Real Options in Telecom Infrastructure Projects - A Tutorial

Mathieu Tahon, Sofie Verbrugge, Peter J. Willis, Paul Botham, Didier Colle, Mario Pickavet, Piet Demeester, *IEEE Fellow*

***Abstract*—The rapid technological change and uncertain future evolutions have a large impact on investment projects in the telecommunication sector. When new infrastructure networks are rolled out, the initial assumptions can prove to be untrue in the future, severely impacting the payoff. It is therefore extremely important that projects offer flexibility to allow the management to react to unforeseen changes. Management must, for example, be able to decide to speed up the project, slow it down, or even completely abandon it. However, the standard method used to evaluate investment projects, the Net Present Value analysis, is unable to capture the value of these different flexibility options. The Real Option concept, derived from financial literature, was proposed as a solution and implements this flexibility in the standard calculations. However, the Real Option Theory is only slowly getting accepted within the telecommunication sector. In this paper, we introduce the basics of real options theory and provide a practical methodology to apply real options to realistic telecom business cases. In addition, we will indicate why the characteristics of this sector make it very well suited to apply real options to investment projects. The rollout of fixed next generation access networks offers a broad range of growth options to the operator, e.g. additional network upgrades or the introduction of new services. Using real options allows one to compare the flexibility value of all these options.**

***Index Terms*—Flexibility, Next generation access networks, Real options, Techno-economics**

I. Why telecom requires an extended economic evaluation approach

In the last decennia, the telecommunication industry has shown rapid growth in technology, products and services, and this evolution is still ongoing. For example, the rollout of fixed and wireless Next Generation Access Networks (NGAN) like Fibre to the Home (FttH) and Long Term Evolution (LTE) is currently drawing a lot of attention from operators, vendors and regulators. However, deployment of these NGANs is not yet observed or it is happening slower than expected due to the risk associated with upfront investments. Another issue for new technologies is the uncertainty linked with them. Doubts about customer adoption, costs and technology performance are only a few of the uncertain factors.

However, it is untrue that this risk and uncertainty within the telecom sector cannot be managed. Managerial flexibility allows the different actors in the market to respond to unforeseen effects during the project lifetime. Acquiring a 4G license is a straightforward example as it offers the flexibility to decide when and where to roll out the mobile network. The 4G mobile operator can start with a study period, testing the new technology in small areas. When the uptake of 4G services proves to be exceeding initial expectations, extra investments can be made to speed up the rollout of the nationwide network. On the other hand, when a telecom project proves to be unprofitable, the management can decide to abandon it completely. For example, only one year after its launch, British Telecom decided to stop its mobile broadcast TV service in 2007.

All investment problems are economically assessed before they are started. In general, this analysis consists of predicting the future costs and revenues of the investment project, discounting them with an appropriate discount factor and then adding them to come to the Net Present Value (NPV) [1]. When this NPV is positive, the project is assessed as profitable. This approach is typically followed by network planners. However, conducting such a standard NPV analysis can yield unintuitive results. Network solutions that are thought of as more flexible or less risky turn out to be less economically interesting according to the NPV analysis. A wireless access network design that can be expanded or contracted for lower cost is more flexible in handling uncertain future customer demand, but is typically more expensive in initial deployment.

Thus, the question arises how the impact of uncertainty, risk and flexibility can be implemented in the standard feasibility analysis of the project. In the standard NPV analysis, two drawbacks can be identified. First, the standard method does not indicate the impact of uncertainty on the analysis. Two extensions covering this impact exist, scenario analysis and sensitivity analysis. In a scenario analysis, the investment project is assessed in a small number of possible scenarios. While NPV analysis offers only one view on the future, scenario analysis compares several alternative futures. For instance, an application provider could compare a scenario of low, normal and high customer uptake. A scenario analysis approach can also consist of comparing different investment projects to assess them based on economic feasibility. Scenario analysis has been applied to different cases in telecommunication research [2], [3].

A second extension is the sensitivity analysis [4]. While a scenario analysis only studies a few possible scenarios, this method analyses the impact of uncertainty in the input factors on the output of the analysis. In a scenario analysis, the input values only take some discrete scenario-dependent values, like low and high market potential. In the sensitivity analysis, this

Manuscript received June 22, 2012.

M. Tahon, S. Verbrugge, D. Colle, M. Pickavet and P. Demeester are with the Internet Based Communication Networks and Services group of the Ghent University, (mathieu.tahon@intec.ugent.be, phone: +32 9 33 14891, fax: +32 9 33 14899

P. J. Willis and P. Botham are with British Telecom, Ipswich, UK.

input is extended with a statistical uncertainty distribution. It allows one to systematically change variables in the model to determine the effects on the final result. In techno-economic research within telecoms, the sensitivity analysis has been used in different papers [3], [5], [6].

The second drawback of the NPV method is the lack of flexibility [7], [8]. The project is seen as a now or never decision, with no possibilities for the decision makers to alter the project during its lifetime. In a realistic business model, this condition is not fulfilled.

While the previous two extensions have been proposed to capture the value of uncertainty, only Real Option (RO) Theory captures the value of managerial flexibility in practical cases. In addition, the concepts offered by this theory make it also of great value for non-financial specialists, as it helps to identify and catalogue intuitive notions of flexible design.

Different frameworks on how to apply real option theory have already been proposed, with [8], [9] both offering a practical approach to real options. We will show why investment projects within the telecommunication sector are well suited for a real option analysis. The different examples given in this introduction already indicate how suited the telecom sector is for applying real options. Since NGAN rollout is drawing a lot of attention from network operators, we developed a realistic business case for the upgrade of the current copper access network towards Fibre to the Cabinet (FttC) and Fibre to the Premises (FttP) in the UK. The standard business case was extended with a broad range of options found in the literature.

In the following section, we will introduce the theoretical background and categorization of real options. An overview of the application domains of real options in the telecommunication sector is given in Section III. Next, Section IV elaborates on a practical Real Option Analysis methodology to evaluate the flexibility value in realistic cases. Next, we will introduce the example case study, namely the upgrade of the current copper access network towards FttC and FttP. In Section V, the value of extending a standard techno-economic evaluation with an RO analysis is demonstrated using the case study proposed above. Finally, Section VI summarizes the most important advantages of an RO analysis, together with some more detailed conclusions drawn from the case study.

II. Background on Real Options

A. Real option basics

For telecom projects, the feasibility of new project proposals is assessed through a techno-economic analysis. Verbrugge et al. [10] propose a clear and practical methodology to conduct such an analysis. It consists of four steps, covering input collection, cost and revenue modelling over the business case analysis to its different extensions. The third step of their methodology consists of a standard business case analysis, the NPV analysis. We refer to their work for an in-depth description of techno-economic modelling. However, we already indicated the flexibility shortcoming of this tool in the introduction.

To implement the value of this flexibility, the real option concept was derived from financial literature. An excellent definition of real options is given in [11]. "Real options is a systematic approach and integrated solution using financial theory, economic analysis, management science, decisions sciences, statistics and econometric modelling in applying options theory in valuing real physical assets as opposed to financial assets, in a dynamic and uncertain business environment where decisions are flexible in the context of strategic capital investment decision-making, valuing investment opportunities and project capital expenditures." As this definition states, the real option theory is based on the option concept as used in financial markets. A financial option is defined as the right to buy or sell an asset for a predefined price during or at the end of an agreed period. When the option can only be exercised at the end of the period, it is a European option. In the other case it is an American option. Hybrid options also exist; the option can be exercised on several dates during the agreed period. These are categorized as Bermuda options. Next to a differentiation between options based on the time they can be exercised, they can also be divided into call and put options. While a call option is the right to buy, a put option refers to the right to sell an asset. Other additional terminology from option theory is the option price and strike price. The first is also known as the option premium, or the price to acquire the option. The latter refers to the price to exercise the option. Options on options also exist and are called compound options.

During the time period before the exercise price, an option can be in, at or out of the money. Assume an American call option, the right to buy a stock for a predetermined price X. In addition, consider that currently the value of the stock is S. When $S < X$, the option is out of the money and it is useless to execute the option today, since it is more interesting to buy the stock on the market. However, this does not mean the option has no value. As long as the option is not expired, the underlying asset can go up in value. This probability of $S > X$, or the option being in the money, on the final exercise date of the option, results in a value for the option. Obviously, the longer before the exercise date, the higher the probability the option will be in the money on this date. As such, the value of an option increases with the time left to the final exercise date. At this date, either $S < X$, and the option will expire, having zero value or, when $S > X$, the option will be exercised with a value of $S - X$. In summary, the value of an option on exercise date equals $MAX(0,S - X)$.

Transferring the financial option concept towards business investment decisions is quite straightforward. For an introduction to the foundations of real option theory, we refer to [8], [9], [12], [13].

Making an initial investment typically results in future flexibility during the entire investment lifetime. RO analysis implements this flexibility in the previous static NPV calculation. For example, the initial static NPV analysis showed the rollout of an LTE network to be profitable under certain uptake assumptions. This may no longer be the case after a few years. The static NPV analysis does not allow any flexibility here but a RO analysis offers the possibility to abandon the project and sell the license. Conducting the RO analysis calculation will result in the value of this option.

B. Real option categories

Different examples of real options were already introduced in the previous sections. In general, these examples can be subdivided into three distinct categories, namely growth, shrink and learning options. The category of growth options are related to possible follow up investments during a later stage in the project. When telecom projects are concerned, examples of growth options are the expansion of the network to adjacent regions, a technology upgrade from ADSL to VDSL2, or even an extension of the product portfolio from double play to triple play. The shrink option category consists of the opposite type of options. When the initial assumptions overestimated the consumer adoption or technology evolution makes some products redundant, management has a disinvestment option. A project can be completely abandoned, like the mobile TV broadcasting service from BT. Regarding the telephony market, the ISDN product was withdrawn when it had no more potential. Learning options are a specific type of options, where investments are postponed until extra information or experience is gained. Conducting market studies or rigorous testing of a new technology before its implementation are only two examples.

The most well-known real options categorisation is the 7S framework by Copeland and Keenan [7]. The different real options categories are summarized in Fig. 1 and some typical telecom examples are added. The different categories are described in the following paragraphs.

1) Scale up and down options: The scale of the project can be expanded or reduced. A scale down option indicates that the scale of the project is reducible. During the rollout phase, opting for a slower rollout is a form of scale down option. The ultimate form of scale down consists of abandoning the project. In this case, revenues are gained from selling the infrastructure. Under positive circumstances, the scale up option becomes more attractive. Rollout can be sped up, or the zone can be expanded to neighbouring regions.

In literature, most of these options are applied in the telecommunication industry. Infrastructure rollout of both wired and wireless networks and the related investment costs are one of the major topics. The scale of such projects covers large areas and both rollout area and speed can be changed to optimize investment return. Abandoning the project due to unsatisfactory results is a special case of a scale down option, where the rollout speed is reduced to zero. One must take into account that abandoning a project results in exceptional revenues from the sale of the assets. After acquiring a 3G licence, management can abandon the rollout of the 3G network in worst case scenarios and put the licence up for sale.

2) Study or start options: Another important option for telecom related projects is the study/start option. When a new technology enters the market, several parameters remain uncertain. The first one is the uncertainty linked with the technology itself. Is it efficient enough to handle high bitrates over long distances? What is the mean time between failure of the different components? Rigorous testing of the technology, field tests and trials can offer more insight into the technological performance and after the testing period, management has the option whether or not to go with the new technology. For example, in Belgium Telenet decided to wait with the nationwide rollout of LTE and started testing it on a small site.

Next to technological uncertainty, adoption of the new product is also a problematic parameter. Before introducing a new product, management can only make an educated guess about the market potential and adoption speed. A wait and see strategy can therefore be interesting. During this period, customer surveys can offer extra insight into the market. For example, in the wireless broadband market, only 0.40% of the world population uses mobile broadband, but this is region dependent [14]. Instead of hitting the national market with mobile broadband offers, an operator could use a wait and see strategy and perform customer surveys to gain better insight into the customer demands.

The last uncertain parameter that can offer study/start possibilities is the regulatory evolution. In the Fibre to the Home (FttH) debate, uncertainty about the future regulatory actions taken by the European Commission in the local loop access postpones the rollout of fibre networks in Europe.

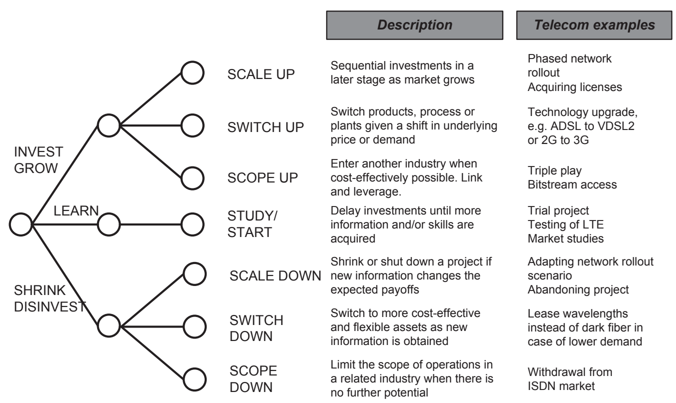

Fig. 1. Overview of the 7S framework [7] and telecom examples

3) Switch up and down options: Next to the scale of the project, several other parameters also render flexibility. In a production environment, managers can choose to upgrade machine technology during the project, e.g. to produce better quality products. Changing technology can prove useful during the project lifetime, but results in an extra cost at the start of the project. So it is important to make the trade-off between the flexibility value and the initial cost of this flexibility. Switching from ADSL to VDSL is an example of a switch up option in fixed access markets. The consumers are offered higher speeds, but this requires an investment by the operators. Fibre needs to be brought closer to the customer, so large deployment investments are typically required.

4) Scope up and down options: The last possible option is the scope up or down option. While a scale option changes the geographical region and the switch option allows flexibility in the technology, the scope option focuses on the flexibility of the product portfolio. Management can choose to offer extra products to the customers, or reduce their offer. The move towards triple play is an example of operators lifting their scope up options.

C. Application domains of real options

Real options have been applied to a wide range of investment projects from mine valuation to initial public offer valuation [9]. Some more telecom related examples are described below. A literature review of real option application to telecom examples can be found in Table I.

Most of the existing literature applies real options to telecom infrastructure rollout [9], [15], [16], [17], [18], [19]. This rollout is related to a large investment covering several years and thus allows for flexibility in the rollout path. The scale of such projects covers large areas, and both the rollout area and speed can be changed during the project to optimize the return on investment. Abandoning the project due to unsatisfactory results is a special case of a real option. A quantitative and simplified example to illustrate real options is the M-commerce project, describing an investment by a telecommunications firm [9]. This is a typical example of a scale up and scale down option. During the project, management has two options, either expanding the project scale by 60% if expectations are exceeded, or abandoning the project completely and reaping the salvage value. Another paper describing scale options in telecom networks is [15]. The feasibility of Mobile WiMAX as an alternative for fixed DSL and HFC networks is analysed, with the possibility of extending the scale of the project. Several rollout scenarios are studied, changing the rollout location from nationwide to only in urban areas and with the option to change rollout speed.

Study/start options have also been applied extensively to telecom network problems. In [16], the rollout of a WiMAX network in Eindhoven is studied. Before starting the complete rollout, the operator has the choice to do a field trial to analyse the technological performance. In the second phase, based on the results from the trial phase, the operator can decide to invest or abandon the project.

Licences for wireless networks are known to be very expensive, so it is important to correctly evaluate the licence investment. For example, in the UK, 35 billion dollars was paid for the 3G licences. In [20], the authors try to estimate the value of these licences based on a real option approach. Buying the 3G licence resulted in acquiring a strong market position and a broad range of options, including scale up, switch up and down and temporarily halting the project. This research showed that with the correct valuation techniques, the value of the 3G licence was close to the price paid for the acquisition. Spectrum management is closely linked with telecom licenses. Dynamic spectrum management, with a two stage assignment through the use of options was proposed in [21]. The option concept allowed calculating the penalty value and the overbooking ratio.

A lot of research has been performed on the impact of regulation on investment decisions by network operators. Regulatory bodies imposed local loop unbundling (LLU) on the incumbent operators to improve competition. For new entrants, LLU has the advantage that they do not have to make large investments in network infrastructure before they can offer network services. However, fixing the price for network access is not straightforward. One should take into account that new entrants should also pay for the financial risk of the incumbent since he did invest in the network infrastructure. LLU in fact offers a study/start option to new entrants, while the incumbent gave up his option when he invested. In [22], this problem has been discussed in more detail. Next to large infrastructure investment cases, real option valuation theory has also been applied to service oriented cases, e.g. [23] applied real options to the case of the Belgian rail operator offering internet services on board.

TABLE I
REAL OPTIONS IN THE TELECOM LITERATURE

Option	Flexibility	Reference	Uncertainty
Scale up/down	Rollout area	[9], [15], [17], [18], [19]	Adoption, Costs, Tariffs
	Speed up/slow down rollout	[15], [19]	Adoption, Costs, Tariffs
	Abandon project	[9], [22]	Adoption, Costs, Tariffs
	Switch up/down Technology	[17]	Firm value, Adoption, Costs, Regulation
Scope up/down	Offering bit stream access		
Study/start	Trial project	[16]	Technology, Performance, Market
	Wait and see	[16], [17], [18]	Technology, Regulation

III. METHODOLOGY

In this section, the methodology commonly used to perform real option analyses is discussed [8], [9]. However, before the RO analysis can be conducted, the business case must be assessed on three conditions. First, there needs to be uncertainty in the project. During the standard NPV evaluation, some assumptions influencing the future costs and revenues have been made. However, some of these assumptions come with a certain degree of uncertainty. Future customer uptake, the future price of raw materials and components can only be estimated. When this is the case, the project meets the first condition. Secondly, the project should offer some kind of flexibility. This flexibility can easily be recognized if one of the options in the 7S framework is present in the case. Such flexibility allows the decision maker to counter the uncertainty. The last condition concerns the timing aspect. A real option analysis can only be performed if the investment decision covers a two (or more) phased project. An initial decision is made at the start of the project, but extra decisions can be made during later stages of the project. For example, an operator can, after completion of the first part of the network, still decide in later stages what his next steps will be. Will he do nothing or extend the network to other regions? After the case has been assessed, based on these three conditions, a clear methodology needs to be followed to perform the RO analysis. In this paper, we use the methodology proposed in [10], which is based on [8], [9]. While a standard techno-economic analysis results in an NPV analysis, the RO analysis methodology extends

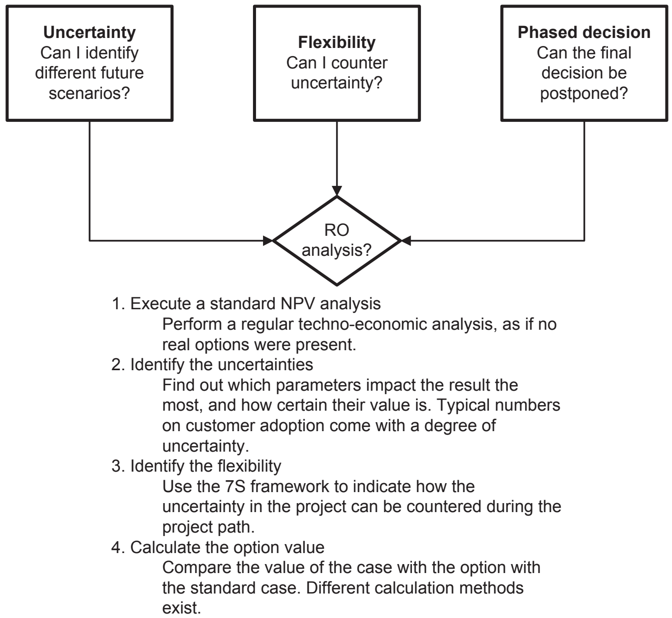

Fig. 2. Conditions and methodology to perform a real options analysis

the techno-economic methodology with three extra steps. The RO analysis thus consists of four steps. First, a standard NPV analysis is conducted. It is clear that the second and third steps of the methodology are closely linked with the preconditions. In essence, the second step comes down to identifying the uncertain input parameters of the project influencing the result. The third step links back to the second and third condition listed above and consists of identifying the options. When the management has no options to act against the changing parameters, performing a real option analysis is pointless. To identify the different options present in the studied case, the 7S framework can be used. The conditions and methodology are summarized in Fig. 2. Before indicating how the different steps work in practice by elaborating a simple toy example, more detail is given on the standard NPV analysis and the different calculation techniques for real options.

A. Basics of the NPV analysis

The goal of an NPV analysis is to indicate the viability of an investment project. The question an NPV analysis answers is the following: "Is the investment creating value for the company and the shareholders?" An investment is basically an expense done today, aimed at generating income later. Obviously, this future income should be larger than the initial expense and generate a required surplus return.

In order to conduct the investment analysis, one should determine the cash flows generated through the investment period. This period equals the economic lifetime of the project, the time after which the investment no longer generates cash flows. It is clear that only cash flows directly linked to the project should be taken into account. While this is a simple principle, it typically is the most difficult phase in valuing the investment project. The following basic rules help to determine the cash flows in any investment project.

- Only incoming and outgoing cash is to be taken into account. It is important to notice that there exists a difference between cost and revenue on one side and income and expense on the other. The yearly depreciation of an asset is a cost, but no expense. As this is no cash flow, it should not be included.
- Cash flows which are independent of the project should not be taken into account. Only the incremental or marginal cash flows related to the project are to be included.
- Cash flows are independent of the financing of the project. As a result, interest payments or dividends are excluded. The cost of financing is included in the required rate of return of the project.
- Tax cash flows are to be included, since the expenses and income influence the taxable profit.

Once the cash flows during the investment period have been determined, the calculation of the NPV is straightforward. As the name says, it returns the present value of the future cash flows based on a given minimum return. This return is based on the return requirements for both shareholders and interest payments for loans. More information on determining r can be found in [1]. The formula for the NPV calculation is given below. All cash flows (CF) of the project are discounted with the minimum return r and summed up.

$$NPV = \sum_{i=0}^{n} \frac{CF_i}{(1+r)^i} \tag{1}$$

The NPV indicates the value the investment creates, since it reflects the total value of the future cash flows, taking into account the required return. When the NPV is larger than zero, the investment returns, in addition to the initial investment and the required return, an extra value equal to the NPV.

B. Real option valuation techniques

As was already introduced above, a real option analysis always starts from the standard NPV, which is currently used by network planners. In fact, the standard Discounted CF approach is a special case of the real option analysis, evaluating the project as if no flexibility is present. It is therefore vital to start any RO analysis with a correct standard NPV valuation. The total value of a project is expressed by the following formula.

$$Project\ value = NPV + Option\ value \tag{2}$$

Three different solution methods have been proposed to calculate the value of real options in investment projects. We will give a short description of each of them in the following sections.

1) Black and Scholes model: Since real options are derived from financial options, it is logical that the calculation methods for financial options were transferred to real option valuation. The mathematical Black and Scholes model is one of the most used option valuation models in the financial sector [24]. It was developed in 1973 to evaluate the value of a European option. This indicates the first underlying assumption of the model, namely the option can only be exercised at the end of the time period. Most of the parameters of the mathematical model are straightforward but others cannot be directly transferred to investment projects. Calculating the static NPV refers to the first step of the proposed methodology. Parameters like the exercise price and lifetime can also be directly linked to the investment problem. The exercise price of the option for an investment project is the income from exercising the option, and can again simply be calculated using the standard NPV analysis. The lifetime equals the time period (in years) during which the company has the opportunity to execute in the option. For the risk free interest rate, the return on assets that are considered risk free is typically used. Examples of such assets are German or US government bonds. However, the parameter posing most problems is the project uncertainty (σ), expressed in percentage terms. For financial assets, this is linked with the volatility of the underlying asset, e.g. stock or oil prices. As these options, or the underlying assets are traded on financial markets, it is easy to calculate this volatility. For real options, where this market is absent, this calculation cannot be made and should be estimated. Estimating this value for an investment project is not that straightforward. What is for example the project uncertainty of a wireless license purchase and the investment in base stations? Another assumption of the Black and Scholes model is that the logarithm of the NPV follows a Brownian motion. Again, for stocks this is a reasonable assumption, but not for investment projects. These drawbacks make this calculation method less suited for realistic business cases. As a result, the Black and Scholes model outcome overestimates the value of the real option.

In addition, there is an important difference between financial and real options, which results in Black and Scholes being less accurate for real option valuation. Financial options are by definition independent of each other. Exercising a call or put option has no influence on the value of other options, or on the value of the underlying asset. Real options typically do interact. In a simple example, a company has a scale up option to expand a factory and a scale down option where the factory is sold. When executing the scale down option, the scale up option loses its value. As Black and Scholes calculates the value of an option portfolio as the sum of the values of the independent options, this cannot be translated to a real option portfolio. These drawbacks make the Black and Scholes formula less suited for real option valuation.

$$Option\ value = S \cdot N(d_i) - X \cdot e^{-r_f t} \cdot N(d_2) \quad (3)$$

With:

$d_1 = \dfrac{\ln \frac{S}{X} + (r_f + \frac{\sigma^2}{2})t}{\sigma\sqrt{t}}$

$d_2 = d_1 - \sigma\sqrt{t}$

$S =$ future cash flows

$X =$ exercise price

$t =$ option lifetime

$\sigma =$ project uncertainty

$r_f =$ risk free interest rate

$N =$ cumulative normal distribution

The Black and Scholes formula to calculate the value of a call option through is shown above. When having a closer look at the two terms of the equation, the two important parts of the Black and Scholes model can be observed. The first term returns the expected benefit of doing the investment right away, while the second term reflects the value of paying the exercise price on the expiration date, weighted by the probability of exercising the option. The formula also indicates the impact of time on the option value. Increasing t will result in a higher d_1 and a smaller d_2, resulting in a higher option value.

In order to calculate the value of a put option through Black and Scholes, the concept of call-put parity for European options can be used. This parity states that the sum of the value of a call option and the present value (PV) of the strike price equals the sum of the value of a put option and the current value of the underlying asset. For more background on financial option valuation information, we refer to [1].

$$C + PV(X) = P + S \quad (4)$$

Application of Black and Scholes to real option valuation

In this simplified illustrative example, the Black and Scholes formula will be applied to the valuation of a put option. A telecom operator bought a license for €3.1 million, valid for 5 years. The expected future cash flows during this period can be found in Table II. Conducting the NPV analysis with a required return of 10%, results in cumulative future expected cash flows of €2.975.339, insufficient to cover the initial expense, and thus a negative NPV of €-124.661. According to this analysis, the project would not be executed. However, the operator has the option to sell the license back after one year for €2 million. As stopping the project is a clear put option, both the Black and Scholes formula for a call option and the call-put parity will be applied here.

In the first step, the required parameters are calculated or estimated (Table III). Above, the expected future cash flows (S), the lifetime of the option (t) and the exercise price (X) were already given. In addition, the formula requires the risk-free interest rate (R_f) and the volatility of the underlying cash flows (σ^2). As already indicated, for R_f the return on risk free government bonds is typically used. However, the volatility of the expected cash flows is much harder to estimate. Here, a value of 50% is used. Choosing a high value indicates that the project is very risky and the prediction comes with a large degree of uncertainty. With these parameters, the Black and Scholes formula for a call option returns a value of €1.191.295.

Using the call-put parity, the value of the put option in this example can be calculated straightforwardly. The PV of the exercise price is €1.902.459, resulting in a put option value

TABLE II
YEARLY CASHFLOWS FROM LICENSE

year	Cash flow
Year 1	€582.000
Year 2	€687.000
Year 3	€821.000
Year 4	€929.000
Year 5	€1.010.000

TABLE III
BLACK AND SCHOLES INPUT PARAMETERS

Parameter	Value
S	€2.975.339
X	€2.000.000
t	1
σ	50 %
R_f	5%

of €260.067. The total value of the project now equals the sum of the NPV and the option value, €135.406.

It is important to notice that the estimation of the project uncertainty has a major impact on the option value. If the future cash flows are assessed as less uncertain, and the operator uses a volatility of 25%, the option value drops to €118.415. With this option value, the total project remains value destroying.

The effect from timing on the option value was already indicated above. The longer the time before expiration, the higher the probability of the option becoming in the money. In this example, if the operator can wait two years instead of one before he has to make the decision to abandon or continue the project, the put option value rises to €432.787.

2) Binomial tree model: The binomial tree model is a discrete time model. A binomial tree model is applicable to simple processes. The main assumption is that the uncertain input can only take discrete values. This allows modelling the problem by a tree structure. The main assumption results in both the greatest advantage and disadvantage of the model. An uncertain parameter only taking discrete values largely simplifies the analysis, but realistic cases are generally subject to continuous uncertainty. Detailed examples using the binomial tree method can be found in [9]. The toy example used to indicate the methodology below is an application of the binomial tree model method.

3) Monte Carlo simulation: The Monte Carlo simulation is the last calculation method we will discuss. While the two previous models allow for a simple option value calculation, they both have their own drawbacks. Their underlying assumptions do not always match reality. A Monte Carlo simulation solves these problems but results in a more complicated calculation method. Sawilowsky defines the Monte Carlo simulation as a repeated sampling to determine the properties of a phenomenon [25].

To perform a Monte Carlo analysis, spreadsheet based solutions exist. In general, these consist of extending a standard NPV analysis with the existing options. Since an option comes down to maximizing payoff, this is quite straightforward. After indicating all uncertain input parameters with an appropriate probability distribution, the Monte Carlo simulation can be conducted. Choosing these probability distributions for the input parameters is the most delicate task in the Monte Carlo simulation. For every simulation, the input parameter is randomly sampled from the defined probability distribution and the best project path is selected. The NPV is calculated for thousands to hundreds of thousands of possible combinations of input parameters within the predefined distribution boundaries. As indicated, the model automatically selects the best option in each scenario. The result from a Monte Carlo analysis is a probability distribution of the expected payoff. From this distribution, an extended NPV can be derived, together with the option value for the studied case. This extended NPV is the average of the probability distribution, while the option value is the additional value of this average compared to the standard NPV. Additional information that can be drawn from such a probability distribution is the impact of the option on the risk associated with the project. Typically, an option decreases the probability of a low payoff, and increases the probability of more positive result. Existing software solutions exist that allows extending an existing spreadsheet techno-economic analysis with specific uncertainties and conduct the Monte Carlo analysis [26]. More information on Monte Carlo basics can be found in [27].

TABLE IV
COMPARISON OF VALUATION METHODS

Technique	Pro	Con
Black and Scholes	Simple to use Spreadsheet calculation	Parameter estimation (volatility!) Option portfolio valuation
Binomial tree	Discrete choices Spreadsheet calculation Intuitive	No continuous uncertainty What about additional uncertain parameters?
Monte Carlo	Realism Based on typical spreadsheet model Option portfolio valuation Intuitive results	Requires advanced software Estimating uncertainty

4) Comparison of the valuation methods: The three valuation methods introduced above each have their advantages and disadvantages. The most important are listed in Table IV.

C. The methodology in practice: a simple example

Before moving to a realistic application of RO analysis, the methodology is applied to a toy example, to allow the reader to become familiar with the different concepts. By following the four-step methodology, the toy example will indicate how uncertainty and flexibility can be identified, categorized and quantified. The following investment project is considered. An entrepreneur has to decide today if he starts an online business or not, but due to uncertain market perspectives, he does not know exactly how many customers will be willing to buy his product online. The entrepreneur believes the probabilities of a small or large market equal 50%. To host all his client data our entrepreneur has the opportunity to keep his current slow server or buy a fast server. Notice that in this short case description, two of the three different conditions to perform a RO analysis are present. We will discuss all conditions in more detail.

- *Uncertainty*
  The entrepreneur is not sure about his customer potential and the revenues related to these customers. He estimates that there is a 50% chance of high sales and a 50% chance of low sales.
- *Flexibility*
  The entrepreneur has two choices. Either he buys a new server for €60, or he keeps his current slow one.
- *Phased process*
  Looking at this case, we do not see two phases in the investment process. However, nothing forces our entrepreneur to decide today if he buys the new server. He can decide today to start with the online business and only invest in a faster server next year.

The results of the first step of the methodology, the standard NPV analysis, are presented in Fig. 3. Where the entrepreneur installs the new server, his payoff is the weighted average of €40 and €340, or €190. The additional cost for the server was already subtracted from the expected revenues. In the other case he will only gain €100. The standard NPV analysis thus indicates that the entrepreneur should buy the fast server today, since this maximizes his payoff. Notice that in order not to overcomplicate the toy example, the required return was set to zero.

The second step, identifying the uncertainties in the case, was performed when describing the three preconditions. The entrepreneur is uncertain about the customer uptake of his service and on the type of server to install. When checking the third condition, the entrepreneur has the flexibility to wait and postpone his investment decision until he has more information on the customer uptake. For the investment decision, he has the choice between keeping his slow server and switching to a faster one. The value of the real option can now be calculated.

We start by analyzing the different scenarios under the uncertainty. In case there is a low customer uptake, not investing in the new server has the best payoff. In case of high customer uptake, installing the fast server clearly returns the best result.

Now remember this project consists of two stages. When identifying the flexibility, we indicated that the entrepreneur had the option to postpone his server investment decision until he had gained extra information on the customer uptake. What is now the value of the option to wait? If he waits, he will be able to better assess the customer uptake on the day he makes the investment decision for the server. Waiting ensures the entrepreneur will make the best decision in the future. If he notices a low uptake he will keep his original server, in the other case he will buy the fast one (Fig. 4). In both the low and high uptake case, he chooses the scenario having the highest payoff. With the option to wait, our entrepreneur knows he has a 50% chance on a payoff of €340 and 50% chance on a payoff of €50, or a total value of the project of €195. It is now straightforward to get the option value from this analysis. Compared with the standard NPV case analysis, the RO analysis returns a RO Value which is €5 higher. This is exactly the value of the option to wait.

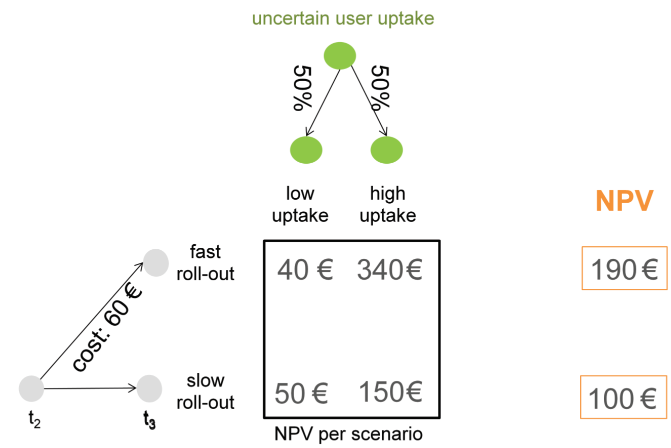

Fig. 3. A simple example - Step 1: NPV analysis.

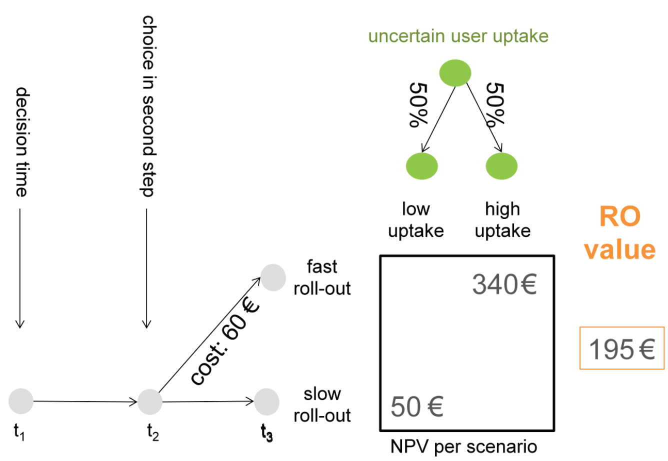

Fig. 4. Step 4: Value of the option to wait

IV. MIGRATION TO FIBRE: STANDARD BUSINESS CASE ANALYSIS

To indicate the power of real options on realistic business cases, the RO analysis technique will be applied to a telecom infrastructure network project. The studied case consists of the rollout of a fibre access network in the UK [28]. FttH networks are the final stage in the continuous upgrade of the copper access networks. However, many networks still require upgrading towards FttC networks. It is this infrastructure investment that is considered in this paper.

An incumbent currently possesses a nationwide copper access network, which has already been upgraded towards Fibre to the Central Office. This allows offering ADSL services to its customers. In order to offer higher access speeds to its end customers, the incumbent has decided to upgrade its network towards FttC, allowing it to offer VDSL services. Two important upgrades are necessary in the access network to migrate towards an FttC network. First, fibre has to be installed between the central offices and the street cabinets. Secondly, the cabinets need to be replaced and Digital Subscriber Line Access Multiplexers (DSLAMs) are required in these street cabinets. At the start of the project, the operator first has to decide on the cabinet size. The operator can decide to deploy cabinets which are large enough to host a connection for each household in the cabinet area. Or he can decide to deploy smaller (and cheaper) cabinets initially, only dimensioned for an estimated uptake percentage of 30%.

A. Technology overview

Before the business case is introduced in detail, a short introduction to FttC and FttH networks is given. Research concerning these technologies is still ongoing, with Wavelength Division Multiplexing - Passive Optical Network (WDM-PON) as one of the most recent technological evolution.

However, the focus in our case is clearly on the passive network infrastructure and its related costs and revenues. Since research has shown that most of the costs for the deployment of new networks are related to the initial installation and in particular the physical installation of the cables in the access network, we will focus on the topology design of FttC and FttH networks [29].

The fixed telecom access network (both for FttC and FttH) can be represented by a tree structure, with the local exchange as the source node. From this local exchange, cables towards the street cabinets depart. At each street cabinet, there are again cables running towards distribution points (DPs) and finally to single households. For FttC, VDSL cabinets are installed on the current cabinet locations, together with the necessary fibre and ducts. For a local exchange, line cards towards the cabinets and towards the core are dimensioned, together with an optical distribution frame (ODF). In the cabinets DSLAM line cards will be installed. When more customers connect, extra equipment is only installed when necessary, in order to follow operational practices. For FttH, passive splitters are installed at the same location as the FttC cabinets and at the distribution points. Comparable to the FttC network, the equipment in the central office and the Customer Premises Equipment (CPE) are only provisioned when required.

B. Basic business case: migration to FttC

As already discussed, the studied case is the migration of the current copper access network towards an FttC network. The standard techno-economic analysis will follow the methodology proposed in [10]. For the London area, a representative exchange is modelled, taking into account average line length, number of cabinets, drop points and the amount of lines per exchange. As indicated, the operator can choose to install large cabinets, offering VDSL access for all customers in the cabinet area, or small cabinets, only dimensioned to provide access for a percentage of the households. Based on the customer adoption, it will be possible to calculate the necessary amounts of equipment in the local exchange and for each cabinet separately.

1) Service adoption modelling: Modelling the adoption of the offered services is an important aspect of the standard business case analysis. While several mathematical models have been proposed to estimate the adoption of services and technologies, [30] has indicated the Gompertz adoption curve as the most appropriate approach to model the adoption of telecom business cases as a function of time. Three parameters need to be estimated in the mathematical formula, inflection point (a), slope (b) and market size (m). The inflection point in a Gompertz curve is at 37%, and indicates the time at which curve shifts from convex to concave. The higher a, the more stretched the adoption curve is. Slope indicates the pace of adoption. The higher b, the faster adoption will occur, with b [0,+]. For telecom cases, values of 4 (a) and 0.3 (b) have been found realistic [29]. The market potential parameter of 20% used in the case is based on industry insight [31].

$$S(t) = m \cdot e^{-e^{-b(t-a)}} [32] \tag{5}$$

2) Network dimensioning: For the rollout of an FttC network, fibre needs to be deployed from the local exchange towards the cabinets. Each cabinet has a unique fibre section and a shared section with the other cabinets. Based on the duct length, fibre cable cost and installation cost per meter, the initial deployment cost can be calculated. The specific cost parameters can be found in [33]. From the customer adoption, the necessary amounts of equipment in the local exchange and for each cabinet can be derived.

3) Modelling costs and revenues: A detailed cost and revenue model is built to conduct the economic analysis of the small and large cabinet scenario. The costs are divided into Capital Expenditures (CapEx) and Operational Expenditures (OpEx). The revenues are based on the adoption model described above. It is important to incorporate both costs and revenues in the techno-economic analysis. When rolling out a fibre network, previous research already focussed on a minimum-cost design [34], but it is important to link the design to the expected revenues, as has been shown in [35].

a) Capital expenditures: CapEx are expenditures creating future benefits and are incurred when the company spends money to buy fixed assets or upgrade existing fixed assets. According to this definition, CapEx costs were subdivided into cable and duct, local exchange, cabinet and CPE costs.

In the rollout of FttC or FttH networks, cable and duct costs are generally the largest expense [29]. To dimension the initial installation, assumptions on the uptake were made. Ducts are installed to host the fibre cables and it is estimated that 80% of the existing ducts can be reused. The installation cost for cables depends on the installation location, with a buried installation being the most expensive (100 GBP/m) and aerial installation the cheapest (15 GBP/m). Footpath and grass installation have a cost between these two extremes. The installation locations were taken from [33]. The dimensioning of the fibre cables depends on the rollout scenario chosen by the operator. For the small cabinet scenario, the operator estimates that migrating 30% of the lines to FttC will suffice. As uptake is only expected to be 20%, these would suffice. For the large cabinet scenario, 60% of the lines are migrated,

TABLE V
COST OF THE DIFFERENT HARDWARE COMPONENTS [33]

Hardware component	Cost (GBP)
Street Cabinet	
Small	1250
Large	1375
ODF (1440 subscribers)	935
GigE card (24 DSLAMs)	3500
Chassis (16 cards)	6000
DSLAM	
Cost per port in small cabinet	60
Cost per port in large cabinet	120
CPE	200
Installation cost CPE	100

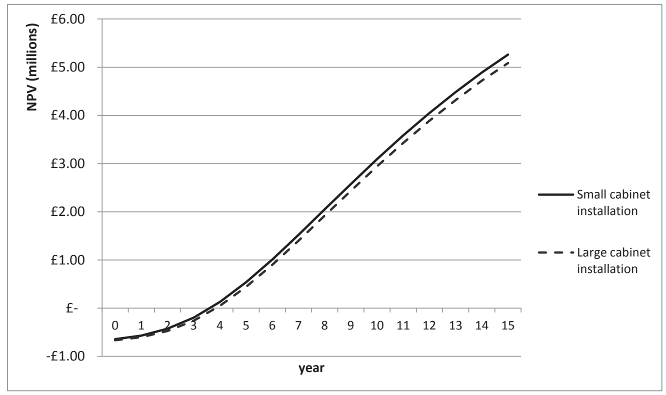

Fig. 5. NPV results for both installation scenarios for different geotypes

since this is the upper level of expected uptake.

To offer VDSL service to customers, the operator needs to install equipment in the local exchange and street cabinet. In the local exchange, an ODF is provisioned, together with a chassis to host the GigE cards towards the cabinet and the core network. One GigE card has 24 ports, with each port capable of hosting one connection towards a DSLAM line card in a street cabinet. These DSLAM line cards can in turn host 32 connections to separate households. For the initial installation, street cabinets are installed, together with one DSLAM line card to host the first connections. When customer adoption takes off, additional cards are installed when necessary.

CapEx at the customer side comprises both hardware cost for the CPE and initial installation cost. These are also only installed when necessary. An overview of the cost figures, based on industry insight, can be found in Table V.

b) Operational expenditures: Operational expenditures are recurring and on-going costs to keep the business running. Generally, expenses like sales and administration and research and development are categorised as OpEx. In this model we have chosen a fractional approach to quantify OpEx. A more detailed quantification for OpEx is possible and has been conducted in several publications [36], [37] but the fractional approach was chosen so as not to overcomplicate the analysis. The two OpEx categories that were identified are electronic equipment and other operations. OpEx for electronics is estimated as a 10 percent fraction of the total CapEx for the electronic equipment, like DSLAM line cards and CPEs. For the non-electronic fixed assets, a yearly one percent fraction is taken into account as OpEx.

c) Revenues: Revenues in this model are based on the adoption assumptions from above. For each cabinet the adoption curve is modelled and the yearly number of customers is estimated. The yearly average revenue per user (ARPU) is estimated at 500GBP.

4) Business case evaluation: standard NPV analysis: The input parameters from the previous paragraphs suffice to build the business model for the FttC infrastructure rollout. Based on adoption percentages and the geotype input parameters, a network dimensioning model was built for both the small cabinet and the large cabinet scenario, calculating the required quantities of equipment in each year of the 15-year project. Other general input parameters were added, like cost erosion for optical and electronic equipment and a discount factor of 10%, which is a standard discount factor for technology projects. The cash flows for each year are calculated, discounted with the discount factor and summed up.

With an NPV over 5 million GBP (€5.3 million) for the London geotype, both choices prove to be highly profitable, but the small cabinet FttC rollout scenario turns out to be the best choice (Fig. 5). Due to the lower cost for the small cabinet and the incremental cost per customer connecting, the total NPV over the 15 year investment period is above the NPV of the large cabinet scenario. Since this difference is limited, the curves remain close together. The initial investment in cabinets results in a negative NPV in year 0, but when customers start connecting to the cabinets, the yearly cash flow from customer revenues improves the NPV over time. Between year 3 and 4, the NPV becomes positive. From this point on, the initial investment is paid back and the project starts generating value. Under the static assumptions, the small cabinet is dimensioned large enough to host all connections in the future, while it is cheaper than the large one. This concludes the standard NPV analysis. Management should choose to install small cabinets to offer VDSL services to its customers.

However, this conclusion is completely dependent on the initial assumptions concerning customer adoption, duct reuse, etc. In the next sections, we will question these input parameters and indicate how they impact the NPV analysis by conducting a scenario and sensitivity analysis. However, these evaluation methods do not allow us to calculate the value of managerial flexibility. Therefore, we extend the standard NPV analysis towards a RO analysis. The value of managerial flexibility will be implemented using the practical methodology introduced above.

V. INTRODUCING FLEXIBILITY - REAL OPTION ANALYSIS

After conducting the standard NPV analysis, it was concluded that the installation of small cabinets was the most profitable investment. However, it should be clear that basing the investment decision on the outcome at this point of the analysis could prove to be suboptimal. It was indicated that three extensions have been proposed to the NPV analysis, and each of them will be applied to the case. A scenario analysis will be conducted comparing the initial installation of small and large cabinets under different customer uptake scenarios. This scenario analysis will be extended with a sensitivity analysis to indicate the impact of uncertainty on the outcome and as such on the final decision made. Thirdly, we will indicate the different real options present in this case and show how they can be quantified using the methodology presented in the previous section. Indeed, when checking for the three conditions necessary to make a business case eligible to extend with a RO analysis, we find all three of them present. Firstly, there is undoubtedly a large degree of uncertainty present in this case. The revenues of the project are based on a mathematical model, where the chosen parameters are in the best case "guesstimates". Secondly, there is flexibility present in the choice of cabinet to install. Thirdly, the network operator is not obliged to stick with the small cabinets when they cannot host extra connections under larger customer adoption. This is where the timing condition can be found. On a later date in the project, the network operator can decide to expand the capacity or to start offering extra services.

This business case lends itself to a real option analysis, since all three conditions are met. Additionally, most option types from the 7S framework can be identified. Once a cabinet is full, a simple scale option exists in placing a second cabinet to host the extra connections. A switch option for full cabinets is the installation of an FttH solution for the extra customers. When a scope option is considered, installing extra equipment in the local exchange to upgrade your internet service portfolio towards IPTV and gaining extra revenues is possible. Since realistic business cases generally possess a wide variety of real options, we also introduce compound real options. It will also be shown how they influence the decision process in the standard case.

A. Impact of uncertainty on the final decision

The standard NPV analysis conducted identified the installation of small cabinets for the London geotype as the most profitable scenario. Step two of the RO analysis methodology requires identifying the uncertainties present in the case. As always in long term infrastructure projects, all input parameters are uncertain, especially in the long run. In order not to overcomplicate the analysis, we have chosen to select two major uncertainties, user adoption and duct reuse.

User adoption is typically the most uncertain factor in an economic analysis. Before the introduction of a new product or service, it is very hard to estimate how many consumers will buy it. On the other hand, it is a factor with a high impact on the final economic assessment [3]. Research into the adoption of new services and products has indicated that consumer adoption generally can be modelled using a bell curve, with the Rogers' bell curve as the most well-known for technology adoption [38]. These models have been translated to mathematical S-curve penetration models, from which we have chosen the Gompertz curve in this business case [32], [39], [40]. However, while these models ex-post show a good fit with the observed adoption, it is hard to estimate the different parameters ex-ante. This is especially true for the market potential, since this can typically only be quantified through market studies. Another difficulty with the adoption of the service for a larger area like London is that the average market potential estimated for the entire area might be correct, but large differences can exist between different subareas. For example, one cabinet could have an FttC uptake over 40%, while another cabinet only has a final uptake potential of 5%. A scenario analysis was conducted for the small and large cabinet scenario with changing market potential. The results can be found in Fig. 6. As long as the market potential stays below 30%, the small cabinets are clearly the correct rollout choice. Once a higher market potential is achieved, large cabinets result in a higher payoff. This is of course a logical conclusion, since for all uptakes below 30% the large cabinet is over dimensioned.

When we extend the scenario analysis towards a sensitivity analysis, a probability distribution on each cabinet potential uptake between 0 and 60 percent, with 20 percent as the most likely was added.

To check the impact of these parameters on the total outcome of the business case, a Monte Carlo analysis was conducted. Crystall Ball, a commercial tool, was used to perform the simulations. This tool allows one to indicate the different uncertainties in a spreadsheet. After selecting the cells to forecast, the tool runs a predefined number of simulations, resulting in a distribution of the value of the forecasted cells, based on the uncertainty distributions added to the assumption cells [25]. The small and large cabinet rollout scenarios are compared, now with uncertainty added on some input parameters. Before the rollout of the FttC network starts, the management has to decide which scenario it will choose. However, we would like to indicate that no options are implemented in the model yet, so once a small cabinet is full, no extra customers can be connected to this cabinet, resulting in a loss of potential revenues. While the previous static NPV analysis results in a fixed number, the sensitivity analysis returns two distributions to compare (Fig. 7). It is immediately clear that the best rollout option is the installation of large cabinets in all areas. On average, the large cabinet scenario outperforms the small cabinet scenario with over 260.000 GBP (+3.88%).

This sensitivity analysis clearly indicates the impact that uncertainty has on the decision process. However, a sensitivity analysis alone does not allow us to implement the flexibility in the project. The assumption that the operator will not act when the small cabinets are full does not hold in reality. In the following section, the different options are identified and the last two steps of the RO analysis methodology are conducted.

B. How managerial flexibility impacts the result - a real option analysis

It is straightforward that when a small cabinet is installed, the option to expand is available. This expansion option can be broken down into three different options from the 7S framework. When the first cabinet is full, the operator can decide to go for a standard scale up option by installing a

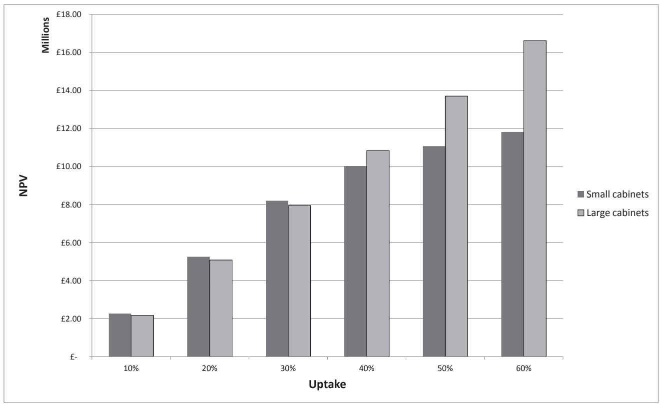

Fig. 6. Small and large cabinet market potential scenario analysis

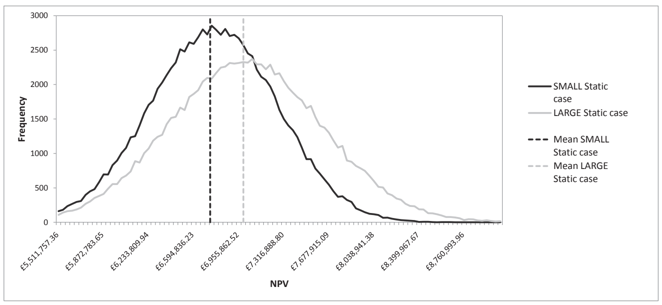

Fig. 7. Impact of uncertainty on the business case outcome

second small cabinet on the location to offer FttC services to the new customers. However, he could also choose a technology upgrade by connecting the extra customers via a more future-proof technology over an FttH network. A third expansion option is raising the ARPU per customer by offering extra services to the existing customers, for example by starting to offer IPTV services. In this section, we will apply these three options to the business case and show how they impact the previous results.

1) Scale up: installing extra small cabinets: The first identified flexibility is the scale up option. Once the small cabinet is full, the operator can install a second cabinet to host the extra connections. Of course, this comes with an additional capital expenditure for a small cabinet and DLSAM line cards. The business case presented above was extended with this scale option. In the small scale scenario, the extra customers on a full cabinet are now connected to an additional small cabinet, and their ARPU is added to the business case. However, the option will only be executed when it is economically interesting. It is as such a simple maximisation function of the small static case and the scale up case.

When comparing the results for the large cabinet and the small scale scenario, we notice that the small scale case is the most interesting for the operator. It yields an average payoff which is 2.23% higher than the large cabinet scenario, which was initially the best choice after the sensitivity analysis (Fig. 8). Compared to the small static case, it is even 6% higher. While the large cabinet scenario is definitely the most future proof option in the scenario analysis, the RO analysis indicates

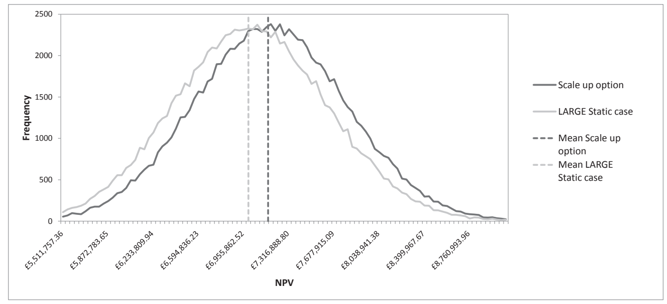

Fig. 8. Overlay chart large scenario and small scale case

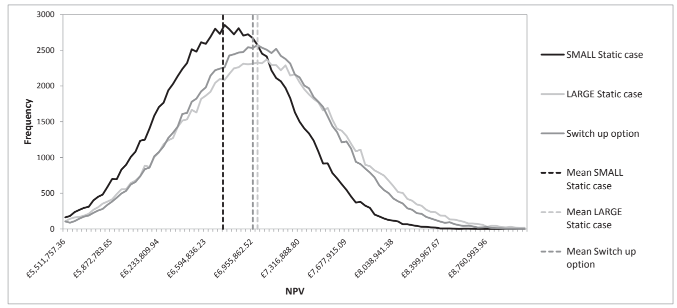

Fig. 9. Improvement of the business case with a switch up option

TABLE VI
COST PARAMETERS FOR AN FTTH DEPLOYMENT [33]

Hardware component	Cost (GBP)
G.PON card (256 customers)	6.000
Cost per G.PON port	500
Passive splitter	210
CPE	80
CPE installation cost	100

there is an extra scale option value in the small cabinet scenario. The scale up option offers the operator the possibility to initially install the cheaper small cabinets and only invest in additional capacity when necessary. Large cabinets offer enough capacity to host all connections, but in most cases this capacity is never used.

2) Switch up: additional capacity through a more future proof network: It was already indicated that the operator could migrate the extra customers on a full cabinet towards a more future proof FttH network. To implement this switch up option in the business case, some extra additions are necessary in the model. Fibre cables need to be installed in the last mile and extra G.PON equipment provided in the local exchange. In the access network, passive splitters ensure the connectivity. The cost parameters are based on industry insight and can be found in Table VI.

The impact of the switch option can be seen in Fig. 9. Again the business case for the small cabinet scenario is greatly improved. However, when comparing with the scale option, we see that an FttH extension is more expensive and does not improve the small scenario enough to outperform the large cabinet scenario.

TABLE VII
IPTV COST PARAMETERS [33]

Component	Cost (GBP)
Video server	20.000
CPE	250
CPE installation cost	200
Extra ARPU	100

TABLE VIII
IPTV GOMPERTZ ADOPTION PARAMETER ESTIMATES

Parameter	Value
a	4.667
b	0.366
m	0.405

3) Scope up: offering extra services over the existing infrastructure: One of the examples given as a scope up option is the extension of the typical telephone and internet incumbent product portfolio towards triple play. We will indicate in this section how offering an IPTV service can be implemented in the business case as a real option. The operator can decide to extend his product portfolio towards triple play in the fourth year of the project.

Before the standard business case is extended, some extra input parameters are required. Offering IPTV to end customers will require extra equipment in the local exchange. In order to avoid unnecessary complexity in the business case, we added a fixed cost for video server per local exchange and other equipment to the scope up business case extension. At the customer's premises, a new CPE needs to be installed (Table VII).

Typically, the adoption of such a service will again follow the S-shaped adoption curve. Since it is not straightforward to translate this adoption into a mathematical model, we have combined given adoption percentages [14] together with statistical software to fit the historic adoption percentages to the mathematical Gompertz model. All parameters were found to be statistically significant. The resulting parameters are summed up in Table VIII.

The results of this RO analysis can be found in Fig. 10. Apparently, the extension of the product portfolio towards triple play services has only marginal value compared with the small cabinet scenario. This means that offering triple play to customers will be not interesting in this scenario, so the option is almost never executed.

4) Combining options: scope and switch up combined: In the previous analysis only single options were presented. However, realistic business cases generally possess a wide spectrum of different options. Consider the three options discussed above. It is clear that the scale and switch up options are mutually exclusive. If a given area is extended with an extra cabinet, the FttH switch up option will become redundant. However, the scale and switch up option can be easily combined with the scope up option.

Consider the case where the triple play services require a network with extra capacity. If the operator chooses to upgrade its network capacity with an FttH network once the first cabinet is full, they can start offering IPTV to these customers. This is in fact a compound option, or an option on an option. The same adoption curve as before was used but is now only applied to the customers who are connected via the FttH network. In contrast with the single scope up option, this now results in a positive option value. The total NPV for this case results in an even larger payoff compared with the small cabinet scenario with the scale option (Fig. 11).

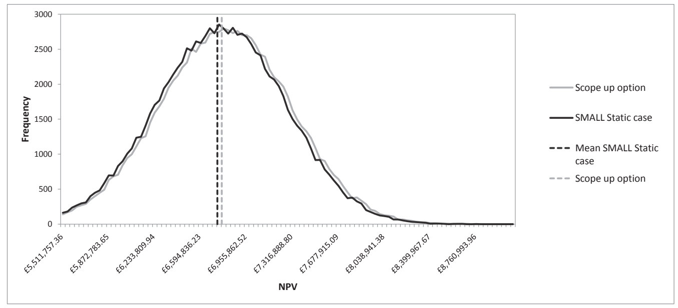

Fig. 10. Scope up option

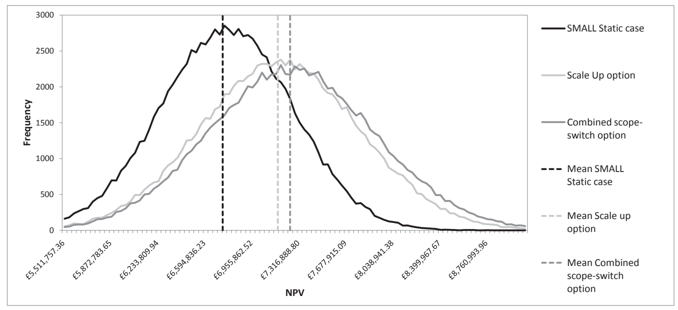

Fig. 11. Compound options: switch up and scope up combined

C. Rollout of an FttC network - case conclusion

The considered business case evaluates the economic feasibility of the rollout of an FttC network in the UK. To achieve the FttC coverage, the network operator can follow two investment paths, full coverage or coverage following demand. The traditional NPV analysis showed the coverage following demand scenario was the most profitable. However, when checking the requirements for an RO analysis, it was clear that uncertainty surrounding the initial assumptions most likely would have an impact on the analysis results.

Therefore, we followed the proposed four-step methodology to extend the case with the real option approach. After every step, we indicated the impact on the results of the analysis. The effect of uncertainty on the business case was assessed by both a scenario and sensitivity analysis. The initial results from the traditional approach were contradicted when the customer uptake assumptions were questioned. When flexibility was implemented in the business case, to allow the decision makers to react to this uncertainty, all option categories were identified in the following demand scenario of the business case. The initial network could be expanded with extra capacity, either via a scale up option or a switch up option. The scale up option installs more of the same, while the switch up option gradually migrates the existing network towards an FttH network. The third scenario investigated offering extra services, following a scope up option path.

In this case, a scale up option is the most designated, as it improves the result of the small cabinet scenario to a level higher than the large cabinet scenario. The switch up option also improves the small cabinet scenario. However, when compared to a static large cabinet scenario, the latter remains more interesting. It has also been shown that offering extra services adds only marginal value to the business case for the small cabinets and is thus almost never executed.

However, in realistic business cases, options almost never occur in isolation. This tutorial extended the example case with a compound option by implementing the scope up option on the switch up option. Using the proposed methodology, this remains a rather straightforward exercise.

VI. Lessons Learned, Shortcomings and Possible Extensions

A. Real option analysis guidelines

The practical RO analysis methodology described in this paper bridges the gap between the financial and technical world in telecommunication firms. In all areas of telecommunication, decisions on new investments need to be made. Design of passive infrastructures by network planners, testing of new technology before implementing it, etc. These decisions are not only based on cost optimizations, but intuitive notions on the capability of the chosen design or technology to counter uncertainty, the inherent flexibility of the design, or the opportunities it offers to reduce risk related to future costs are also taken into account. Real options translate this intuition into the language of the financial department. The three conditions required for a RO analysis can help the network planners to identify the presence of real options in their network plan. Additionally, the 7S framework can help to categorize these options. With the four step methodology, the standard NPV analysis executed today can easily be extended towards a full RO analysis. In order to identify real options and quantify their impact, the following guidelines are offered. First, when making network design decisions, ask three questions.

- How uncertain is the future?
  Uncertainty surrounding future conditions will typically have a large impact on your decision. Identifying several future scenarios can help to see how this uncertainty would impact your decision.
- Where is the flexibility?
  If uncertainty is present, different actions may exist to counter it. Indicating how to alter the initial project path under different conditions helps to identify the different options. The 7S framework can be a guideline.
- When do I have to decide?
  Flexibility and uncertainty are not sufficient to have options in the investment case. Flexibility is only interesting if it can be executed in later phases of the project.

When these three conditions are met, real options are present in the investment project. It is then important to check how they impact your decision.

- Conduct a standard NPV analysis
  Real options extend the standard NPV analysis, and their valuation starts with a clear understanding of the value of the project in absence of uncertainty and options.
- Identify the uncertainties
  Future uncertainty is a condition for RO analysis, and should therefore be identified before the quantification of the real option value. The impact of uncertainty on the investment project can be checked through a scenario or sensitivity analysis.
- Identify the flexibility
  Without the ability to react against uncertainty, no real options are present. Here, the 7S framework can be a guideline to formalize the intuitive notions on managerial flexibility present during the project lifetime.
- Calculate the option value
  While the Monte Carlo analysis is designated for extended techno-economic cases, a more simple back of the envelope binomial tree analysis can offer initial insights.

B. Pitfalls of RO analysis

A RO analysis is a helpful tool to value inherent flexibility in typical telecom investment projects. However, when conducting a RO analysis, several things should be kept in mind.

First, the value of an option is a function of the uncertainty attributed to the different input factors. The higher the uncertainty, the higher the option value. This effect can easily be observed in the Black and Scholes formula. Estimating this uncertainty remains a difficult exercise and should be handled with care. Although commercial software allows the user to attribute uncertainty to all input parameters, it is important to focus on the uncertainties with the highest expected impact, e.g. customer adoption, lifetime of the technology, etc.

Secondly, the results of a RO analysis give an indication of the average extra value the option generates. In a Monte Carlo analysis, thousands of possible futures are calculated and, from the resulting probability distribution, several conclusions can be drawn. It indicates how the option impacts the risk associated with the investment. An option typically reduces the risk of a low payoff, but it does not guarantee a positive payoff. For example, a project with a scale option can in the future still turn out to be unprofitable, since the customer uptake is much lower than expected, turning the scale option value to zero.

Finally, a RO analysis always attributes value to waiting. In a project with an option to wait, the further the investment can be postponed, the more value the option typically generates. This effect was, for example, indicated in the Black and Scholes formula. In practice, decision makers do not have the option to postpone decisions forever. The threat of competitive entry pushes decision makers to move as fast as possible. In a competitive environment, the value of waiting erodes quickly, since there is typically a first mover advantage.

C. Future work

One of the most important future research directions in real option analysis is its interaction with competition. Typically, the impact of competition is analysed through a game theoretic analysis. Game theory is another extension of the standard techno-economic analysis. For a clear case study on the impact of competition on an economic assessment of a realistic business case, the authors refer to [41].

However, as was already indicated above, in realistic business cases, the decision maker has to take both his options and competition into account. There is a trade-off between the value of waiting and reducing uncertainty, and the first mover advantage. While waiting typically increases value in option theory, it decreases value when competition comes into play.

Steps towards this integration have already been made. Option games allow for such an integration, but they have currently only been applied to more simple illustrative examples [42]. In option games, basic binomial tree games are extended by a game theoretic analysis of the end nodes. While this can indicate the value of a combined option-game thinking, it should be extended towards more realistic settings, to increase its applicability in day-to-day decision making. Another approach is through sensitivity games [43] where the impact of uncertainty is assessed on the game theoretic analysis and the resulting equilibria. Extending the underlying business cases with the value of options would offer new insight into the dynamic interplay between options and games.

VII. Conclusion

The broad range of uncertainties concerning future technological evolution, customer adoption and regulation which is characteristic of the telecommunication sector definitely requires managerial flexibility in large investment projects in this field. However, the traditional economic evaluation methods cannot capture the value of this flexibility. Different extended evaluation models have been proposed to solve this problem. In particular, the real option theory has shown great potential to integrate managerial flexibility with the standard evaluation methods. However, this extended model is only slowly finding acceptance. To indicate the importance of real options for telecom investment projects, a wide range of realistic examples was introduced showing the broad array of options existing in all telecom sectors. The abandon option in the mobile broadcast TV service of British Telecom or the testing periods of LTE by Telenet in Belgium are just two examples.

It may be clear that the application of RO Theory in telecommunication projects should be a logical extension to the traditional evaluation methods. However, a common complaint regarding this theory is the lack of a practical framework for realistic cases. In this tutorial, we extended the overview of real option basics and the application domains in telecom with a practical approach to extend realistic business cases with a real option analysis. We stressed the importance of the three requirements for a RO analysis and the four-step methodology to implement it. Before a business case is eligible for a RO analysis, uncertainty surrounding the project should be present. This uncertainty can however be handled by the managerial flexibility in the project at a later point in time. When these preconditions are met, the calculation of the option value is quite straightforward. In the standard NPV analysis model, both the uncertainties and flexibilities need to be identified and added to the model. Executing a Monte Carlo simulation on this extended model then results in the real option value of the project.

To indicate the strength of such a practical framework, we applied it to the investment project for a next generation fixed access network rollout. The migration towards an FttC network in the UK was studied. It was indicated that the operator had two rollout choices, either installing small or large cabinets. From the traditional NPV analysis, the small cabinet installation proved to be the most profitable. However, uncertainty surrounding the several input parameters could have an important impact on the final outcome. Therefore, the standard NPV analysis was extended with a scenario, sensitivity and real option analysis. While the scenario and sensitivity analysis allowed adding uncertainty to the investment project, it is only the RO analysis that includes the value of managerial flexibility in the decision process. Four different options were identified in the case, each having a different impact on the decision process of the management.

In this tutorial, we indicated the importance of real options in the telecommunications sector. The authors hope to speed up the application of real options within this sector by providing some clear real-life examples of firms executing their options and by offering a complete real option analysis of an existing business case.

Acknowledgments

This research was partly carried out as a collaboration between BT and iMinds.

The work leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 249025.

This research was partially supported by the iMinds TERRAIN project. This project is co-funded by iMinds, IWT and Acreo AB, Alcatel-Lucent, Comsof, Deutsche Telekom Laboratories, Digipolis, FTTH Council Europe, Geosparc, Stad Gent, TMVW, TE Connectivity, UNET and WCS Benelux BV.

References

[1] S. A. Ross, R. W. Westerfield, and J. F. Jaffe, Corporate Finance. McGraw-Hill, 2006.

[2] C. Lange, T. Monath, E. Weis, M. Kind, M. Adamy, and N. Gieschen, "Techno-Economic Comparison of Passive Optical Network Scenarios," in BroadBand Europe, pp. 3-5.

[3] J. Harno, D. Katsianis, T. Smura, T. G. Eskedal, R. Venturin, O. P. Pohjola, K. R. R. Kumar, and D. Varoutas, "Alternatives for mobile operators in the competitive 3G and beyond business," Telecommunication Systems, vol. 41, no. 2, pp. 77-95, Apr. 2009.

[4] A. Saltelli, M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana, and S. Tarantola, Global Sensitivity Analysis: The Primer. John Wiley & Sons, 2008.

[5] T. Rokkas, D. Katsianis, T. Kamalakis, and D. Varoutas, "Economics of Time and Wavelength Domain Multiplexed Passive Optical Networks," Optical Communications and Networking, IEEE/OSA Journal of, vol. 2, no. 12, pp. 1042-1051, Nov. 2010.

[6] K. Casier, S. Verbrugge, J. Van Ooteghem, D. Colle, R. Meersman, M. Pickavet, and P. Demeester, "Impact of sensitivity and iterative calculations on cost-based pricing," in 6th Conference on Telecommunication Techno-Economics (CTTE), 2007.

[7] T. E. Copeland and P. T. Keenan, “How much is flexibility worth?,” McKinsey Quarterly, no. 2, pp. 38-50, 1998.
[8] T. E. Copeland and V. Antikarov, Real Options - a practitioner’s guide. Texere, 2003.
[9] W. De Maeseneire, The real options approach to strategic capital budgeting and company valuation. Financiële cahiers, Larcier, 2006.
[10] S. Verbrugge, K. Casier, J. Van Ooteghem, and B. Lannoo, “Practical steps in techno-economic evaluation of network deployment planning,” IEEE Globecom, Tutorial, vol. 11, 2008.
[11] J. Mun, “Real options and Monte Carlo simulation versus traditional DCF valuation in layman’s terms,” in Managing enterprise risk: what the electric industry experience implies for contemporary business, K. B. Leggio, D. B. Bodde, and M. L. Taylor, Eds. Elsevier, 2006, pp. 75-100.
[12] L. Trigeorgis, Real options: Managerial flexibility and strategy in resource allocation. The MIT Press, 1996.
[13] B. Chevalier-Roignant, C. M. Flath, A. Huchzermeier, and L. Trigeorgis, “Strategic investment under uncertainty: A synthesis,” European Journal of Operational Research, vol. 215, no. 3, pp. 639-650, Jun. 2011.
[14] Point Topic, “The leading websource on DSL and broadband,” 2013. [Online]. Available: http://point-topic.com. [Accessed: 25-Jan-2013].
[15] B. Lannoo, S. Verbrugge, J. Van Ooteghem, B. Quinart, M. Casteleyn, D. Colle, M. Pickavet, and P. Demeester, “Business Model for a Mobile WiMAX Deployment in Belgium,” in Mobile WiMAX, no. June 2004, K.-C. Chen and J. R. . de Marca, Eds. John Wiley & Sons, 2008, pp. 349-369.
[16] B. Sadowski, M. Verheijen, and A. Nucciarelli, “From experimentation to citywide rollout: Real options for a municipal WiMax network in the Netherlands,” Communications & Strategies, no. 70, pp. 101-123, 2009.
[17] V. P. Tanguturi and F. Harmantzis, “Migration to 3G wireless broadband internet and real options: The case of an operator in India,” Telecommunications Policy, vol. 30, no. 7, pp. 400-419, Aug. 2006.
[18] J. J. Alleman and E. M. Noam, The new investment theory of real options and its implications for telecommunications economics. Springer, 1999.
[19] M. Tahon, S. Verbrugge, B. Lannoo, J. Van Ooteghem, P. De Mil, M. Pickavet, and P. Demeester, “Parking sensor network: economic feasibility study of parking sensors in a city environment,” in Telecommunication, Media and Internet Techno-Economics, 9th Conference, Proceedings, 2010, pp. 1-8.
[20] M. Basili and F. Fontini, “The option value of the UK 3G Telecom licences: Was too much paid?,” info, vol. 5, no. 3, pp. 48-52, 2003.
[21] L. Mastroeni and M. Naldi, “Options and overbooking strategy in the management of wireless spectrum,” Telecommunication Systems, vol. 48, no. 1-2, pp. 31-42, May 2010.
[22] R. S. Pindyck, “Mandatory unbundling and irreversible investment in telecom networks,” 2004.
[23] J. Van Ooteghem, B. Lannoo, D. Colle, M. Pickavet, I. Moerman, and P. Demeester, “Internet service option on trains: an application in Belgium Railway,” in Annual international conference on Real Options, 12th, Presentations, 2008.
[24] F. Black and M. Scholes, “The pricing of options and corporate liabilities,” The journal of political economy, vol. 81, no. 3, pp. 637-654, 1973.
[25] S. S. Sawilosky, “You think you’ve got trivials,” Journal of Modern Applied Statistical Methods, vol. 2, no. 1, pp. 218-225, 2003.
[26] Oracle, “Crystall Ball Decision Optimizer.” [Online]. Available: www.oracle.com/us/products/applications/crystalball/index.html. [Accessed: 04-Dec-2012].
[27] M. H. Kalos and P. A. Whitlock, Monte carlo methods. Wiley-VCH, 2009.
[28] M. Tahon, S. Verbrugge, P. J. Willis, P. Botham, D. Colle, and M. Pickavet, “Migration to Next Generation Access Networks?: a Real Option Approach,” in Proceedings of ROC 2012, 2012, p. 11.
[29] K. Casier, “Techno-economic Evaluation of a next generation access network deployment in a competitive setting (Doctoral dissertation),” 2009, p. 283. Available: http://www.intec.ugent.be/sites/default/files/docs/PhD_KoenCasier.pdf
[30] A. Cárdenas, M. García-Molina, S. Sales, and J. Capmany, “A New Model of Bandwidth Growth Estimation Based on the Gompertz Curve?: Application to Optical Access Networks,” Lightwave Technology, vol. 22, no. 11, pp. 2460-2468, 2004.
[31] The information society EURIM, “Making broadband investment markets work - summary,” 2011.
[32] B. Gompertz, “On the nature of the function expressive the law of human mortality, and on a new method of determining the value of life contingencies,” Philosophical Transactions of the Royal Society, vol. 36, pp. 513-585, 1825.
[33] Analysys Mason, “The costs of deploying fibre-based next-generation broadband infrastructure,” 2008.
[34] M. J. O’Sullivan, C. G. Walker, M. L. O’Sullivan, T. D. Thompson, and A. B. Philpott, “Protecting local access telecommunications networks: Toward a minimum-cost solution,” Telecommunication Systems, vol. 33, no. 4, pp. 353-376, Dec. 2006.
[35] K. Casier, J. Van Ooteghem, M. Sikkema, S. Verbrugge, D. Colle, M. Pickavet, and P. Demeester, “Influence of geomarketing on the rollout of new telecom network infrastructure,” in Telecommunication, Media and Internet Techno-Economics (CTTE), 10th Conference of, 2011, pp. 1-7.
[36] S. Verbrugge, D. Colle, M. Pickavet, P. Demeester, S. Pasqualini, A. Iselt, A. Kirstädter, R. Hülsermann, F.-J. Westphal, and M. Jäger, “Methodology and input availability parameters for calculating OpEx and CapEx costs for realistic network scenarios,” Journal of Optical Networking, vol. 5, no. 6, pp. 509-520, 2006.
[37] K. Casier, S. Verbrugge, R. Meersman, D. Colle, and P. Demeester, “On the costs of operating a next-generation access network,” in Proceedings of CTTE2008, the 7th Conference Telecom, internet and media Techno-Economics (CTTE), 2008.
[38] G. M. Beal, E. M. Rogers, and J. M. Bohlen, “Validity of the concept of stages in the adoption process,” Rural Sociology, vol. 22, no. 2, pp. 16-168, 1957.
[39] J. Fisher and R. Pry, “A simple substitution model of technological change,” Technological Forecasting and Social Change, vol. 3, pp. 75-88, 1971.
[40] F. M. Bass, “A new product growth for model consumer durables,” Management Science, vol. 15, no. 5, pp. 215-227, 1969.
[41] M. Tahon, B. Lannoo, J. Van Ooteghem, K. Casier, S. Verbrugge, D. Colle, M. Pickavet, and P. Demeester, “Municipal support of wireless access network rollout: A game theoretic approach,” Telecommunications Policy, vol. 35, no. 9-10, pp. 883-894, Jun. 2011.
[42] B. Y. N. Ferreira, J. Kar, and L. Trigeorgis, “Option Games The Key to Competing in Capital-Intensive Industries,” Harvard Business Review, no. March, pp. 101-108, 2009.
[43] K. Casier, B. Lannoo, J. Van Ooteghem, S. Verbrugge, D. Colle, M. Pickavet, and P. Demeester, “Game-theoretic optimization of a fiber-to-the-home municipality network rollout,” Journal of Optical Networking, vol. 1, no. 1, p. 30, Jun. 2009.

Mathieu Tahon Mathieu Tahon graduated as Master in Applied Economics, option Finance in 2009 at Ghent University. He joined the IBCN research group of the Department of Information Technology as PhD student in August 2009, at the same university. He is affiliated with the techno-economic research cluster, where he performs research on the application of advanced evaluation techniques in broadband network rollout (both fixed and wireless) and new service introduction (smart meters, electric vehicles). He specifically focuses on the use of real option and competition modeling in the economic evaluation.

He was involved in various national and European research projects, including the European FP7 ICT-STRONGEST project and the national IBBT-ICON TERRAIN, where he led the work package on extended evaluation techniques. He is currently working within the European FP7 project ICT-TREND, studying cooperative models in wireless networks in order to reduce cost and energy consumption.

Sofie Verbrugge Sofie Verbrugge received an MSc degree in computer science engineering from Ghent University (Ghent, Belgium) in 2001. She obtained the PhD degree from the same university in 2007 for her thesis entitled "Strategic planning of optical telecommunication networks in a dynamic and uncertain environment".

She is currently working as a researcher affiliated to iMinds, a research institute to stimulate ICT innovation in Flanders, where she is a coordinator for the techno-economic research within the Internet Based Communication Networks and Services group (IBCN). Her main research interests include infrastructure as well as operational cost modeling, telecom service and network deployment planning, advanced evaluation techniques including real options and game theory. She has been involved previously in several European as well as national research projects in these domains, including the COST-action Econ@tel. She led the work package on "Business modeling" with the European FP7 project ICT-OASE and is currently working within the FP7 project ICT-Flamingo.

Peter Willis Peter Willis is Chief Data Networks Strategist, Research & Innovation at British Telecom. Peter is researching the future of networks covering everything from photonics to network applications. He is now working on Network functions Virtualisation, which is implementing network functions as software running on high volume standard servers. Peter previously worked on the development of PBB-TE, BT's 21st Century Network Architecture and BT's Internet service. He has a long term interest in developing business cases for introducing new technologies into networks which lead to the work on applying Real Options Analysis techniques to network investments.

Paul Botham Paul Botham joined BT with a D.Phil. in theoretical physics from Oxford University. Within Research and Innovation, he has worked in a variety of network modelling roles, applying mathematical techniques to develop software tools for designing least-cost, resilient BT networks. This has involved a wide range of technologies in both core-transport and access environments. Paul is currently working on optimised deployment of next-generation network technology, incorporating risk analysis for BT business cases.

Didier Colle Didier Colle received a M. Sc. degree in electrotechnical engineering (option: communications) from the Ghent University in 1997. Since then, he has been working at the same university as researcher in the department of Information Technology (INTEC). He is part of the research group INTEC Broadband Communication Networks (IBCN) headed by prof: Piet Demeester. His research lead to a Ph.D degree in February 2002. He was granted a postdoctoral scholarship from the Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT-Vlaanderen) in the period 2003-2004. Currently, he is co-responsible for the research cluster on network modelling, design and evaluation and is coordinating the research on fixed internet architectures and optical networks. His research deals with design and planning of communication networks. This work is focussing on optical transport networks, to support the next-generation Internet. Up till now, he has actively been involved in several national and international research projects. His work has been published in more than 250 scientific publications in international conferences and journals.

Mario Pickavet Mario Pickavet received an M.Sc. and Ph.D. degree in electrical engineering, specialized in telecommunications, from Ghent University in 1996 and 1999, respectively. Since 2000, he is professor at Ghent University where he is teaching courses on discrete mathematics, multimedia networks and network modeling.

He is co-leading the research cluster on Network Modeling, Design and Evaluation (NetMoDeL) covering 4 research topics: Fixed internet architectures and optical networks, techno-economic studies, green-ICT and design of network algorithms (DNA). In this context, he is currently involved in several European and national projects.

He has published about 300 international publications, both in journals (IEEE JSAC, IEEE Comm. Mag., Journal of Lightwave Technology, ...) and in proceedings of conferences. He is co-author of the book 'Network Recovery: Protection and Restoration of Optical, SONET-SDH, IP, and MPLS'.

Piet Demeester Piet Demeester is professor in the faculty of Engineering at Ghent University. He is head of the research group "Internet Based Communication Networks and Services" (IBCN) that is part of the Department of Information Technology (INTEC) of Ghent University. He is also leading the Future Internet Department of the strategic research center iMinds. He is Fellow of the IEEE. The IBCN group is focusing on several advanced research topics: Network Modeling, Design & Evaluation; Mobile & Wireless Networking; High Performance Multimedia Processing; Autonomic Computing & Networking; Service Engineering; Content & Search Management and Data Analysis & Machine Learning."