mathrm{OVA}_{2,j,k} \tag{3}$$

The contribution (attribute) of project $P_{2,j}$ to project $P_{1,k}$ is $OV_{2,j,k}$. That is, the whole option value of project $P_{2,j}$ given by:

$$OVA_{2,j,k} = \mathrm{OV}_{2,j,k} = \max\left(V_{2,j} - C_{2,j}, 0\right) \tag{4}$$

Soft positive dependencies between projects

In this case, project $P_{1,k}$ is not a prerequisite for project $P_{2,j}$. However, the former contributes to the increase in benefits of the latter. We consider that option/project $P_{2,j}$ is enhanced by its predecessor, project $P_{1,k}$.

The maximum potential Expanded NPV of project $P_{1,k}$ is given by:

$$ENPV'_{1,k} = \mathrm{NPV}_{1,k} + \mathrm{OVA'}_{2,j,k} \tag{5}$$

The challenge here is to estimate the contribution (attribute) of option value, $OVA'_{2,j,k}$, of project $P_{2,j}$ to project $P_{1,k}$.

Since project $P_{1,k}$ contributes only partially to the subsequent project $P_{2,j}$, the RO value of the latter should be quantified only to some extent for the estimation of the overall value of $P_{1,k}$.

The contribution (attribute) of project $P_{2,j}$ to project $P_{1,k}$ is calculated as:

$$OVA'_{2,j,k} = \mathrm{OV'}_{2,j,k} - \mathrm{OV'}_{2,j} \tag{6}$$

The following expressions are the option values for full and limited scale capabilities of project $P_{2,j}$:

$$OV'_{2,j,k} = \max\left(V_{2,j} - C_{2,j}, 0\right) \tag{7}$$

$$OV'_{2,j} = \max\left(\left(1 - s_{k,j}\right) * V_{2,j} - C_{2,j}, 0\right) \tag{8}$$

Expression 7 is the option value for project $P_{2,j}$ implemented with full-scale capability, meaning that project $P_{1,k}$ was implemented.

Expression 8 is the option value for project $P_{2,j}$ implemented with limited scale capabilities, meaning that project $P_{1,k}$ was not implemented.

Soft negative dependencies between projects

Similarly, in the case of negative dependencies between projects $P_{1,k}$ and $P_{2,j}$, the attribute (contribution) of option value of project $P_{2,j}$ to project $P_{1,k}$ is given by:

$$OVA''_{2,j,k} = \mathrm{OV''}_{2,j} - \mathrm{OV''}_{2,j,k} \tag{9}$$

The following expressions are the option values of project $P_{2,j}$ when project $P_{1,k}$ is not implemented (10) and when it is implemented (11):

$$OV''_{2,j} = \max\left(V_{2,j} - C_{2,j}, 0\right) \tag{10}$$

$$OV''_{2,j,k} = \max\left(\left(1 - g_{k,j}\right) * V_{2,j} - C_{2,j}, 0\right) \tag{11}$$

Hence, the minimum potential Expanded NPV of project $P_{1,k}$ is given by:

$$ENPV'_{1,k} = \mathrm{NPV}_{1,k} - \mathrm{OVA''}_{2,j,k} \tag{12}$$

Therefore, the initial project $P_{1,k}$ that negatively influences a subsequent investment opportunity $P_{2,j}$ experiences an economic performance decrease in the overall portfolio's analysis. The value of this decrease depends on the option value attributes of the future investment opportunities that have been negatively influenced by project $P_{1,k}$.

In this section, we adopted the option theory and presented a nested options model for portfolio prioritization. However, we completely focused on quantitative analysis and ignored any contribution of the qualitative factors in the overall value of investment opportunities. In the following section, we integrate quantitative issues (factors) coming from the ROs framework with qualitative ones that characterize ROs analysis but cannot be considered by existing ROs models.

3. ROAHP: A COMBINED ROS AND AHP MODEL

The ROs models found so far in literature deal with quantitative factors analysis for both benefits and costs. Very often, however, the decision analysis process for ICT projects should consider a number of qualitative factors as well. Managerial flexibility, which is expressed by the ROs analysis, may apply to both quantitative and qualitative factors. However, the known ROs models consider only the tangible factors. In this section, we expand our nested ROs model by adopting the AHP methodology and constructing a specific multi-criteria decision analysis model. One of the AHP's strengths is the value it places on a decision maker's opinions and the crucial role these opinions play in the decision-making process. Additionally, AHP is capable of integrating both qualitative and quantitative criteria into the decision-making process. Finally, through the pair-wise comparison process, AHP decomposes large, complex decisions and allows the decision maker to focus his attention on every criterion [22]. Thus, we integrate ROs and AHP into a common decision analysis framework. We call this new portfolio prioritization model, ROAHP. It must be stated that Cooper et al. [23] have earlier worked on the problem of qualitative and quantitative criteria integration, in a general approach, concerning project portfolio management. Their aim was to help managers create a new product development portfolio that is strongly linked with the firm's strategy. This portfolio may contain both quantitative and qualitative attributes.

A. AHP in ICT Investments Valuation

AHP is a multi-criteria decision analysis technique. It aims to choose from a number of alternatives based on how well these alternatives rate against a chosen set of qualitative as well as quantitative criteria [24],[25],[26]. AHP was developed at the beginning of the 1970s to tackle complex, multi-valued political and economic decision problems. Using AHP, it is possible to structure the decision problem into a hierarchy that reflects the values, goals, objectives, and desires of the decision-makers. Thus, AHP fits the strategic investments problems and the framework of this study. The main advantage of the AHP approach is that different criteria with different measures can be easily transformed into a single utility measure. As inputs, AHP uses the judgments of the decision makers about alternatives, evaluation criteria, relationships between the criteria (importance), and relationships between the alternatives (preference). In the evaluation process, subjective values, personal knowledge, and objective information can be linked together. As output, the goal hierarchy, the priorities of alternatives and their sensitivities are derived.

Bodin et al. [27] proposed the AHP method to determine the optimal allocation of a budget for maintaining and enhancing the security of an organization’s information system. Hallikainen et al. [28] proposed an AHP-based framework for the evaluation of strategic IT investments. They applied the principles of AHP to compare a number of Information Technology investment alternatives. Tam and Tummala [29] formulated and applied an AHP-based model for selecting a vendor for a telecommunications system. Lai et al. [30] applied AHP to the selection of a multimedia authoring system. Kim [31] used AHP to measure the relative importance of Intranet functions for a virtual organization. Karsten and Garvin [32] used AHP for selecting participants in a telecommuting pilot project. Santhanam and Guimares [33] applied AHP to the problem of evaluating Decision Support Systems. Roper-Lowe and Sharp [34] used the AHP model for the selection of a computer operating system. They mixed tangible and intangible factors in a benefits hierarchy to prioritize three scenarios for a British Airways operating system upgrade. AHP has also been applied in other fields. For example, Greiner et al. [22] integrated AHP and integer goal programming to provide the decision maker with an effective and efficient decision support process that also models constrained resource environment. They applied it to select weapon-systems development projects. Finally, Vaidya and Kumar [35] presented an excellent literature review of the AHP applications.

B. Integration of ROs and AHP - The ROAHP Model

The structure of the decision analysis framework contains four levels: (1) portfolio level, (2) projects interdependencies level, (3) options level, and (4) cost-benefit level (Figure 2). In the first level, the portfolio's M distinct projects are recognized. Our target is to prioritize the initial K infrastructure projects on which the rest M-K projects are based. The second level models depict the dependencies between the portfolio's projects. As mentioned before, we model hard, soft positive and negative dependencies between projects depending on their influences on each other. In the third level, we consider that the initial infrastructure projects possess a number of future investment opportunities, (i.e. M-K), which can be treated as ROs. We assume various types of ROs, such as option to defer the project, option to expand scale of the existing infrastructure project, option to implement investment in stages in order to mitigate risks, and option to growth that involves strategic future investment opportunities. Although, in our analysis, we are mainly focusing on option to growth and option to defer, other option types may be easily incorporated in our model. Finally, in the fourth level, we have the AHP structure. The overall utility factor of the AHP structure is divided into cost and benefit factors. These factors may be further decomposed into their applicable sub-criteria, which are closely related to the ROs and the investment issues coming from this analysis. We apply the pair-wise comparisons for the intangible factors, while we use the nested options model (presented in Section 2) for the estimation of the maximum or the minimum as well as all the potential ENPV values of the initial

K infrastructure projects. The final result of the analysis, at the top, is the prioritization of the ICT projects according to the overall utility factor.

-------------------------------Figure 2------------------------------------

Cost-Benefit level analysis

The terms costs and benefits mean any factor, tangible and intangible that can affect overall costs and benefits of the portfolio's projects. The positive (good) attributes are represented in the benefits hierarchy, while the negative attributes are represented in the costs hierarchy. We consider the following costs and benefits factors:

Cost Factors Analysis

- One time Cost that corresponds to the sunk, irreversible cost to exercise the option and implement the project (C, Tangible).

The core idea of ROs is the value of investment delay for more efficient control of uncertainties. However, deferring investment for some period may be costly. In our analysis, we consider the following cost factors:

- Option Cost of delay coming from revenue losses due to high Customers' Demand (OCCD, Intangible).
- Option Cost of delay coming from Competition Threat (OCCT, Intangible).
- Option Cost of delay due to Environmental or regulatory Changes (OCEC, Intangible).

Naturally, if the firm waits it will lose some revenues. *Learning-by-waiting* helps to resolve market risk, competition risk, and organizational risk. However, competitors may preempt the RO owner. In addition, customers' demand may be high enough to overcome the need to clarify any uncertainty. If demand is significantly high during the waiting period it may be better to proceed with the implementation of the investment instead of deferring it. More importantly, waiting too long could lead to market share gains by competitors who had no prior presence in the market. The same applies for regulatory or other environmental issues, which may also eliminate investment opportunity during the waiting period. The cost of delay in ROs literature is modeled as a divided yield [1]. Instead, we propose qualitative modeling for these factors by providing pair-wise comparisons amongst candidates. We qualitatively model the possibility of preemption by competition, which can eliminate future option value. We do this since typical options models such as the Black-Scholes formula (in continuous time domain) and Binomial models (in discrete time domain) do not consider threats from the competition. Although until recently, ICT literature was focused on quantitative competition modelling [20],[21], we still consider qualitative modeling to be more practical and flexible, especially in cases of multi-options analysis where the complexity of the models increases dramatically. In particular, after the liberalization of ICT markets, the intensity of competition has increased dramatically and the players in the ICT investment field are usually so many that oligopoly models have become too complicated to be used in practice. Hence, quantitative analysis of competition influence in ICT investment opportunities is a very difficult task that requires high-level mathematical models, so much so that managers and practitioners prefer not to adopt it.

Benefits Factors Analysis

- ENPV' is the maximum or minimum value of a potential investment that contains the option(s) contribution of future investment opportunities (Tangible). Without loss of perspective, we associate this factor with benefits, though it integrates both tangible benefits (revenues) and costs.

- Information Effects-Transformation Effects (ITE, Intangible) are benefits that apply especially to cases where the project is focusing more on internal use and exploitation, having the goal of reengineering the firm.
- Strategic-Long Term benefits (investment opportunities modeled as growth options) are created by the initial project and its predefined options and cannot be clearly quantified (SE, Intangible).
- Competition Effects-Increased Market Share (CA, Intangible). The firm can gain competitive advantage by the project implementation, which can be translated to increase of market share. We model these as intangible factors.

Strategic-Long Term benefits (investment opportunities) that are created by the initial projects and their predefined options usually cannot be quantified at the outset. In particular, beyond the operational benefits that the company will receive from phase 1 projects, there are certain long-term strategic goals that can be achieved (e.g., the entry of more value-added advanced telecommunication services). In ROs literature, investment opportunities, defined in advance based on initial infrastructure projects, are treated as growth options, while compound options models are utilized for the estimation of their values [19]. However, growth investment opportunities in reality can hardly be defined during the decision phase. For this reason, we qualitatively model the existence of growth investment opportunities, which are based on projects in previous phases and cannot be quantitatively defined in advance. An extension of our work would be to consider the qualitative interactions between current projects and subsequent ones that can mainly be arrived at in the long term and cannot be modeled in advance.

As seen in our case, we use two tangible and six intangible factors. Other intangible factors that may be included in our analysis are: (a) internal resource availability and required expertise for project development, (b) shareholders' commitment and fund handling, and (c) project complexity.

While numerical values pertaining to quantitative objectives have been readily used for tangible factors, AHP priorities have been elicited and used for qualitative objectives. To achieve homogeneity between various types of objectives, as shown below, we have to normalize the quantitative values into the range of [0,1]. We also use Expert Choice, a commercial software system for AHP [36].

The methodology follows the following steps:

1. Recognize the overall portfolio's projects as well as the initial infrastructure projects as chains of investment opportunities.
2. Identify all hard and soft dependencies between all combinations of projects $P_{1,k}$ and $P_{2,j}$, where $k = 1, 2, 3, \ldots, K$ and $j = K+1, K+2, \ldots, M$.
3. Identify the option presence and type for all projects.
4. Apply the AHP methodology for intangible factors while integrating the tangible factors as estimated by the aforementioned options model.
    a. Estimate the maximum or minimum potential ENPV values for the infrastructure projects $P_{1,k}$ including the options attributes of subsequent investment opportunities.
    b. According to the specific options presence, perform pair-wise comparisons for the estimation of intangible factors mainly resulting from ROs thinking.
5. Perform sensitivity analysis to understand the contribution of each factor.

High number of pair-wise comparisons

If the number of comparisons is large, then the complexity of the methodology is increased significantly. One disadvantage of the APH methodology is the large number of pair-wise comparisons to be undertaken. When evaluating ICT investments, there can be tens or even more of potential business alternatives available, making pair-wise comparisons a frustrating and time-consuming process. Therefore, a preliminary reduction "routine" is needed to shorten the AHP process. With ICT investment decisions, the great number of alternatives can be restricted by setting various thresholds to qualify "finalists". These thresholds may be applied with certainty for quantitative factors, while thresholds for qualitative factors can be set at least intuitively by the company's management.

Some further discussion on the need for ROs and AHP integration

In a future work, we will consider extra factors (tangible and intangible) that involve more practical business issues. Here, the extent of our discussion focuses on the interface between ROs and AHP.

ROs analysis produces a number of factors that cannot be easily quantified by existing ROs models and methodologies. Fichman et al. [37] called them potential pitfalls of option thinking for investment evaluation. We can adopt some of them in our model to achieve a balance between quantitative and qualitative analyses and enhance the decision analysis process. Among others, not all investments can be divided into stages. Sometimes a firm should consider the investment as a whole entity, such as when external funds must be raised or when co-investment from other parties is required. Another issue is that stakeholders may prefer funding all at once to obtain maximum control of the investment and have extra time to get a troubled investment back on track before facing the next track of justification. We may introduce this possibility in our analysis by considering the intangible factor "*Capability-Interest of staging the investment*" (CSI).

Furthermore, building in the option to abandon or contract operation may involve intangible costs related to credibility and morale. We can model this possibility by the intangible factor "*cost of scaling down operation*" (CSO). Furthermore, creating a growth option usually involves making the ICT platform more generic and modular for obtaining higher flexibility, while experiencing higher cost. We model this issue as an intangible factor called "*cost of systems flexibility-modularity*" (CSM).

Another factor that can be integrated in a future work is the *higher uncertainty clearness-control (UC) during waiting period.* In our model, we consider the amount and type of uncertainty control achieved by each of the portfolio's projects. We do not want to substitute the UC, achieved by the ROs analysis and quantified by the volatility of the stochastic parameters, such as investment revenues V and one time investment cost C (σ_v, σ_c). However, the overall uncertainty of an investment opportunity cannot be easily quantified. For example, the uncertainty of customers' demand may be quantified by estimating its contribution in the overall investment's volatility, while the contribution of technology and the firm's uncertain capability to optimally exploit investment benefits may not. By adopting qualitative analysis, we can model some of the uncertainties inherent in the investment opportunity that cannot be quantitatively estimated and included in the overall investment's volatility.

Benaroch [19] provided a method for estimating the overall investment's uncertainty (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 uncertainty may be impossible. We may extend this work by considering that some of the overall components of the uncertainty may be treated as qualitative factors, while the sources of uncertainty that can be quantified and included in the estimation of the overall volatility can be integrated into the typical ROs models.

In addition, an investment opportunity treated as an RO with a specific deferring period at t_{s1} or at t_{s2}, $t_{s2}>t_{s1}$, may have the same risk (uncertainty) control (e.g., for customers' demand) as quantified by the value of revenues volatility. In practice, however, the longer the period in which the option is held, the higher the control of the customers' demand uncertainty will be. Hence, for the same future investment opportunity considering different “time windows” of the same length where this opportunity is held, we may experience different uncertainty “clearness” and hence different option premium.

We can qualitatively model this uncertainty clearness as:

- Customers’ demand uncertainty (more efficient clearness of competition).
- Cannibalization of future investments (by investing the specific project may influence negatively the revenues of a specific future investment opportunity).
- Anticipated action of regulatory bodies.
- Competition risk control (more efficient clearness of competition).

Finally, in this work we focus on portfolio prioritization. However, the ROAHP model may also be applied to find the optimum deployment strategy for a mega-project, which spawns future investment opportunities. Benaroch [19] provided an ROs framework for finding the optimum deployment strategy for an ICT investment opportunity. He adopted multi-options analysis and considered that an investment may be deployed in stages where each stage may contain various types of options such as to defer, expand or abandon. The target is to adopt the combination of options where risk is mitigated and investment performance takes the highest value. Our work may be considered as an extension of this work since, in addition to multi-options analysis, we introduce intangible factors and integrate them in a common decision analysis framework.

Real options limitations and need for qualitative perspective integration

In business practice, several conceptual and practical issues emerge when trying to use options theory as proposed in the current ICT literature. It is accepted that all ROs models provide approximate valuations of ROs values [38]. Even the so-called accurate ROs models such as the Black-Scholes formula require some assumptions whose validity is still under criticism in the field of ICT investments [39]. In particular, while ROs analysis is widely proposed for evaluating ICT investments, it is still accepted that ROs 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 to estimate the correct discount factor of ICT investments. The theoretical foundation of the ROs analysis and its relevance to ICT investments has been discussed and applied in practice by Benaroch and Kauffman [8],[9] as far as the real asset non-tradability issue and risk-neutrality of the investor are concerned. However, its limitation is still under discussion.

Existing models for ROs valuation assume a certain distribution of the resulting cash flows, based on an efficient market. However, this is rarely the case in the context of investments in the ICT business field, which is known for its uncertain and unpredictable conditions. It has also been recognized that finance-oriented option valuation models are too complex for managerial decision-making practice, when real life business conditions are considered. In particular, after the liberalization of the ICT market, the required competition modeling has increased the complexity of existing options models. It is very difficult for senior managers to accurately estimate the parameters of a statistical distribution of outcomes and mainly volatility since they do not really have a "gut feel" for the estimation of the volatility, even though they understand its technical definition as a statistic. Options theory in its present state does provide a conceptual decision framework to evaluate ICT investments but, in many cases, cannot be considered as a fully operational tool for management [40]. If it is expected that practitioners and senior managers will resist the use of formal options pricing models, then the qualitative option valuation can be an alternative analysis process. This is based more on the intuition of decision makers and forecasting for risks profiles, and less on sharply quantified prediction for parameters used in the formal options models.

Qualitative ROs analysis requires the management and business analysts to qualitatively recognize the options during the lifecycle of an investment opportunity that can at least partially control specific risks. For qualitative analysis, we focus on the aforementioned term UC that is the amount of the uncertainty that is resolved as time passes and as new information becomes available to the decision maker. Decision makers have to intuitively compare (using AHP) all ICT projects in the portfolio in terms of the UC.

Overall, these issues suggest that even quantified ROs analysis could produce only approximate valuations, which in some cases can cause serious mistakes in ICT investment decisions [41]. For these reasons, we may adopt typical DCF techniques such as NPV instead of ENPV value and combine tangible factors with qualitative ROs thinking. Hence, our multi-criteria decision analysis framework can be extended including typical tangible factors from financial perspective and intangible ones from qualitative ROs thinking.

4. A CASE ILLUSTRATION

To illustrate the proposed ROAHP model, we apply it to an ICT portfolio investment decision for a growing Water Supply and Sewerage Company, which we refer to here as WSSC to protect its identity and its projects. The company's principal business is the supply of water and sewerage services to over 1.5 million people. Furthermore, the company is in the process of developing a fiber optics network for its commercial exploitation.

WSSC faces challenges in several areas. First, there is an opportunity for the WSSC to offer advanced water management services to its existing customers. This results in enhanced service quality and efficient control of its operating expenses. In addition, its service area will significantly increase, thus attracting new customers. To achieve all this, WSSC management is focusing on the significance of ICT applications that could transform the company's relationships with customers, suppliers, other partners and environment regulators. WSSC is interested in prioritizing four ICT infrastructure projects. Each project will generate a number of future investment opportunities to improve automation aspects of its operations, decision-making methods, customer services, as well as new strategic opportunities in long-term perspective. Each project owns one clearly defined expand/growth option. The management also considers that there are some possible future investment opportunities. However, since they are not clearly defined at the time of the initial valuation, they cannot be included in the quantitative nested options analysis; rather, they will be treated as growth options in a qualitative way.

Hence, there are eight clearly defined projects. The portfolio's projects are grouped into two phases. Phase 1 (infrastructure) projects represent projects that do not have any prerequisites and serve as building blocks for future projects in phase 2. Phase 2 projects (ROs) involve significant investment decisions in a competitive environment and these projects depend on the capabilities deployed in phase 1. Table 2 provides a brief description of the project portfolio and the soft positive and negative interdependencies between phase 1 and phase 2 projects. First, we apply the proposed nested options model to prioritize the portfolio's projects according to their ENPV' values. Afterwards, we introduce the AHP methodology for combining the tangible and intangible factors as taken by the ROs analysis.

-------------------------------Table 2------------------------------------

A. Application of the Nested Options Model

Dependencies analysis

Figure 3 shows the overall portfolio structure and indicates the hard and soft dependencies between phase 1 and phase 2 projects. In particular, $P_{2,1}$ has hard dependency with $P_{1,1}$ and soft positive dependency with $P_{1,2}$. $P_{2,2}$ has hard and soft negative dependency with $P_{1,2}$ and $P_{1,3}$ respectively. Finally, $P_{2,3}$ and $P_{2,4}$ have hard dependencies with $P_{1,3}$ and $P_{1,4}$ respectively.

-------------------------------*Figure 3*------------------------------------

Finally, Table 3 shows the dependencies between phase 1 and phase 2 projects in a matrix structure.

-------------------------------Table 3-----------------------------------

The symbol H indicates hard dependency. Soft positive (or negative) dependency is indicated as the percentage reduction in the overall revenues value of a project in phase 2 in case the phase 1 soft dependent project were not implemented (or were implemented).

Nested options analysis

We consider that phase 2 projects are ROs to expand or grow one year after the implementation of their necessary predecessor infrastructure projects in phase 1. The challenge is to estimate the option attribute of project $P_{2,j}$ to the predecessor project $P_{1,k}$. Alternatively, we want to estimate to what extent we should allocate the overall options value of project $P_{2,j}$ to project $P_{1,k}$.

We use a 50-step Log Transform Binomial (LTB) model to estimate the option values. We also take into account both revenues and cost uncertainty by using the one-step Extended Log Transformed Binomial (ELTB) model and compare it with the one-step LTB model. As seen in Table 3 of Appendix A, when cost uncertainty is also considered, the managerial flexibility or option value embedded in a phase 2 project presents higher value. However, we only consider revenues uncertainty for the estimation of option value. We adopt the 50-step LTB model for more accuracy as the complexity of the ELTB model increases dramatically for a similar number of steps. We use the risk-free rate of return (r_f=5%).

In the following, we estimate the ENPV' value for the four infrastructure projects taking into account the various inter-project dependencies with their future investment opportunities, following the methodology presented before.

Initially, we estimate the option values of phase 2 projects:

$$P_{2,1} : \mathrm{OV}_{2,1,1} = \max(\mathrm{V}_{2,1} - C_{2,1}, 0)$$

$$P_{2,2}:\mathrm{OV}_{2,2,2}=\max(\mathrm{V}_{2,2}-C_{2,2},0)$$

$$P_{2,3}:\mathrm{OV}_{2,3,3}=\max(\mathrm{V}_{2,3}-C_{2,3},0)$$

$$P_{2,4}:\mathrm{OV}_{2,4,4}=\max(\mathrm{V}_{2,4}-C_{2,4},0)$$

Table 4 in Appendix A shows the option values for phase 2 projects. For comparison, we provide the projects values as estimated by the NPV analysis.

The next step is to estimate the option attributes of the initial infrastructure projects following the process described before. For each phase 1 project, the ENPV' is given by its NPV value plus or minus, depending on the dependency and the contribution of phase 2 projects/options. Hence, the ENPV' for each phase 1 project/cluster, including the following investment opportunities, is given by the following:

$$ENPV'_{1,1}=\mathrm{NPV}_{1,1}+\mathrm{OVA}_{2,1,1}$$

$$ENPV'_{1,2}=\mathrm{NPV}_{1,2}+\mathrm{OVA}_{2,2,2}+\mathrm{OVA'}_{2,1,2}$$

$$ENPV'_{1,3}=\mathrm{NPV}_{1,3}+\mathrm{OVA}_{2,3,3}-\mathrm{OVA''}_{2,2,3}$$

$$ENPV'_{1,4}=\mathrm{NPV}_{1,4}+\mathrm{OVA}_{2,4,4}$$

We start with project $\mathrm{P}_{1,1}$ that possesses an attribute of option to growth $\mathrm{OV}_{2,1}$. There is a hard dependency between projects. The contribution of option value $\mathrm{OV}_{2,1}$ to project $\mathrm{P}_{1,1}$ is given by the total value of the specific option:

$$\mathrm{OV}_{2,1,1}=\max(\mathrm{V}_{2,1}-C_{2,1},0)=\mathrm{OVA}_{2,1}=197\mathrm{k\$}$$

Hence, the $\mathrm{ENPV'}_{1,1}= -150 + 197 = 47$ k$.

We add the overall "amplitude" or option value of project $\mathrm{P}_{2,1}$ to that of $\mathrm{P}_{1,1}$, since $\mathrm{P}_{2,1}$ could not exist without $\mathrm{P}_{1,1}$.

Then, we work in a similar way with $P_{1,2}$. Project $P_{1,2}$ has hard dependency with project $P_{2,2}$ and soft dependency with project $P_{2,1}$. Finally, $P_{2,2}$ has negative dependency with $P_{1,3}$. The option value attribute (contribution) $OVA'_{2,1,2}$ of project $P_{2,1}$ to project $P_{1,2}$ is given by

$$OVA'_{2,1,2} = \mathrm{OV}'_{2,1,2} - \mathrm{OV}'_{2,1} = 146\text{ k\$}$$

The following expressions give the option values for full and limited scale capabilities of project $P_{2,1}$:

$$\mathrm{OV}'_{2,1,2} = \max\left(\mathrm{V}_{2,1} - C_{2,1}, 0\right) = 197\text{k\$}$$

$$\mathrm{OV}'_{2,1} = \max\left((1-0.25) * \mathrm{V}_{2,1} - C_{2,1}, 0\right) = 51\text{k\$}$$

As seen in Table 4 of Appendix A, $OVA_{2,2,2}$ = 209 k\$. Hence, the overall attributes of the options for project $P_{1,2}$ is 146 + 209 = 354 k\$. Finally, the $ENPV'_{1,2}$ = –100 + 354 = 254 k\$.

Similarly, the $OVA''_{2,2,3}$ of project $P_{2,2}$, which represents soft negative dependency with project $P_{1,3}$, is given by:

$$OVA''_{2,2,3} = \mathrm{OV}''_{2,2} - \mathrm{OV}''_{2,2,3} = 145\text{ k\$}$$

The overall attributes of options to project $P_{1,3}$ is 114-145 = -31 k\$. Hence, the $ENPV'_{1,3}$ is 69 k\$ (=100-31). Finally, the $ENPV'_{1,4}$ is 405 k\$.

Table 5 in Appendix A shows the ENPV' values for phase 1 infrastructure projects.

Assumptions taken

In this case study, we assume that all interdependent projects are chosen to be implemented. To show the influence of the interdependencies on the overall utility factor for each project, we need to consider that all these projects are implemented and thus contribute positively or negatively to each other. However, in this sense, we do not consider the indirect dependencies of phase 1 projects.

Also, we can consider that each cluster of projects that experience direct and indirect interdependencies is chosen as a whole, and we need to prioritize the specific cluster of the projects against the projects of another cluster. However, in this case, the second cluster is just a single project that owns a future option. Then, we can decide which cluster of projects should be assigned higher priority to be implemented. Another practical application of our model can be in the case when we have four business activities/units, and some of them also have positive and negative interdependencies, and we want to allocate in advance the overall utility value of these activities. In addition, if we wish to choose only one project, then we follow the same analysis but ignore the project interdependencies. Finally, if we wish to select only some projects out of many, we estimate the ENPV' for each of the phase 1 projects under the condition that indirect dependent project(s) in phase 1 are either chosen or not chosen. We take all the combinations for the projects that are dependent on each other. However, the complexity increases as the number of projects increases. Table 6 shows the combinations of all projects to be ranked for each case. The target here is to apply the ROAHP model and select the projects that are ranked first across all potential project combinations.

-------------------------------Table 6------------------------------------

B. Application of the ROAHP Model

Next, we proceed with the last two steps of the methodology. Applying AHP, the pair-wise comparison matrices are derived and the relative performance measures are computed for both tangible and intangible factors. This case study is conducted intuitively and we make the pair-wise comparisons by ourselves. Roper-Lowe and Sharp [34] 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. We select the consistency ratio level according to AHP to be less than 0.10 [22].

Tables 7 and 8 in Appendix B present the analysis as well as the resulting weights and consistency ratios for the intangible factors of our ROAHP structure. The tangible data for the ENPV and One-Time costs are also normalized for comparison purposes (Table 9 in Appendix B). To introduce them into the AHP analysis, we use their relative tangible values between each other for their pair-wise comparisons. Since tangible factors (TF) are by definition measurable in quantitative units, we normalize them to maintain parity among all tangible factors included in the evaluation [42]. In particular, we use the notation tf_{lk} that indicates the normalized TF $_l$ in project k for k=1,2,3,4 and is given by:

$$tf_{lk} = TF_{lk} / \sum_{k=1}^{4} TF_{lk} \qquad (13)$$

It is used to ensure that any tangible benefit and cost factor will be compatible with others in the evaluation. The greater the value a tangible factor has, a relatively larger effect is considered in the selection process for this factor. Finally, Table 10 in Appendix B presents the criteria for pair-wise comparison matrices and their relative priority weights.

After making all paired comparisons for all alternatives according to the principles of the AHP with respect to all criteria defined in the ROAHP model, we compute the total priorities for the alternatives using the Expert Choice tool. The prioritization result for the phase 1 projects is given in Figure 4.

-------------------------------*Figure 4*------------------------------------

As can be seen here, project $P_{1,3}$ has the first priority to be implemented even though project $P_{1,4}$ presents a higher ENPV value. It is the contribution of intangible factors that changes the final ranking compared to the result extracted by the single ROs analysis where only the ENPV value was taken into account (last column of Table 2 in Appendix A).

Sensitivity analysis

By performing sensitivity analysis, we can study how sensitive the priorities of the alternatives are to the changes of the input data, i.e. the importance of the criteria. Figure 5 shows the sensitivity analysis of the results with respect to the importance of cost factors. For cost factor weights from 0.2 up to 1, project $P_{1,3}$ achieves the highest priority. For cost weight (importance) lower than 0.2, project $P_{1,1}$ becomes the most valuable investment opportunity.

-------------------------------Figure 5------------------------------------

The left vertical axis shows the priorities of the four alternative projects while the horizontal axis shows the overall weight or importance of costs factors compared to the overall weight or importance of the benefits factors.

Similarly, Figures 6 and 7 analytically present the sensitivity analysis for the benefits and costs factors.

-------------------------------Figure 6------------------------------------

-------------------------------Figure 7------------------------------------

The input data are quite subjective, especially the intangible ones. For this reason, it is important to study the dynamics of the sensitivities carefully. For example, if the importance of Opportunity Costs due to Competition Threat (OCCT) decreases significantly, the priorities of $P_{1,3}$ and $P_{1,1}$ change. In addition, since all criteria are interrelated, a change in one criterion results in changes to all other criteria too.

5. CONCLUSIONS

In this work, we provide a decision analysis framework for prioritizing a portfolio of ICT infrastructure projects. We combine strategic non-financial and financial tangible goals using a multi-options model.

We first rank the portfolio's projects by using ROs analysis. We model the interactions among projects, particularly when the implementation of one project may result in a reduction or increase in the value of another. In addition, we combine tangible and intangible factors using the AHP. Finally, we apply the proposed model to a specific case showing how it can be formulated and resolved. In this case, we show that the ranking of the projects can change when tangible and intangible factors are integrated, compared to the purely tangible factors analysis performed by a purely ROs methodology.

Analytically, our main contributions are the following:

1. We take into account project interdependencies by considering both positive and negative dependencies between projects and by analyzing them using a compound options model.
2. We provide an AHP structure to combine tangible and intangible factors into one utility function. In the literature, ROs models so far employ only a quantitative factors analysis for both benefits and costs. Very often, however, an ICT project also owns a number of qualitative factors that should be taken into account along with the quantitative ones. In addition, ROs analysis produces a number of factors that cannot be quantified, at least not easily, by existing ROs models and methodologies. For this reason, we combine ROs and AHP into a common framework of analysis providing a new portfolio prioritization model called ROAHP.

Limitations and future research

A limitation of this study is the assumption that interdependencies of projects can be identified ex ante (before projects are initiated). Apart from this, growth investment opportunities are often difficult to clearly identify and quantify in advance since ICT business conditions change rapidly. In this work, we qualitatively model the possible existence of growth investment opportunities, which are based on projects in previous phases and cannot be defined quantitatively in advance. An extension of our work would be to take into account the qualitative interactions among current projects and subsequent ones that will mainly be realized in the long term and cannot be modeled in advance. Another limitation is that we do not take any competition characteristic into consideration quantitatively. We are planning to extend our work and take into account competitive interactions among firms in the ICT business field.

Furthermore, we take into account a relatively small number of intangible factors. In a future work, we shall include more detailed intangible factors into the ROAHP model. Also, in real life cases, further analysis is required for ranking of projects in a portfolio before adopting the final solution. The decision makers should perform extended sensitivity analysis for estimating the amount of influence of each priority as well as the weights factors before adopting the final solution of ranking.

Finally, our framework can be used for finding the optimum deployment strategy for a cluster of projects. In particular, instead of considering a portfolio of ICT projects to be optimized, we can consider only one cluster or a single mega project and examine the various alternative deployment scenarios. The criteria in the proposed model can include tangible, intangible and risk factors. In this case, the optimum deployment strategy for an investment scenario will be extracted by a multi-criteria analysis, considering both tangible and intangible factors coming from the ROs thinking and applied to the ICT business field.

APPENDIX A

ROs valuation results

--------------------------------Table 4------------------------------------

--------------------------------Table 5------------------------------------

------------------------------Table 6---------------------------------

APPENDIX B

AHP parameters

For the intangible factors, we present the pair wise matrices and their relative weights as estimated by the Expert Choice Tool.

For the intangible factors, we use the nine-point scale as suggested by Saaty et al. [25]. We declare our portfolio's projects as extreme (E), very strong (VS), strong (S), moderate (M) and equal (E) including intermediate values between the main characterization types. By using the Expert Choice and making judgments according to the aforementioned nine-point scale, we derive the pair-wise comparison matrices.

--------------------------------Table 7------------------------------------

--------------------------------Table 8------------------------------------

For any tangible benefit and cost factor, we estimate the value and normalize it to be compatible with others in the evaluation using the Expert Choice tool.

--------------------------------Table 9------------------------------------

-------------------------------Table 10-----------------------------------

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Tables

Table 1. Notations Used in the Real Options Model

Notation	***Definition***
M	Total number of ICT projects
K	Number of initial infrastructure projects.
N	Number of phases considered.
$P_{1,k}$	Infrastructure project k in phase 1, k = 1,2,…,K
$P_{2,j}$	Project j in phase 2, j = K+1, K+2, ….,M
$NPV_{1,k}$	Net Present Value of project $P_{1,k}$, k=1,2,…K.
$ENPV'_{1,k}$	Potential Expanded NPV of project $P_{1,k}$ that contains the option(s) value(s) of future interdependent investment opportunities
$V_{2,j}$	Present value of operating revenues of project $P_{2,j}$
$C_{2,j}$	One time cost of implementing project $P_{2,j}$. Investment expenditure required to exercise the option (cost of converting the investment opportunity into the option's underlying asset, i.e., the operational project)
$OV_{2,j,k}$ ($OVA_{2,j,k}$)	Option value contribution (attribute) of project $P_{2,j}$ if project $P_{1,k}$, which is prerequisite for project $P_{2,j}$ is implemented– Hard dependency
$OV'_{2,j,k}$	Option value of project $P_{2,j}$ if project $P_{1,k}$, which enhances positively the performance of project $P_{2,j}$, is implemented
$OV'_{2,j}$	Option value of project $P_{2,j}$ if project $P_{1,k}$, which enhances positively performance of project $P_{2,j}$, is not implemented
$OVA'_{2,j,k}$	Option value contribution (attribute) of project $P_{2,j}$ to project $P_{1,k}$, which enhances the performance of project $P_{2,j}$ if it is implemented – Soft positive dependency
$OV''_{2,j,k}$	Option value of project $P_{2,j}$ if project $P_{1,k}$, which influences negatively the performance of project $P_{2,j}$, is implemented.
$OV''_{2,j}$	Option value of project $P_{2,j}$ if project $P_{1,k}$, which influences negatively the performance of project $P_{2,j}$, is not implemented.
$OVA''_{2,j,k}$	Option value contribution (attribute) of project $P_{2,j}$ to project $P_{1,k}$, which influences negatively the performance of project $P_{2,j}$ if it is implemented – Soft negative dependency
$s_{k,j}$	Soft positive dependency of project $P_{2,j}$ on project $P_{1,k}$ (the percentage of reduction of operating revenues of project $P_{2,j}$ if it is not preceded by project $P_{1,k}$).
$g_{k,j}$	Soft negative dependency of project $P_{2,j}$ on project $P_{1,k}$ (the percentage of reduction of operating revenues of project $P_{2,j}$ if it is preceded by project $P_{1,k}$).
TF_{lk}	Value of tangible factor l (l=1,…L) in project k, (in our model L=2: One time cost and ENPV)
tf_{lk}	Normalized of TF_{lk}

Table 2. Portfolio of 8 ICT projects

Project	**Description**	**Dependency type**
$P_{1,1}$	StruMapOut - a Hydraulic Analysis Application, which helps the Water Network Modeling and therefore the Water Management. It is focusing on the outside (backbone network) water network	-
$P_{1,2}$	GIS Platform - a Geographical Information System (GIS) that allows users to create, view, access and analyze map (geo-referenced) data.	$P_{1,2}$ contributes positively to future investment opportunity $P_{2,1}$. Actually, GIS data of $P_{1,2}$ can enhance operation efficiency of $P_{2,1}$.
$P_{1,3}$	Siebel/Asset Management – An ICT application that provides capabilities for efficient asset management and customers services support.	$P_{1,3}$ contributes negatively to $P_{2,2}$ benefits. Part of the modules of $P_{1,3}$ is assigned to $P_{2,2}$ project. Actually, Equipment Management provided by $P_{2,2}$ stay inactive while these needs are fulfilled by $P_{1,3}$ project. Hence, benefits from this module are allocated to $P_{1,3}$.
$P_{1,4}$	ICAT-Telemetry – Information Communication and Automation Technology Infrastructure to enable WSSC to perform more efficient water network management	-
$P_{2,1}$	StruMapIn - Extension of StruMap on Internal (distribution network) optimization	Hard Dependency with $P_{1,1}$.
$P_{2,2}$	Extension of GIS platform application to Equipment Management providing an information portal for factors affecting customers demand and support	Hard Dependency with $P_{1,2}$.
$P_{2,3}$	Extension of Siebel to information portal (customers support) providing also on line question and answer service to WSSC customers.	Hard Dependency with $P_{1,3}$.
$P_{2,4}$	Expand Operation Capability of the existing ICAT platform	Hard Dependency with $P_{1,4}$.

Table 3. Dependencies between phase 1 and phase 2 projects

	$P_{2,1}$	$P_{2,2}$	$P_{2,3}$	$P_{2,4}$
$P_{1,1}$	H	-	-	-
$P_{1,2}$	25%	H	-	-
$P_{1,3}$	-	-15%	H	-
$P_{1,4}$	-	-	-	H

Table 4. Real Options analysis for phase 2 projects/options, (values in k$).
Projects volatilities (σ) as well as correlation level (ρ) between benefits and costs are given in the first column.

Investment Opportunity and risk level	One-time cost C $_{\text{option to expand}}$ at t = 1 (PV at t=0)	V (revenues – operating costs) at t=0	**NPV**	**ENPV'/OV (NPN with option value) - Only Revenues uncertainty (LTB model 50 steps)**	ENPV'/OV (NPN with option value) –Revenues uncertainty **(LTB model 1 step)**	ENPV'/OV (NPN with option value) – Both Revenues and Costs uncertainty **(ELTB model 1 step)**
Project/Option 21 ($P_{2,1}$), σ_v = 30%, σ_C = 30%, ρ_{vC} = -0,5	900 (855)	1000	145	**197**	220	292
Project/Option 22 ($P_{2,2}$), σ_v = 20%, σ_C = 20%, ρ_{vC} = -0,5	2000 (1900)	2000	100	**209**	240	341
Project/Option 23 ($P_{2,3}$), σ_v = 30%, σ_C = 20%, ρ_{vC} = -0,5	1200 (1140)	1100	-40	**114**	138	193,4
Project/Option 24 ($P_{2,4}$), σ_v = 40%, σ_C = 30%, ρ_{vC} = -0,5	2500 (2375)	1900	-475	**155**	150	330

Note: The real numbers for cost and revenues have been changed to protect WSSC confidentiality.

Table 5. Real Options analysis for phase 1 portfolio's projects, (values in k$).

Investment Opportunity	One-time cost C $_{\text{initial infrastructure cost}}$ at t = 0	V (revenues – operating costs) for phase 1 only at t=0	NPV (no option value) for phase 1 projects	Overall NPV with all future investment phases (for comparison purposes – hard dependencies only)	**Overall ENPV' (NPN with nested option value) - Only Revenues uncertainty**
Project ($P_{1,1}$)	1000	850	-150	-5	**47**
Project ($P_{1,2}$)	1500	1400	-100	0	**254**
Project ($P_{1,3}$)	2000	2100	100	60	**69**
Project ($P_{1,4}$)	1200	950	250	-225	**405**

Note: The real numbers for cost and revenues have been changed to protect WSSC confidentiality.

Table 6. ENPV’ estimation and projects to be ranked with ROAHP for each combination of phase 1 projects (actually the scenario 1,3,7 are the same as well as the scenario 2,8)

	Condition 1 $P_{1,2}$ is chosen	Condition 2 $P_{1,2}$ is not chosen	Condition 3 $P_{1,1}$, $P_{1,3}$, are chosen	Condition 4 $P_{1,1}$ is chosen, $P_{1,3}$ is not chosen	Condition 5 $P_{1,1}$ is not chosen, $P_{1,3}$ is chosen	Condition 6 $P_{1,1}$, $P_{1,3}$, are not chosen	Condition 7 $P_{1,2}$ is chosen	Condition 8 $P_{1,2}$ is not chosen
ENPV’$_{1,1}$	▨	▨						
ENPV’$_{1,2}$			▨	▨	▨	▨		
ENPV’$_{1,3}$					▨	▨	▨	▨
ENPV’$_{1,4}$	▨	▨	▨	▨	▨	▨	▨	▨
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
	Projects to be Ranked	Projects to be Ranked	Projects to be Ranked	Projects to be Ranked	Projects to be Ranked	Projects to be Ranked	Projects to be Ranked	Projects to be Ranked
	$P_{1,1}$	$P_{1,1}$	$P_{1,1}$	$P_{1,1}$			$P_{1,1}$	$P_{1,1}$
	$P_{1,2}$		$P_{1,2}$	$P_{1,2}$	$P_{1,2}$	$P_{1,2}$	$P_{1,2}$	
	$P_{1,3}$	$P_{1,3}$	$P_{1,3}$		$P_{1,3}$		$P_{1,3}$	$P_{1,3}$
	$P_{1,4}$	$P_{1,4}$	$P_{1,4}$	$P_{1,4}$	$P_{1,4}$	$P_{1,4}$	$P_{1,4}$	$P_{1,4}$

▨ To be estimated for each combination of inter-dependent projects

Table 7. Pair wise matrices and weights for costs intangible factors

OCCD (Option Cost due to high Customer Demand)

	Project ($P_{1,1}$)	Project ($P_{1,2}$)	Project ($P_{1,3}$)	Project ($P_{1,4}$)	Weight
Project ($P_{1,1}$)	1	7	3	8	0.566
Project ($P_{1,2}$)		1	1/6	3	0.080
Project ($P_{1,3}$)			1	8	0.311
Project ($P_{1,4}$)				1	0.042

Inconsistency 0,08

OCCT (Option Cost due to Competition Threat-Preemption)

	Project ($P_{1,1}$)	Project ($P_{1,2}$)	Project ($P_{1,3}$)	Project ($P_{1,4}$)	Weight
Project ($P_{1,1}$)	1	4	1/4	4	0.218
Project ($P_{1,2}$)		1	1/9	1	0.062
Project ($P_{1,3}$)			1	9	0.657
Project ($P_{1,4}$)				1	0.062

Inconsistency 0,02

OCEC (Option Cost due to Environmental Changes

	Project ($P_{1,1}$)	Project ($P_{1,2}$)	Project ($P_{1,3}$)	Project ($P_{1,4}$)	Weight
Project ($P_{1,1}$)	1	2	4	5	0.504
Project ($P_{1,2}$)		1	2	3	0.267
Project ($P_{1,3}$)			1	½	0.103
Project ($P_{1,4}$)				1	0.126

Inconsistency 0,05

Table 8. Pair wise matrices and weights for benefits intangible factors
ITE (Information & Transformation Effects)

	Project ($P_{1,1}$)	Project ($P_{1,2}$)	Project ($P_{1,3}$)	Project ($P_{1,4}$)	Weight
Project ($P_{1,1}$)	1	3	1	3	0.385
Project ($P_{1,2}$)		1	1/3	2	0.131
Project ($P_{1,3}$)			1	5	0.396
Project ($P_{1,4}$)				1	0.088

Inconsistency 0,03

SE (Strategic Effects)

	Project ($P_{1,1}$)	Project ($P_{1,2}$)	Project ($P_{1,3}$)	Project ($P_{1,4}$)	Weight
Project ($P_{1,1}$)	1	4	1	5	0.411
Project ($P_{1,2}$)		1	1/3	½	0.091
Project ($P_{1,3}$)			1	5	0.389
Project ($P_{1,4}$)				1	0.109

Inconsistency 0,06

CA (Competitive Advantage)

	Project ($P_{1,1}$)	Project ($P_{1,2}$)	Project ($P_{1,3}$)	Project ($P_{1,4}$)	Weight
Project ($P_{1,1}$)	1	½	4	1/5	0.152
Project ($P_{1,2}$)		1	3	1/3	0.217
Project ($P_{1,3}$)			1	1/6	0.065
Project ($P_{1,4}$)				1	0.567

Inconsistency 0,06

Table 9. Weights for costs and benefits tangible factors

	PV 1+2 One time cost C (normalized)	Overall – ENPV’ (normalized)
Project ($P_{1,1}$)	0,17	0,06
Project ($P_{1,2}$)	0,22	0,33
Project ($P_{1,3}$)	0,29	0,09
Project ($P_{1,4}$)	0,33	0,52

Table 10 Criteria pair-wise matrices and weights

Weights for tangible and intangible cost factors (inconsistency 0.07)

Investment Opportunity	One time cost C	OCCD	OCCT	OCEC	Priority
C	1	3	1/3	1/3	0.151
OCCD	1/3	1	1/5	1/3	0.075
OCCT	3	5	1	3	0.508
OCEC	3	3	1/3	1	0.265

Weights for tangible and intangible benefit factors (inconsistency 0.07)

Investment Opportunity	ENPV’	ITE	SE	CA	Priority
ENPV’	1	3	1/5	1/3	0.129
ITE	1/3	1	1/5	1/3	0.074
SE	5	5	1	3	0.549
CA	3	3	1/3	1	0.248

Figures

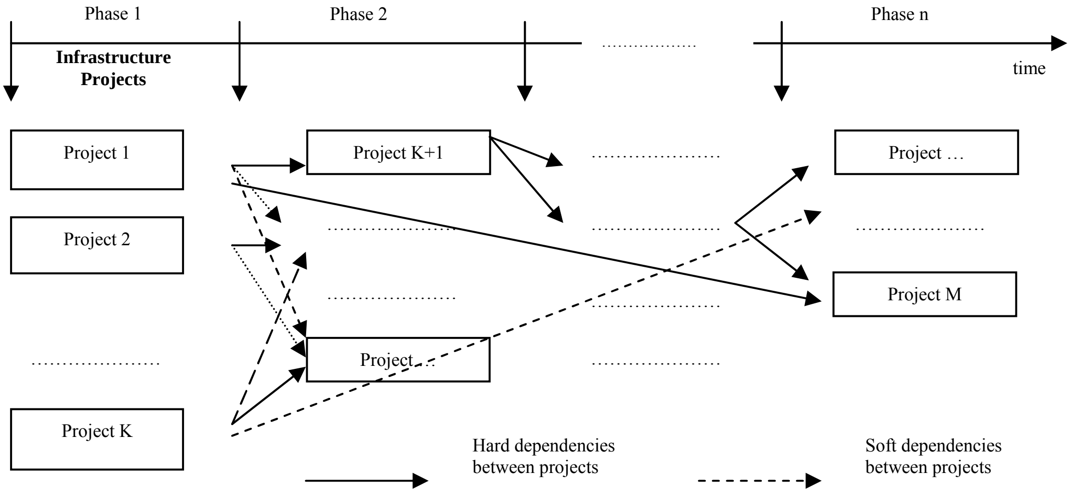

Fig. 1. Portfolio's ICT projects deployed in n phases

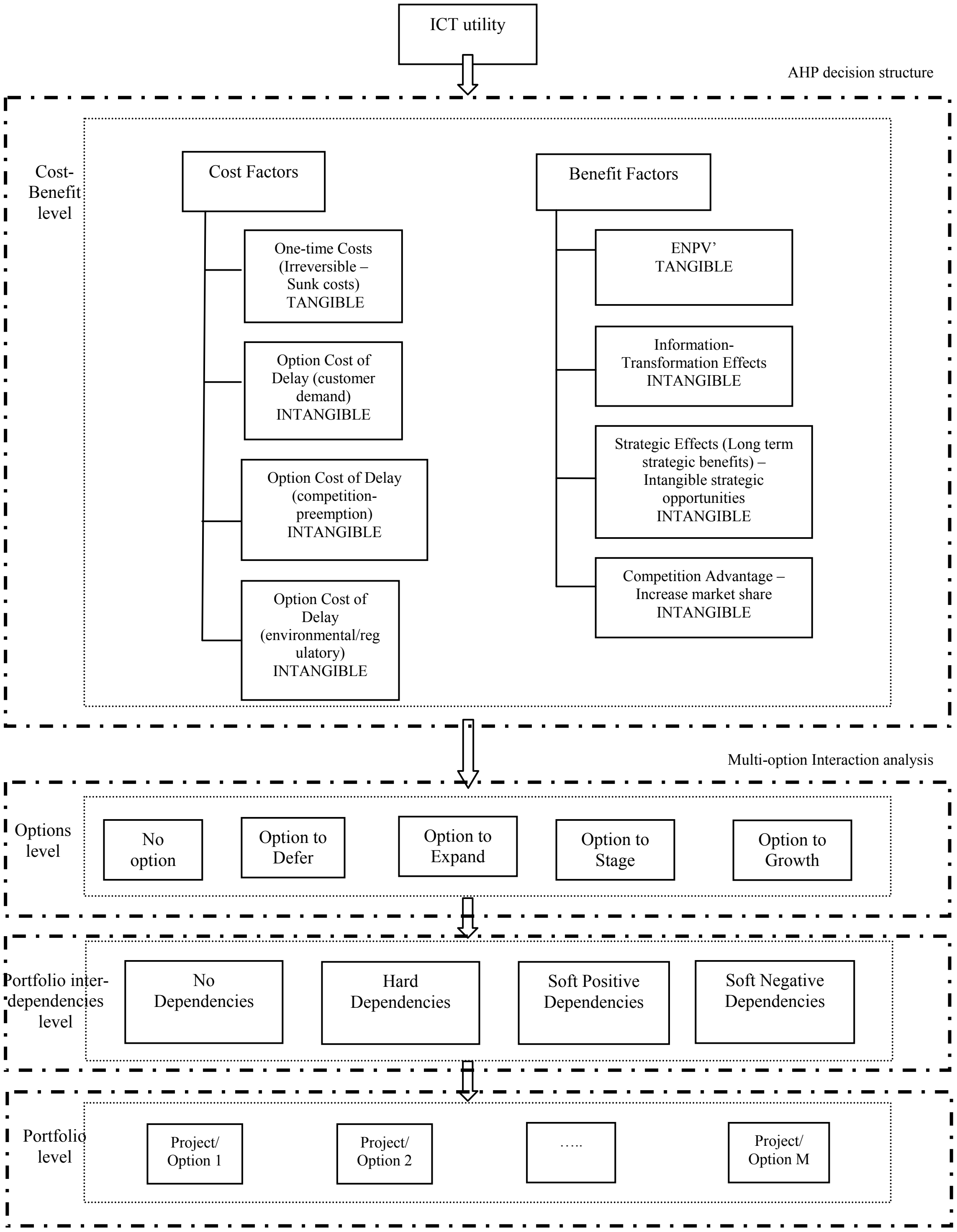

Fig. 2. Portfolio Optimization framework – Analytical view of the ROAHP model

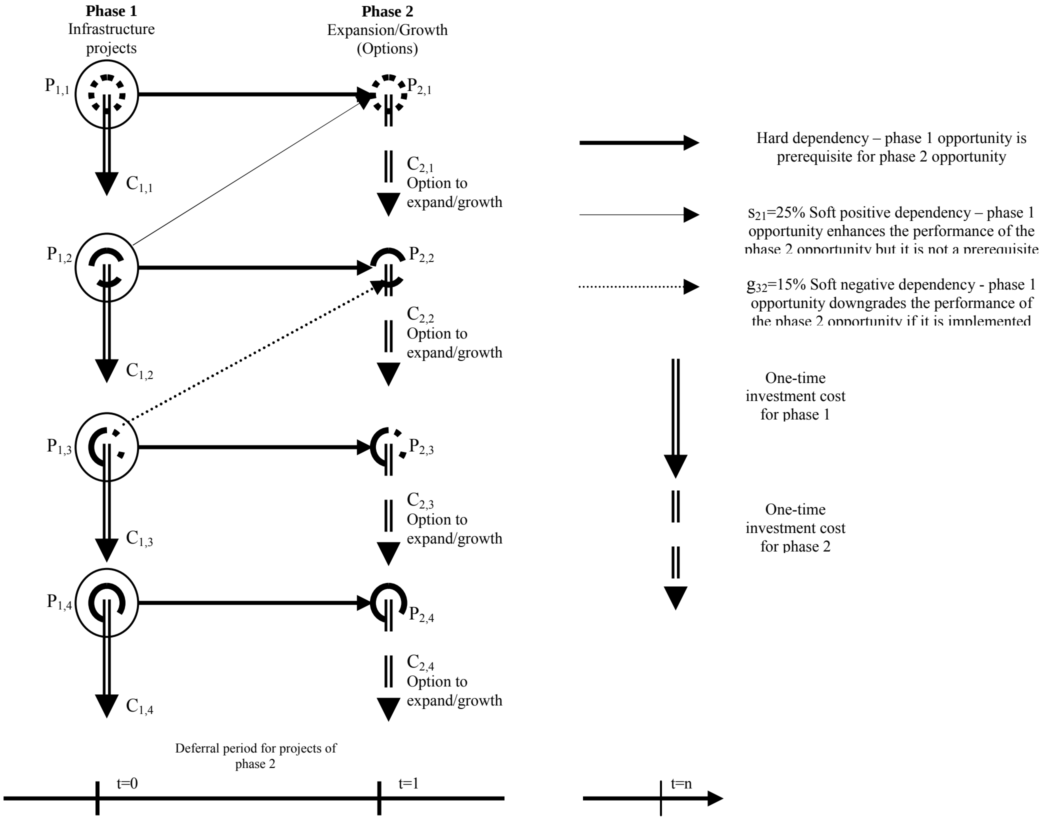

Fig. 3. Eight ICT projects for the WSSC

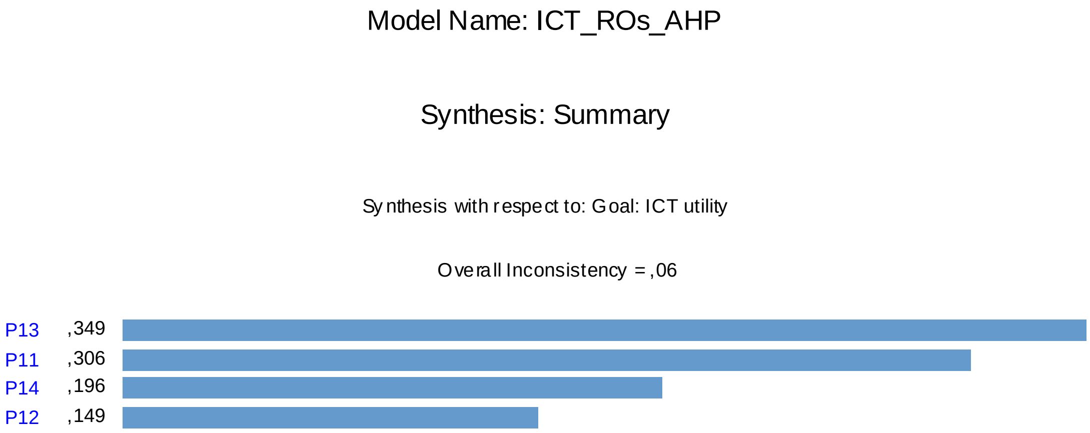

Fig. 4. Project prioritization performed with the Expert Choice tool

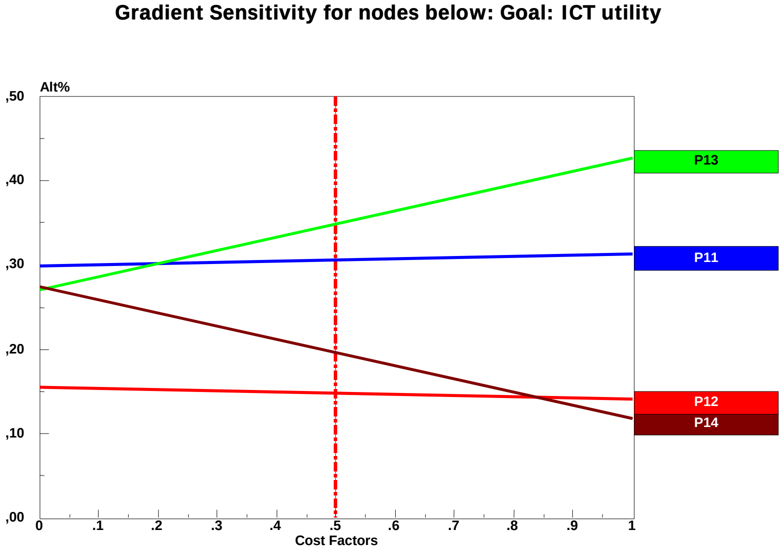

Fig. 5. Sensitivity analysis for cost factors

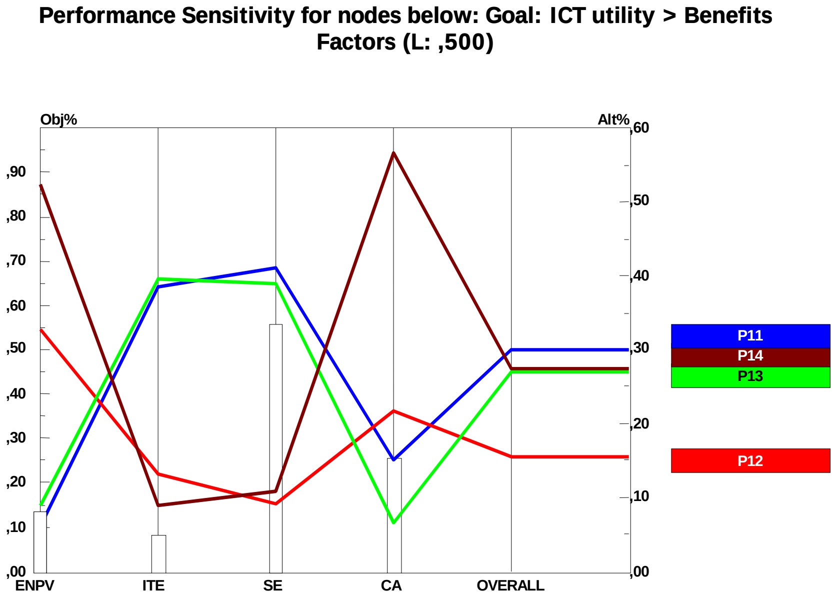
Performance Sensitivity for nodes below: Goal: ICT utility > Benefits Factors (L: ,500)

Fig. 6. Sensitivity analysis for benefit factors analytically

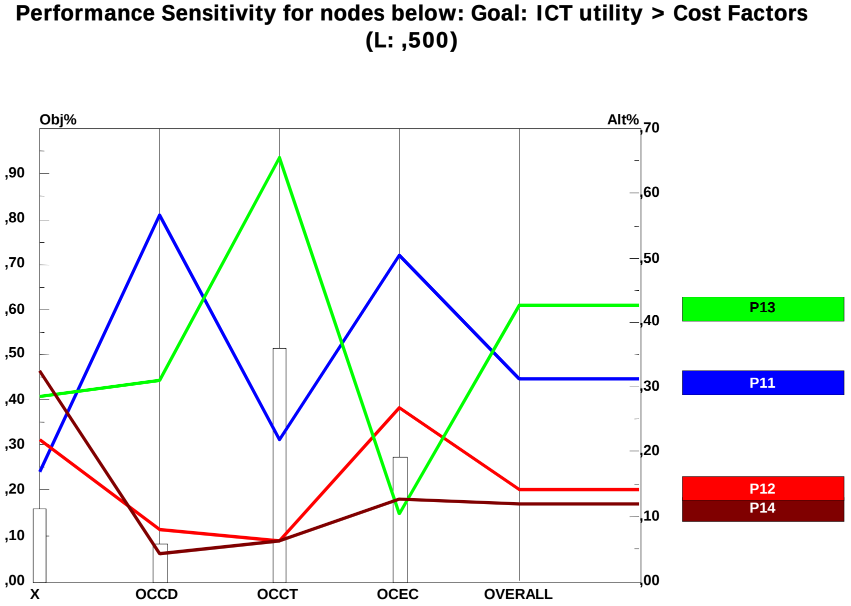
Performance Sensitivity for nodes below: Goal: ICT utility > Cost Factors (L: ,500)

Fig. 7. Sensitivity analysis for cost factors analytically