Flexibiliteit, competitieve en coöperatieve interacties in telecommunicatienetwerken: een model voor uitgebreide techno-economische evaluatie

Flexibility, Competitive and Cooperative Interactions in Telecommunication Networks: a Model for Extended Techno-Economic Evaluation

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Gent, november 2013
Mathieu Tahon

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3G	Third Generation
3GPP	3rd Generation Partnership Project
4G	Fourth Generation

A

ADSL	Asymmetric Digital Subscriber Line
ANP	Alternative Network Provider
AON	Active Optical Network
AP	Access Point
ARPU	Average Revenue Per User
AS	Active Star
AWG	Array Waveguide Grating

B

BOD	Benefit Of Doubt
BPI	Broadband Performance Index
BQS	Broadband Quality Score

C

CapEx	Capital Expenditures
CDC	Cumulative Discounted Cost
CIC	Customers Inclined to Change
CO	Central Office (equipment)
	Cable Operator (actor)

CPE	Customer Premises Equipment
CRM	Customer Relationship Management
CRT	Cathode Ray Tube

D

DAE	Digital Agenda for Europe
DL	Download
DOCSIS	Data Over Cable Service Interface Specification
DP	Distribution Point
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
DSO	Distribution System Operator
DVD	Digital Versatile Disc
DWDM	Dense Wavelength Division Multiplexing

E

EPC	Evolved Packet Core
ESCO	Energy Service Company
EU	European Union

F

FAC	Fully Allocated Cost
FDD	Frequency Division Duplex
FTTC	Fibre To The Cabinet
FTTH	Fibre To The Home
FTTP	Fibre To The Premises
FTTx	Fibre To The x (any type)

G

G.PON	Gigabit Passive Optical Network
GigE	Gigabit Ethernet
GIS	Geographic Information System
GSM	Global System for Mobile Communication

GT	Game Theory

H

HEC	Home Energy Controller
HFC	Hybrid Fibre Coax
HHI	Herfindahl-Hirschman Index
HP	Homes Passed
HRN	Home Run Network
HSDPA	High-Speed Downlink Packet Access
HSPA	High-Speed Packet Access
HSUPA	High-Speed Uplink Packet Access

I

ICT	Information and Communication Technologies
IP	Internet Protocol
IPTV	Internet Protocol Television
ISDN	Integrated Services Digital Network
ITU	International Telecommunication Union

L

LCD	Liquid Crystal Display
LLU	Local Loop Unbundling
LP	Linear Programming
LRIC	Long Run Incremental Cost
LTE	Long Term Evolution

M

MAC	Media Access Control
MIMO	Multiple-Input Multiple-Output
MIP	Municipal Infrastructure Provider
MNO	Mobile Network Operator
MTBF	Mean Time Between Failure
MVNO	Mobile Virtual Network Operator

N

NE	Nash Equilibrium
NGAN	Next Generation Access Network
NOC	Network Operating Centre
NPV	Net Present Value
NRA	National Regulatory Authority

O

OADM	Optical Add Drop Multiplexer
ODF	Optical Distribution Frame
OECD	Organisation for Economic Cooperation and Development
OLO	Other Licensed Operator
OpEx	Operational Expenditures
OTT	Over The Top
OXC	Optical Cross Connect

P

P2MP	Point to Multi Point
P2P	Point to Point
PC	Personal Computer
PI	Performance Index
PIP	Physical Infrastructure Provider
PLC	Power Line Communication
PON	Passive Optical Network
PPP	Public Private Partnership
PSTN	Public Switched Telephone Network

Q

QoS	Quality of Service

R

R&D	Research and Development

RO	Real Option
ROW	Right Of Way

S

SAC	Stand Alone Cost
SCU	Strongest Cost Unit
SLA	Service Level Agreement
SME	Small and Medium Enterprises
SMP	Significant Market Power
SP	Service Provider
SPOC	Single Point Of Contact

T

Telco	Telecommunication Company
TV	Terminal Value

U

UMTS	Universal Mobile Telecommunications System

V

VDSL	Very high speed Digital Subscriber Line

W

WDM	Wavelength Division Multiplexed
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WSN	Wireless Sensor Network
WSON	Wavelength Switched Optical Network
WSS	Wavelength Selective Switch

X

xDSL	x Digital Subscriber Line (of any type)

Nederlandstalige samenvatting - Dutch Summary

Dit proefschrift onderzoekt de verschillende aspecten van een uitgebreide techno-economische analyse. Sinds de introductie van telecomgerelateerde diensten, heeft de sector een constant snelle evolutie gekend, die vooral gedreven wordt door technologische vooruitgang en regulering.

Voor netwerkplanners, ontwikkelaars van applicaties, aanbieders van diensten, regulatoren en producenten van apparatuur vormt deze evolutie een uitdaging wanneer ze strategische beslissingen moeten nemen. Techno-economische analyse biedt een kwantitatieve methode om deze beslissingen op te baseren.

Techno-economie is gebaseerd op de combinatie van een uitgebreide technische en economische analyse. Wanneer de haalbaarheid van de uitrol van een netwerk onderzocht wordt, moeten de onderliggende technische factoren meegenomen worden om de correcte netwerkdimensionering te bekomen. Gebaseerd op dit gedetailleerd model kunnen dan de stuklijst voor de apparatuur, de kost van operationele processen en de geschatte inkomsten van alle klantensegmenten berekend worden. Maar als de technologie evolueert, de klantpreferenties wijzigen, nieuwe spelers actief worden en kostprijzen evolueren, hoe wordt dit gereflecteerd in de techno-economische analyse? Algemener, hoe incorporeert men onzekerheid, flexibiliteit, competitieve en coöperatieve interacties in deze analyse?

Het is op deze vraag dat dit proefschrift een antwoord formuleert. Vertrekkende vanuit de bestaande techno-economische methodologie en door aanvullingen en oplossingen aan te reiken voor typische problemen in telecom, bieden we hier een brede set van tools aan om een uitgebreide techno-economische analyse uit te voeren.

De eerst stap in de techno-economische analyse omvat steeds het verzamelen van de benodigde input, gaande van kostprijsinformatie over marktgrootte tot de technische paramaters van de onderzochte case. Gebaseerd op deze input worden daarna de gedetailleerde modellen gebouwd voor netwerkdimensionering, het bepalen van de stuklijst voor apparatuur en de operationele processen. Maar de analyse moet ook ruimer getrokken worden, en verschillende omgevingsfactoren incalculeren. Welke spelers zijn er actief binnen dezelfde sector of markt? Moeten we rekening houden met harde concurrentie of zijn er mogelijkheden om samen te werken met andere spelers? Om deze analyse te voeren, brengen we waardenetwerkanalyse aan. Door het probleem op te splitsen in kleine functionele rollen en de mogelijke interacties tussen deze rollen aan te duiden, krijgen we inzicht in twee aspecten. De rollen zijn bouwstenen voor de latere kwantitatieve techno-economische modellering, terwijl de interacties opportuniteiten voor samenwerking of mogelijke concurrentie aanduiden. Een waardenetwerk voor de vaste breedbandmarkt wordt voorgesteld in dit werk, waarbij we verschillende niveaus van samenwerking en competitie identificeren.

Om de kwantitatieve analyse correct uit te voeren, is het kennen van de objectieven van de verschillende actoren vereist. Voor de meeste actoren zijn dit financiële objectieven, maar binnen de telecomsector zijn ook andere spelers aanwezig. Overheden en regulatoren gaan voor een maximalisatie van welzijn en niet voor monetaire doelen. Voor de breedbandmarkt zijn dit doelen als betaalbare diensten, toegang voor iedereen en netwerken met een hoge snelheid. Om deze doelen te kwantificeren, ontwikkelen we in dit werk een breedbandprestatie-index.

Maar zoals vermeld, onzekerheid, flexibiliteit en competitie zullen een invloed hebben op al deze objectieven. Om een techno-economische analyse uit te voeren, is een predictie van de toekomstige evolutie van verschillende factoren vereist. Hoeveel extra capaciteit zal ik nodig hebben de komende jaren om aan alle vraag te voldoen? En als de initiële predictie fout is, ben ik flexibel genoeg om snel aanpassingen te doen aan het model? Het is deze flexibiliteit die reële opties kwantificeren. Doorheen ons onderzoek hebben we opties in verschillende telecom cases geïdentificeerd en geclassificeerd, zoals de uitrol van sensornetwerken in een gemeente, de migratie van vaste toegangsnetwerken naar glasvezelnetwerken en de upgrade van bestaande core netwerken. Gebaseerd op het inzicht uit al deze cases hebben we een tutorial gebouwd die toelaat om flexibiliteit te identificeren, te modelleren en te kwantificeren via reële opties als uitbreiding op de bestaande techno-economische analyse.

Daarnaast is de telecomsector een geconcentreerde sector, en dus zullen interacties tussen verschillende spelers vaak voorkomen. In de meeste West-Europese landen zijn er bijvoorbeeld al verschillende breedbandnetwerken aanwezig, die zo goed als de volledige huishoudelijke markt bedienen. Wanneer een extra netwerk uitgerold wordt naast de bestaande netwerken, zal dit dus klanten aantrekken van deze netwerken. Er moet dus rekening gehouden worden met de impact van competitie met andere spelers op je eigen marktaandeel. Daarnaast moet ook rekening gehouden worden met de competitie tussen aanbiedingen van dezelfde speler. Hiervoor is in dit werk een marktmodel ontwikkeld die deze impact capteert, waardoor er een realistische inschatting van adoptie gemaakt kan worden. Deze adoptie is de belangrijkste input voor de stuklijst en dimensionering die in de volgende stap van de techno-economische analyse bepaald wordt.

Hoewel competitie een vaak voorkomende interactievorm is, moet er ook rekening gehouden worden met samenwerkingsmogelijkheden. Terwijl competitieve interactie een invloed heeft op het mogelijke marktaandeel en de inkomsten, zorgt samenwerking voor mogelijkheden tot het delen en mogelijk verminderen van kosten. Samenwerken tijdens de infrastructuurwerken van de uitrol van een ondergronds vast telecommunicatie netwerk kan tot een besparing van 6 tot 21% leiden, afhankelijk van de locatie waar uitgerold wordt. En wanneer de infrastructuur gedeeld wordt tussen verschillende spelers, worden niet enkel kosten verminderd, maar ook de mogelijke klantenbasis van deze infrastructuur verhoogd. Publiek private partnerships zijn een voorbeeld van zo’n samenwerkingsverband. Door gebruik te maken van slechts één netwerk wordt de kost duidelijk verlaagd, omdat bepaalde apparatuur niet gedupliceerd hoeft te worden. Daarenboven kan de totale kost ook gespreid worden over de gecombineerde klantenbasis van de partnership.

Wanneer concurrentie speelt in de sector waarbinnen de techno-economische beslissing genomen wordt, speelt ook de interactie tussen spelers een rol, en kunnen verschillende strategieën een verschillende uitkomst hebben. Hiervoor biedt speltheorie een gepaste methodologie. Om speltheorie toepasbaar te maken voor gedetailleerde kwantitatieve techno-economische cases, werd binnen dit onderzoek een toegepast speltheoretisch model gebouwd. Dit model werd toegepast op verschillende cases binnen dit proefschrift, zoals de uitrol van draadloze en vaste toegangsnetwerken.

Als laatste duiden we in dit proefschrift de mogelijkheden en voordelen van de integratie van reële opties en speltheorie aan. Beide theorieën modelleren verschillende aspecten van hetzelfde vraagstuk. Reële opties modelleren stochastische onzekerheid, in abstractie van competitieve interactie, terwijl speltheorie net abstractie maakt van deze onzekerheid. De combinatie van beide theorieën kan de soms tegengestelde uitkomsten van beide wegnemen en waardevol inzicht meebrengen.

English Summary

This dissertation takes a close look at the various aspects of extended techno-economic analysis. Since the introduction of telecom services, the sector has known a constant and rapid evolution, driven by technological advances and regulation. During the most recent years, the speed of this evolution has even increased.

In this environment, network planners, application developers, service providers, equipment vendors, regulators and many more have to constantly make strategic decisions. Making correct decisions are of vital importance, as a wrong decision may force them out of the market and result in serious financial distress for the company. To make the correct decisions, the decision makers rely on techno-economic analysis.

Techno-economics focus on the analysis of different problems from both a technical as economic point of view. For any network rollout, a clear view on the technical solution, its requirements and limitations and the cost-benefit related economic aspects is required. Based on the detailed modelling of the bill of material, operational processes and revenues, the project is assessed on its viability. However, due to the constant change in the environment, the standard techno-economic tools fail to correctly incorporate this underlying environment. How to measure competition, value uncertainty and flexibility and address possible changing competitive or cooperative interactions with other players?

This dissertation provides an answer to these questions. By describing existing methodologies and developing new approaches to typical problems, we offer a broad toolset for an extended techno-economic evaluation.

The first step in any techno-economic analysis is gathering sufficient input. This step is required for building a detailed bill of material, cost models on the equipment and processes, but also on the environment. Which other actors are present, what is the level of competition we can expect, are there opportunities for cooperation with other actors? Value network analysis is particularly suited for providing an answer to these questions. It splits up the environment in roles, which can serve as input for the cost modelling. Indicating the interactions between these roles and mapping the actors offers valuable insight in possible

competitive or cooperative relations. By performing such an analysis on the broadband access network, we were able to identify different levels of competition and cooperation between players, going from vertical integration to open access.

The next requirement is knowing your objectives. One cannot assess a decision to be good or bad without knowing the intended objective. For private players, these objectives are mainly related to financial goals in terms of monetary value, market share, etc. For public players, the exercise is less straightforward. Public players, like governments and regulators, do not primarily aim at the increase of their own monetary value, but at so-called social welfare. On the broadband access market, they strive for affordable access, full coverage, sufficient competition, etc. In this work, we introduce a composite index which allows to quantify these broadband policy objectives.

However, the aforementioned aspects, uncertainty, flexibility and competition, will most likely impact these objectives. The quality of the result of a techno-economic analysis is only as good as the quality of the used input data. An assessment of a techno-economic problem requires a prediction of future evolutions of certain parameters. How will my market share evolve, what is the estimated cost evolution of certain components? Although uncertainty surrounding these parameters will impact the outcome of the case, decision makers will flexibly adapt to changing conditions. In case uptake is higher than expected, the service can be extended to new regions. It is the value of this flexibility that real options capture. Throughout our research, we have applied real option thinking to various telecom infrastructure cases. The different migration paths towards future core networks were studied, as well as the deployment of sensor networks. In case of fixed broadband access networks, we showed how incremental planning, starting of small and gradually growing following demand is the designated strategy. Based on our insights from different cases, we developed a tutorial presenting a four-step methodology on how to apply real option thinking in telecom infrastructure investments.

In a concentrated environment like the telecom sector, interactions with other market players will occur, and these will impact the objectives aimed for. In typical Western European cities, (copper-based) fixed broadband infrastructures are already present. In addition, the market is already close to saturation. If a fibre-based access network is deployed in these areas, the presence of other infrastructures will impact the uptake of the new network. This market share impact of competitors should be taken into account in the techno-economic analysis. A market response model was developed, allowing to estimate market share evolution of different offers, based on prices, elasticity and churn concepts. Applying such a market response model allows to adequately estimate the evolution of the market share of competing broadband offers.

Although competition is mainly focussed on, cooperation between players offers important opportunities for actors. Through cooperation, synergies can be gained. We studied cooperation in the deployment phase of physical infrastructure, and found cost savings of up to 15% in the initial deployment cost. Next to cooperation to achieve cost savings, cooperation can also be a result of the search towards increasing customer base. Public private partnerships are an example of such a cooperation strategy. By cooperating in the rollout of network infrastructure, a partnership achieves two goals. First, as only one infrastructure is deployed, no duplication takes place. Secondly, with only one network present, the customer base of this network is doubled compared to two independent rollouts.
In light of the impact of competition on market share and cost savings through cooperation, it needs to be assessed which strategy is to be preferred, taking into account that competitors have similar strategies. Here, game theory provides a suitable framework. In order to evaluate competitive interaction between different detailed techno-economic models, we developed a hands-on game theory framework. Again, we applied this framework to the case of access network rollout.
Finally, we indicate the opportunities of having an integrated option – game approach. As these concepts can sometimes result in conflicting outcomes, analysing their combined effect can provide valuable insight.

1 Introduction and Publications

"Economy does not lie in sparing money, but in spending it wisely",
Thomas Huxley

The telecommunication sector is characterised by a constant and rapid evolution. Mobile telephony evolution from Global System for Mobile Communication (GSM) towards Third Generation (3G) and Long Term Evolution (LTE), the increasing fixed broadband access network speed through technology updates with different types of Digital Subscriber Line (xDSL) and Fibre To The Home (FTTH) and the still ongoing development of new applications are only a few examples. These fast technology changes bring important problems for the actors on the telecommunication market when investment opportunities are considered. The rollout of new access networks typically covers large areas and longer time spans. The operator can flexibly change his rollout plan according to the evolution of the uptake of the new network. Under high demand, the network can be expanded faster towards adjacent regions. Or the operator can gradually upgrade the offered access speeds, based on technological evolution and demand. However, additional aspects need to be taken into account. Regulation can impact the required dimensioning. The requirement to offer open access to third parties has an impact on the bill of material and the operational processes. Secondly, the network or service is operated in an open environment. When a new access network is rolled out, there will be competition with existing networks. As this impacts the expected uptake, it is also reflected in the initial dimensioning.

For private companies, projects are approved or disapproved after a thorough techno-economic feasibility analysis. During this analysis, one should estimate future user adoption, conduct an equipment dimensioning, calculate the bill of material and model the operational processes, translate these into the cost structure, revenues and the risks attached to the project. Only when this analysis shows that the project is economically interesting, the project should be executed. The most known and used tool is the Net Present Value (NPV) analysis. This method gives a good indication about the economic feasibility of the project, but the underlying assumptions of the model are no longer consistent with the reality actors are confronted with today.

The NPV method handles investment decisions as now or never decisions. In a closed environment, where the future evolution of most parameters is known in advance, such an approach is indeed appropriate. However, the reality has changed significantly over the last decades. Actors in the telecom sector no longer operate in a closed environment. Until the liberalisation of the 1990s in Europe, most operators were historic natural monopolies. But after this liberalisation of the market, new entrants appeared, increasing the level of competition. Making investment decisions should now be made in light of these possible competitive reactions. Adapting your own strategy can (and most likely will) impact the strategy of your direct competitors. An investment decision is made in order to increase value. However, competitive or cooperative interactions typically impact the possible value creation of your competitors. When your value increase churns on the value of your competitors, reciprocating actions by these competitors will occur, as they aim at maximising their own value as well. Attracting a higher market share results in a decrease of revenues for competitors, who will react and try to regain their lost customers and their revenues. A well-known example of such interaction is a price war, where all companies decrease their prices to defend their market share. As a result, the market division stays the same, but the overall price level dropped, decreasing the profit of all competitors. In this dissertation, we will hand tools to assess the impact of competition on market division, and introduce a hands-on game theoretic approach to model competitive interactions. Game theory is a very useful tool to assess competition, as its main goal is to model those situations in which decision makers make actions that have possibly conflicting consequences.

While assessing these competitive interactions already increases the difficulty of making good investment decisions, a second factor complicating the process is the uncertainty surrounding the future evolutions. When launching a new product or service, several assumptions, e.g. customer uptake or technology evolution and performance, come with a certain degree of uncertainty. Regarding customer uptake, market research can offer an indication of the market potential evolution. But although such prognoses offer an indication for the initial uptake, the further in the future, the higher the uncertainty on this estimation. Consumer taste can change, a technological breakthrough can make the product redundant, or cost evolutions can make the product unprofitable. These uncertainties should be taken into account when making the investment decision.

In reality, when the environment changes, the decision makers will adapt the project to counter these changes. Under an unfavourable evolution, the company can decide to stop the sale of the product or service. In the telecom market, the withdrawal of the Integrated Services Digital Network (ISDN) service is an example of such a decision. Decision makers have considerable flexibility to counter unexpected changes in the environment. And this is where the NPV method falls short, as it tackles investment problems as now or never decisions, which cannot be turned back or adapted. As a solution to this drawback, real option theory has been developed. We will indicate why this theory is the designated approach for the analysis of large investment projects, as it manages to take both uncertainty and flexibility into account.

The application of the NPV method, or its different extensions developed throughout this dissertation, focuses primarily on the analysis of future cash flows. As such, it lacks the possibility to assess the impact of investment or strategic decisions on the other goals of decision makers. For example, in the European telecom market, the European Commission and National Regulatory Authorities continue to monitor the evolution of this market. On the fixed broadband market, they aim at increasing the coverage and penetration of high speed broadband, the uptake of broadband based services, at reducing price levels and promoting competition on the retail market. When new regulation or policy is issued, it should be tested if it has the desired effect. This effect can no longer be measured through financial tools like the NPV analysis. The question thus arises how the impact of policy and regulation on different, sometimes inversely proportional parameters, can be captured in a quantitative approach. By introducing a composite broadband performance index in this work, we will indicate how other goals can be analysed in an extended techno-economic analysis.

1.1 Overview of This Work

In this dissertation, a general overview of the aspects of performing an extended techno-economic analysis is given, focussing on the application of the different frameworks on fixed and mobile broadband network deployment. The most important results obtained during the course of our research in this field are presented in this work. A complete list of all publications realised is given in section 1.2. An overview of the different chapters is given below, linking these chapters with the related publications.

In Chapter 2, we start by providing a clear motivation for extended techno-economic analysis. We delve deeper into two factors complicating the analysis, uncertainty and competitive interaction. After a description of the standard techno-economic analysis, we indicate in more detail the shortcomings of this methodology and how the two complicating factors are related to these shortcomings. We also touch the requirement for measuring non-financial aspects in techno-economics. The chapter concludes with a description of a case study, which will be used and referred to throughout this dissertation, the deployment of a fixed broadband access network. Techno-economic analysis and the proposed extensions are best explained by showing how they impact a detailed numerical example. In more detail, the case studies the migration of existing broadband access networks towards FTTH networks. Based on network topology, equipment dimensioning and customer uptake, it estimates the viability of such a deployment. The selected example touches two flavours of fixed broadband network deployment, a Brownfield and Greenfield rollout. In the Greenfield rollout, the deployment is started from scratch, while in the case of a Brownfield deployment, there is already an existing network present, allowing for a migration strategy towards faster broadband of this network. The selected case has been elaborated on in several publications ([4], [7] and [17]).

The case is well suited to indicate the impact of uncertainty, flexibility and competition on the techno-economic analysis. Upgrading a fixed access network towards higher capacities is bound to several factors of uncertainty. Expected uptake is one of the major uncertainties. How much additional capacity is required to meet customer demand? What are the different technology options available to meet this demand? The operator could provide additional capacity by duplicating equipment, but a migration towards a more performing network technology is also possible. But since demand only comes gradually, the decision does not need to be made today, but can be postponed until the initial installation reaches its capacity limits.

The impact of competition is also covered in the case. Several access networks are already installed today offering broadband access. Deploying a new network or upgrading an existing one will impact the competitive equilibrium. As higher access speeds can be offered, how much more customers will be attracted to the network, and how does this impact the required equipment and operational processes? And what are the possible counterstrategies of our competitors. Do they have the possibility to perform a network upgrade as well to offer higher access speeds?

Performing an extended techno-economic analysis requires a clear view on the environment in which the studied case is set. Chapter 3 provides methods to analyse this environment. Multi-actor analysis is introduced as a methodology to identify the different actors and their interactions. These actors perform different roles, the basic building blocks of a value network. A multi-actor analysis is performed for two different cases, the introduction of smart energy meters and the rollout of a fixed broadband access network ([7], [13], [16]).

Once the different actors and roles are identified, a quantitative techno-economic analysis is only possible if the objectives of the actors are well known. The second part of Chapter 3 handles this aspect. A distinction is made between financial and non-financial objectives. In techno-economics, financial objectives are typically measured through NPV or other cash flow based methods. Non-financial objectives pose more problems, as the quantification of such goals is not straightforward, especially if multiple conflicting goals are present. In case of broadband access networks, national regulatory authorities (NRA) have such non-financial goals. They aim at increasing coverage, speed and competition and attaining acceptable price levels. To measure these objectives, we developed a composite broadband performance index ([18], [21]).

Chapter 4 discusses the impact of the first complicating factor in techno-economic analysis, namely uncertainty and how decision makers can react to this. Real option analysis has been selected as designated approach to quantify these aspects. During our research, we have applied real options to a variety of cases, resulting in a tutorial for telecom professionals on how to apply real option analysis in their decision process [3]. These cases cover the migration to FTTH networks, but also deployment of sensor networks, core network migration and even pricing aspects of local loop unbundling. The different cases real options have been applied to are described in several publications ([2], [8], [10], [17], [19], [20]).

Chapter 5 focuses on the impact of competition on techno-economic analysis, more specifically on market interactions. Two types of market interaction are discussed, competition and cooperation. The influence of competition on the outcome of a techno-economic analysis cannot be overestimated. Customers are the main driver for both revenues and variable costs. As the number of customers in any market is limited, competitive interaction will influence the attained market share of all players. A market response model was developed during this research to model market share evolution over time ([5]).

However, cooperation models are as important as competition in techno-economics. Actors cooperate to develop technology standards through various associations and alliances. In addition, cooperation also aims at cost sharing possibilities. In large infrastructure rollouts, synergies during the outside plant deployment can be gained, as described in [3] and [12].

In Chapter 6, game theory is introduced as a methodology to capture competitive and cooperative interaction in techno-economic analysis. Game theory is an established field, offering various concepts for selecting equilibria[1], the expected outcome of competition. Despite the broad toolset game theory offers, it has not penetrated into techno-economics, and especially not in business case analysis. In this chapter, we present a hands-on game theory approach, suited for extended techno-economic analysis. We have developed a framework implementing this approach, which was used in different publications ([1], [9]).

Chapter 7 combines the option thinking from Chapter 4 with the game theory approach from Chapter 6. Two main approaches are described, option games and sensitivity games. We elaborate on a toy example to describe the option game methodology. Sensitivity games are the first step towards extending the hands-on game theory approach we developed in Chapter 6 with the concepts of real options. A typical game is extended with underlying uncertainty, to assess how this uncertainty impacts the outcome. To move towards a real option extension of the hands-on approach, a move towards continuous flexible games is required. These extensions are qualitatively introduced as a part of future work.

This dissertation is concluded with a short overview of the work and its results, together with a general conclusion. We also link back to the topics for future work identified.

[1] An equilibrium is a state in which competing influences are balanced. In scope of this dissertation, equilibrium refers to the equilibrium concepts of game theory. In game theory, different equilibrium concepts exist. Two definitions will be applied throughout the dissertation, namely a state in which no player can gain by unilaterally changing its strategy (Nash) and a state in which no player can gain without decreasing the gain for any other player (Pareto).

1.2 Publications

The results of our work are disseminated in several papers published in international journals and presented on international conferences. Below an overview is given of all publications realised during the course of this research.

1.2.1 A1 Publications Referenced in the Science Citation Index

[1] **Tahon, M.**, Lannoo, B., Van Ooteghem, J., Casier, K., Verbrugge, S., Colle, D., Pickavet, M., et al. “Municipal support of wireless access network rollout: A game theoretic approach.” Telecommunications Policy, 35(9-10), 883–894. doi:10.1016/j.telpol.2011.06.007, November 2011

[2] **Tahon, M.**, Van Ooteghem, J., Casier, K., Verbrugge, S., Colle, D., Pickavet, M., & Demeester, P. “Improving the FTTH business case - a joint telco-utility network rollout model.” accepted for publication in Telecommunications Policy

[3] **Tahon, M.**, Verbrugge, S., Colle, D., Pickavet, M., Demeester, P., Wright, P., & Lord, A., “Valuing Flexibility in the Migration to Flexgrid Networks”, Journal of Optical Communications and Networking (JOCN), 5(10), A184-A191

[4] **Tahon, M.**, Verbrugge, S., Willis, P.J., Botham, P., Colle, D., Pickavet, M., & Demeester, P. “Real Options in Telecom Infrastructure Projects – A Tutorial”, accepted for publication in IEEE Communications: Surveys and Tutorials

[5] **Tahon, M.**, Casier, K., Verbrugge, S., Colle, D., Pickavet, M., & Demeester, P. “Market Response Modelling under Competition: A Modular Approach”, submitted to The Engineering Economist

[6] Vannieuwenborg, F., **Tahon, M.**, Verbrugge, S., Pickavet, M., & Colle, D. "Deploying charging infrastructure for electric vehicles; viability analyses for municipal and private car parking facility operators", submitted to European Journal of Transport and Infrastructure Research

[7] Van der Wee, M., Verbrugge, S., **Tahon, M.**, Colle, D., & Pickavet, M., “Evaluation of the techno-economic viability of fiber access infrastructure deployment in Europe”, submitted to Journal of Optical Communications and Networking (JOCN)

1.2.2 P1 Publications Referenced in Conf. Proc. Citation Index

[8] Casier, K., **Tahon, M.**, Bilal, M., Verbrugge, S., Colle, D., Pickavet, M., & Demeester, P. (2010). Estimating the economic value of flexibility in access network unbundling. NETWORKING 2010 (pp. 362–372). Springer.

1.2.3 Other Publications

[9] Lannoo, B., **Tahon, M.**, Van Ooteghem, J., Pareit, D., Casier, K., Verbrugge, S., Moerman, I., et al. (2009). Game-theoretic evaluation of competing wireless access networks for offering Mobile Internet. Competition and Regulation in Network Industries, 2nd Annual conference, Proceedings.

[10] **Tahon, M.**, Verbrugge, S., Lannoo, B., Van Ooteghem, J., De Mil, P., Pickavet, M., & Demeester, P. (2010). Parking sensor network: economic feasibility study of parking sensors in a city environment. Telecommunication, Media and Internet Techno-Economics, 9th Conference (CTTE), Proceedings (pp. 1–8).

[11] **Tahon, M.** (2010). Flexibility and competition in the telecom sector: an integrated model for techno-economic evaluation. 11e UGent-FirW Doctoraatssymposium.

[12] **Tahon, M.**, Van Ooteghem, J., Casier, K., Deschuttere, L., Verbrugge, S., Colle, D., Pickavet, M., et al. (2011). Cost allocation model for a synergetic cooperation in the rollout of telecom and utility networks. 10th Conference of telecommunication, media and internet techno-economics (CTTE) (pp. 1–7).

[13] Van Ooteghem, J., **Tahon, M.**, Degadt, W., Braet, O., Verbrugge, S., Colle, D., Pickavet, M., et al. (2011). Evaluation of the techno-economic viability of smart metering value network configurations based on a consumer oriented approach. Competition and Regulation in Network Industries, 4th Annual conference, Proceedings (pp. 17).

[14] Verbrugge, S., Van Ooteghem, J., Casier, K., Van der Wee, M., & **Tahon, M.** (2012). Cost-Efficient NGN Rollout. Telecommunication Economics, Lecture Notes in Computer Science 7216, pp. 138–147.

[15] Strobbe, M., Mets, K., **Tahon, M.**, Tilman, M., Spiessens, F., Gheerardyn, J., De Craemer, K., et al. (2012). Smart and secure charging of electric vehicles in public parking spaces. Proceedings of the International conference on Innovation for Sustainable Production (i-SUP) (pp. 3–8).

[16] **Tahon, M.**, Van Ooteghem, J., Verbrugge, S., Colle, D., Pickavet, M. (2012). How to overcome barriers for smart meter introduction? A techno-economic analysis. Telecommunication, Media and Internet Techno-Economics (CTTE), 11th Conference of. Athens, Greece.

[17] **Tahon, M.**, Verbrugge, S., Willis, P. J., Botham, P., Colle, D., & Pickavet, M. (2012). Migration to Next Generation Access Networks : a Real Option Approach. Proceedings of ROC 2012 (pp. 11). London.

[18] **Tahon, M.**, Casier, K., Verbrugge, S., Colle, D., & Pickavet, M. (2012). Promoting Next Generation Network Investment Through Adapted Performance Indices. TPRC. Washington DC, USA.

[19] Verbrugge, S., **Tahon**, **M.**, Evenepoel, S. "Valuing flexibility in telecom infrastructure projects using real options thinking,", Tutorial in Networks 2012, Rome, Italy, Oct 15 – Oct 19, 2012.

[20] **Tahon, M.**, Verbrugge, S., Colle, D., Pickavet, M., Wright, P., & Lord, A. (2013). Valuing Flexibility in the Migration to Flexgrid Networks. Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013, NTh1I.6. doi:10.1364/NFOEC.2013.NTh1I.6

[21] **Tahon, M.**, Verbrugge, S., & Colle, D. (2013). Measuring fixed broadband policy through composite indices. 5th ITS Europe PhD seminar.

[22] **Tahon, M.**, Van der Wee, M., Verbrugge, S., Colle, D., & Pickavet, M. "The impact of inter-platform competition on the economic viability of municipal fiber networks", Submitted to Optical Fiber Communication Conference 2014.

2
The Need for Extended Modelling Techniques in Techno-Economics

"Years ago, I noticed one thing about economics, and that is that economists didn't get anything right", Nassim Nicholas Taleb

The focus of this dissertation is on the requirement for advanced evaluation techniques for techno-economic analysis. Two main reasons can be identified in the current economic environment to motivate this need, namely uncertainty and competition.

Following this introduction, this chapter will provide the necessary background on the standard techno-economic analysis methodology, indicating why it fails at capturing the impact of uncertainty and competition. As a result, the main research questions addressed in this dissertation will be introduced, with a link to the identified solutions, which will be tackled in later chapters of this work.

In order to indicate the need for advanced techniques and the methodologies proposed in this work, a case study will be covered in this chapter. The considered case studies the migration towards Fibre to the Home (FTTH) access networks. Every following chapter will link back to this case to indicate the impact of the different methodologies and tools offered.

2.1 Uncertainty and competition in the environment

The first reason motivating the need for advanced evaluation techniques is the constant and rapid evolution in the telecom sector, clustered with the doubt surrounding future economic growth. This increases the uncertainty of the environment in which companies make investment decisions. Several real-life examples reflect this uncertainty. The financial crisis has reduced the consumer confidence, resulting in a decrease in consumption by these consumers. As a result, turnover growth rates have decreased. Another example is linked to the ongoing technological evolution in the mobile phone sector. Cell phones have evolved from portable phones to handheld computer devices, allowing users to be connected everywhere, every time. This evolution is reflected in the market evolution during the past decade. While Nokia has been the largest mobile phone producer from 1998 to 2011, Samsung has overtaken them in 2012. The main cause is the small market share of Nokia on the smart phone market, where Google (Android) and Apple (iOS) dominate. In this smart phone market, Nokia's market share is not even in the top five. In the overall mobile phone market, Nokia's share has been steadily dropping to 15%. Linked to the evolution of devices, customers require an ever increasing bandwidth. The first mobile phones were only used for voice communication. The Global System for Mobile Communication (GSM) standard describes the protocols for second generation digital cellular networks. As data communication became more important, new standards were developed, leading to third (3G) and even fourth generation (4G) protocols. Long Term Evolution (LTE) already offers a peak download data rate of 100Mbit/s, while LTE Advanced can handle data rates up to 1 Gbit/s. Another source of technological uncertainty is linked with the performance of new technologies and equipment. Achieved speeds of wireless technologies are impacted by several environmental factors. Attenuation of signal strength is impacted by line of sight, physical obstacles like walls and interference with other technologies. And how is such uncertainty handled when planning and dimensioning the network?

Next to general economic environment and technological evolution, a third uncertainty driver is regulation. Regulatory regimes can have a large impact on the initial viability assessment of business cases, but this regime can also change significantly during the project lifetime. For example, in Brussels, the government has decided to only allow antennas with a electromagnetic field up to 3 volt per meter. In addition, in a radius of 200 meter around the antenna, only 1.5 volt per meter is permitted. As regulation impacts the technology modelling, resulting in the requirement to install a denser mobile network, this increases the costs and thus reduces the viability of a 4G network deployment by a mobile network operator in the capital of Belgium. As spectrum licences have already been acquired for a larger geographic area, this regulation in turn reduces the economic viability of the 4G spectrum investment. In the fixed broadband market, European National Regulatory Authorities (NRA) have implemented two aspects concerning local loop access. First, incumbents must provide access to their local loop to other licensed operators. Providing such access requires the installation of extra equipment in the central offices and results in extra operational processes when customers are connected or migrated. Secondly, price caps for this access to the local loop were introduced. New entrants pay a fixed monthly rental fee per customer to get access to the network of the incumbent. By enforcing such prices, regulation clearly impacts the profitability of both the incumbent's and new entrant's business case.

The second motivation is the continuing trend in market structure. As a result from the liberalisation in Western economies, only few industries remain protected. All other sectors are characterised by competition between different companies. Two examples of such sectors are the energy and telecom market, which have undergone significant liberalisation in the last two decades [2.1]. In the European energy market, former monopolies have been opened up to new, possibly foreign entrants. Today, consumers can purchase energy from different suppliers, those suppliers can buy their energy on a market where different producers offer energy. Only the transport and distribution networks remain a natural monopoly. However, by splitting the previously vertical integrated providers, extra operational processes are now required, e.g. in the case of billing, customer migration, etc. In the telecom market, a similar trend has occurred. In the 1990s, the former incumbents have lost their monopoly on voice and data transmission, increasing the dynamism, uncertainty and competition. At the same time, other sectors previously populated with multiple firms have noticed a trend of continuous consolidation, resulting in oligopolistic markets.

These two aspects can be categorised as increased uncertainty and competition. Within this environment, companies need to make investment decisions, taking into account that whatever they decide; the outcome of the investment project is subject to a lot of uncertainty and might trigger competitive reaction. Cost evolution and customer preference are only two aspects impacting the outcome. In addition, within the concentrated market, the company needs to take into account the effect of their decision on its competitors, and possible reciprocal actions. Price wars are just one example of such competitive interaction. One firm decides to lower its price in order to attract a higher market share, churning customers from competition. However, when competitors observe this effect, they lower their prices as well. With such dynamics, a vicious circle can occur, where companies continue to lower their prices, up to the level of their marginal production cost. As a result, some firms will be forced out of the market, as they can no longer generate profit, while the remaining firms operate at very low or even zero profit margins.

However, competition is not the only possible market interaction. In a concentrated industry, cooperation models emerge as well. While overt and tacit collusion are forbidden, firms can cooperate in order to gain competitive advantage. This can be by striving for cost reductions, but also in search of new standards. In case of the development of the successor of the DVD format, different industry players cooperated in the Blue-Ray disc Association. Other examples are 3GPP and the Wi-Fi Alliance. In case of Wi-Fi, early Wi-Fi (802.11) suffered from interoperability problems. As a result of a compromise in the standardisation process, two incompatible modulation options were provided. A group of vendors founded the Wireless Ethernet Compatibility Alliance (later the Wi-Fi Alliance) to resolve this issue and promote their preferred option. They set up the testing and certification under the Wi-Fi certification logo [2.2].

When operating in this environment, companies face two challenges in managing these aspects. The first one links to uncertainty surrounding future evolutions. Following your gut feeling tells you it is better to remain flexible to react to unforeseen changes, than to commit all your resources into a do-or-die decision. In a static environment, the latter would be without risk, but with fast and unpredictable changes, the former is the most interesting. Committing without flexibility to change comes with high risk. As a result, in every investment decision, it should always be checked if you can react flexibly to a changing environment. In absence of competition, it is better to wait with the investment until no more uncertainty remains.

The second challenge is managing competition, and more specifically, gaining and maintaining a competitive advantage. In this case, gaining a first mover advantage is typically the key to gain the advantage. When moving first, the company cam pre-empt competition. Research and Development (R&D) efforts in order to obtain patents or the purchase of a wireless spectrum licence fit under gaining such a competitive advantage. However, the decision to make the investment in R&D or in licences must thus be made under a large amount of uncertainty. The chances of R&D in resulting in the discovery of new medicine are small, and a wireless license is acquired before introduction of the new service, thus resulting in a large uncertainty on the potential customer uptake and the related revenues, or even on the performance of the new technology in the field.

As a result, companies operating in the current environment are constantly balancing these two opposite ideas. They want to remain as flexible as possible, postponing investment until the uncertainty clears, and trying to move as fast as possible to keep ahead of their competitors. Translating these two concepts so they are reflected in the project valuation is a main question arising today. Traditionally, such valuations are conducted through a techno-economic analysis.

A typical techno-economic analysis consists of modelling cost and revenue predictions. The modelling is based on a clear understanding of the underlying technologies, hence techno-economics. Performing a techno-economic analysis of the deployment of a mobile broadband access network (e.g. 4G) requires insight in the provided data rates, cell capacities, impact of line of sight, etc. From this modelling, an interpretation of the economic viability of the project can be made. However, this approach can only be followed when the actor conducting the project has financial objectives. In reality, actors have additional non-financial objectives. Or even no financial objectives at all, e.g. regulators. More background on players and their objectives can be found in Chapter 3.

2.2 Standard techno-economic approach

All investment problems are economically assessed before they are started. In general, this analysis consists of obtaining a clear view on the underlying technology, predicting the future incoming and outgoing cash flows of the investment project for each discrete time period, discounting them with an appropriate discount factor and then adding them to come to the Net Present Value (NPV) (eq. 2.1) [2.3]. When this NPV is positive, the project is assessed as profitable and the project is executed. This is the approach typically followed by network planners. We refer to Section 3.5.1 for an in-depth discussion of NPV.

$$NPV = \sum_{i=0}^{n} \frac{CF_i}{(1+r)^i} \tag{2.1}$$

2.2.1 Techno-economic methodology

In [2.4], Verbrugge et al. introduced their techno-economic methodology (Figure 2-1). The approach consists of four steps, covering all required aspects in the analysis, going from identifying and delineating the problem, over modelling of the different sub-problems to economic evaluation with possible extensions. We refer to their work for a detailed description. This methodology will be applied to analyse the case study in Section 2.3.

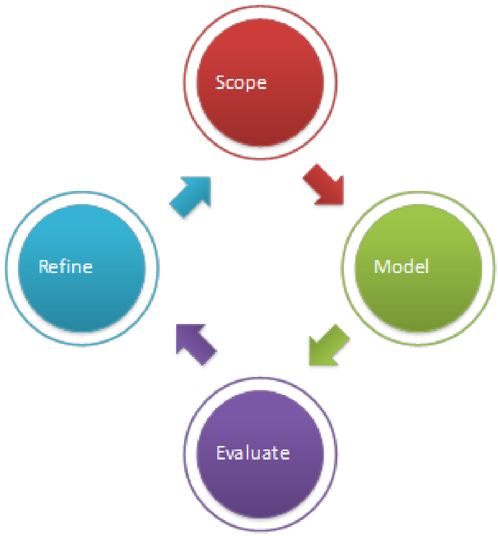

Figure 2-1: Techno-economic analysis methodology [2.4].

The first step is scoping the problem and it consists of three phases. To start an economic evaluation, all necessary data needs to be collected. This includes information about the targeted area, the market situation and the technologies that can be used. In the second phase, the problem as a whole is divided into smaller, more manageable problems. The targeted area is divided in smaller areas, and users are put in target groups. In addition to that, the services offered are discussed, and cost and revenue impact factors are summed up. In the last phase of planning, the input data collected from the previous steps is processed. Business modelling, technical design and user adoption are covered. Already in this first step, the impact of uncertainty, flexibility and competition comes into play. How correct is the gathered input data on user adoption and technical parameters like data rates? In addition, if two technical designs are compared, they will differ in the amount of flexibility they offer towards future migration. A Fibre to the Cabinet (FTTC) network using Very high speed digital Subscriber Line (VDSL) can offer comparable data rates as a Hybrid Fibre Coax (HFC) network using DOCSIS 3.0 or a point-to-multipoint FTTH network, but the upgrade possibilities of each physical infrastructure and network technology differ.

In the modelling step, using all the input data from the planning step, the costs and revenues structures are developed. Both capital expenditures (CapEx) and operational expenditures (OpEx) are considered. Top-down and bottom-up approaches are possible. The modelling performed here will be impacted by the additions proposed to the first step. Uncertainty in customer adoption impacts the modelling of the required equipment through the bill of material. Is spare capacity provided to host all households in an area or is only a partial rollout performed. In the first case, sufficient capacity is present in all cases, but this obviously comes at a higher initial cost compared to the second option. In the second case, capacity could run out, requiring the operator to provision for flexible extensions of the initial installation.

In the evaluation step, the economic evaluation is carried out. The standard method to evaluate financial feasibility is the NPV analysis. This figure gives a first indication of the financial feasibility of the project. When multiple actors are present in the value network, a NPV calculation needs to be performed for each one of them. The total NPV of the project is then equal to the sum of the individual NPVs.

In the fourth step, the initial analysis is refined. This refinement is driven by the several shortcomings of the NPV analysis to reflect the underlying challenges and opportunities the technical design and the environment offers. The main focus of this dissertation is on the various refinements possible in techno-economic analysis. The topics investigated in this dissertation and their relation with the techno-economic analysis are indicated in Figure 2-2. We discuss the driving factors for these refinements and their solutions in the next section.

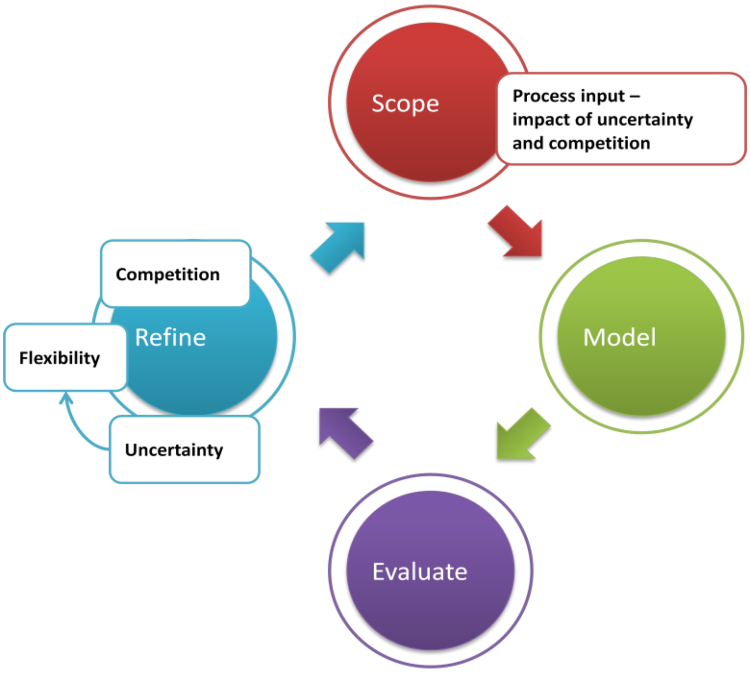

Figure 2-2: Investigated topics and their relation with the techno-economic analysis methodology

2.2.2 Shortcomings of NPV methodology

Conducting a standard NPV analysis can yield unintuitive results, both in light of uncertainty and competition. These unintuitive results are linked to the two main drawbacks of the NPV analysis.

2.2.2.a Measuring uncertainty and flexibility

In an NPV analysis, the future cash flows of the investment are projected. In this cash flow projection, several assumptions on future evolutions are made, but they are assumed certain. In reality, this assumption does not hold. When the required equipment is dimensioned for the rollout of a Fibre to the Cabinet network, several aspects are driven by the number of customers. A street cabinet can only host x cards, each card can only host y users, etc. However, this number of customers comes with a certain degree of uncertainty and is impacted by the level of competition with other installed infrastructures. In addition, it will differ between several regions. Business areas could for example require more connections compared to rural ones.

Secondly, the project path used in the NPV analysis is considered fixed. Once the decision to invest is made, no deviation from the initial project path is possible. Again, in any business environment, such an assumption does not reflect reality. In case of the FTTC network, the initial street cabinet could reach full capacity, e.g. due to an underestimate of the customer uptake. Once this happens, the operator can install extra capacity, or even upgrade its network.

As such, it can be stated that the NPV analysis does not indicate the impact of uncertainty and flexibility on the analysis. However, it still remains the most widely used tool to assess investment viability.

Although the standard NPV analysis suffers from these serious drawbacks, extensions to this method have been proposed to tackle these problems. In order to include the impact of uncertainty on the analysis, two extensions have been proposed, namely the scenario analysis and the 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 and how this impacts the required equipment. 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 [2.5], [2.6].

The second extension is the sensitivity analysis [2.7]. While a scenario analysis only studies a few possible scenarios, the sensitivity analysis studies 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 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 [2.6], [2.8], [2.9].

While incorporating uncertainty in the analysis might still be a straightforward exercise, flexibility cannot be handled as intuitively [2.10], [2.11]. In NPV analysis, 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 case, this condition is not fulfilled. Real Option (RO) Theory has been formulated to capture 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. The concepts of RO are introduced in Chapter 4.

2.2.2.b Measuring competitive and cooperative interaction

The second drawback of the NPV analysis is the lack of possibilities to incorporate competitive and cooperative interaction. When conducting the analysis, the decision maker has to define the future cash flows. However, once the project is conducted, there might be an impact on the market equilibrium, resulting in counteractions by competitors. Two aspects come into play here. Take the example of the introduction of a new fixed broadband service offer in an already saturated market. The only way this offer can gain market share is by churning on the market share of the other existing offers. When conducting the techno-economic analysis, it is thus required to be able to model the future adoption evolution under competition. More information on market modelling can be found in Chapter 5.

Secondly, competitors might counteract, and these counteractions can impact the viability of the initial strategy, and it could be that another strategy was better chosen at the beginning. Note that such counteractions can also consist of cooperative actions. In order to model such behaviour, it is required to estimate the viability of different strategies under different competitive or cooperative counter strategies. In this case, the strategy resulting in the highest payoff might never be reached, as competitors will not choose the strategy maximising your payoff. Here, more advanced tools are required to find the strategy and the resulting payoff. Game Theory (GT) methodology provides such a toolset, and is described in detail in Chapter 6.

2.2.3 Other issues in techno-economic analysis

Up to now, it was assumed that decision makers had one objective, value creation, which is measured in financial terms, typically through NPV. However, value maximisation is not always the sole goal. Private players have other objectives next to the financial ones. Market share, customer satisfaction or operational excellence are just a few of these objectives. In case of public players, financial objectives can be absent altogether. In broadband networks, the goal of regulators is sufficient competition on the market, large penetration, high bandwidths, etc.

In a multi-objective environment, these – sometimes – conflicting goals increase the complexity of the analysis. A correct quantification of these objectives is therefore important for a more realistic techno-economic analysis. This issue will be tackled in the next chapter.

2.3 Case – the deployment of a fixed broadband access network

Techno-economics focuses on the analysis of investment problems, taking into account both the technical background as the economic implications of the problem. Throughout the previous sections, we already referred to various telecom related examples in which uncertainty, flexibility and competition played an important role. To indicate how the different extensions to this analysis discussed in this dissertations work in practice, we will apply them to a case study, the rollout of a fixed broadband access network in a city environment. However, other applications will be introduced throughout the different chapters.

The first steps of the standard techno-economic analysis of the case is conducted in this section, and we will indicate where this analysis fails to capture the underlying reality. In the following chapters, we will link back to this case to indicate how the different tools introduced impact the case.

2.3.1 Case – description

The installation of fibre access networks has been drawing a lot of attention in techno-economic research in the last years. In order to meet the increasing consumer demands for higher bandwidth, both in downstream and upstream, the existing copper based access networks require upgrading towards higher speeds. To achieve this access speed increase, the installation of fibre in the access network is required. The closer fibre is brought to the customer, the higher the potential speed offered to the customer. When the entire access network consists of fibre, the network is a so-called Fibre to the Premises (FTTP) or Fibre to the Home (FTTH) network.

Two different approaches can be identified to install such an FTTP network. The first approach is typically followed by operators currently operating their own physical infrastructure. Since they have their own infrastructure, they opt for a gradual migration of this network towards FTTP. Currently, fibre is installed up to the Central Office (CO). Following a stepwise migration, towards FTTC and FTTP, the investment is spread over time, sweating the existing assets. The second approach consists of building the FTTP network from scratch. Obviously, this will require higher upfront expenditures compared to the first approach. We will discuss both approaches in this section. In the migration case, the migration of the copper network in London will be studied [2.12], while the rollout of a Greenfield FTTP network focuses on the city of Ghent.

2.3.2 Migration to FTTC in London

When the stepwise migration to FTTC and FTTP is considered, we focus on an incumbent currently possessing a nationwide copper access network, which has already been upgraded towards Fibre to the Central Office. This allows offering Asymmetric Digital Subscriber Line (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 Very high bit-rate Digital Subscriber Line (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 (DSLAM) 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%.

2.3.2.a Technology overview

Before the business case is introduced in detail, a short introduction to FTTC and FTTH networks is given. In order to provide consumers with higher bandwidths, network operators are migrating the current copper access networks towards FTTC and even FTTH networks. Research concerning the technologies used to provide these higher bandwidths is still ongoing, with Wavelength Division Multiplexing – Passive Optical Network (WDM-PON) as the most recent technological evolution. However, the focus in the 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 first focus on the topology design of FTTC and FTTH networks [2.13]. This design is a key input in the techno-economic analysis, as the choice of the design impacts the resulting installation costs.

FTTC topology

The fixed telecom access network can be represented by a tree structure, with the local exchange as the source node. From this local exchange, copper cables towards the street cabinets depart. At each street cabinet, there are again copper cables running towards distribution points (DP) and finally to single households. For the initial installation, VDSL cabinets are installed on the current cabinet locations, together with the necessary fibre and ducts in the A and B segments. 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. A graphic representation of the access network can be found in Figure 2-3.

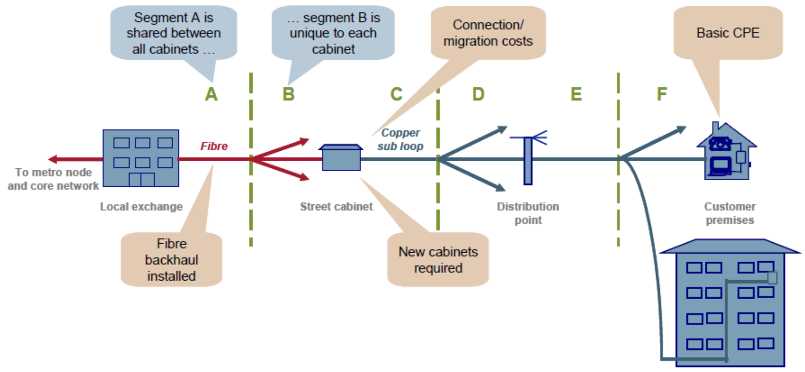

Figure 2-3: Overview of a copper access network topology [2.14]

FTTH topology

For the FTTC solution described above, fibre cables have only been installed up to the street cabinets. Now, for an FTTH solution, a fibre will need to be deployed towards the customer's premises. Figure 2-4 shows the topology for the FTTH network. The C segment is cabinet specific, so it is only installed once. As the F segment is customer specific, this can be deployed when the customer wants to connect. The D and E segment are splitter specific and should thus be installed per splitter. Since customers will be geographically dispersed at the street cabinet location, we cannot expect the splitters to fill up gradually. Therefore, a splitter fill rate was taken into account, requiring that a new splitter and the according D and E segments are provisioned after 40% of the previous splitter is full.

Next to extra fibre deployment in the access network, the migration towards an FTTH network also requires new optical equipment in the local exchange. For an FTTH network, G.PON cards need to be provisioned in this exchange. At the customer's premises, a Customer Premises Equipment (CPE) is installed.

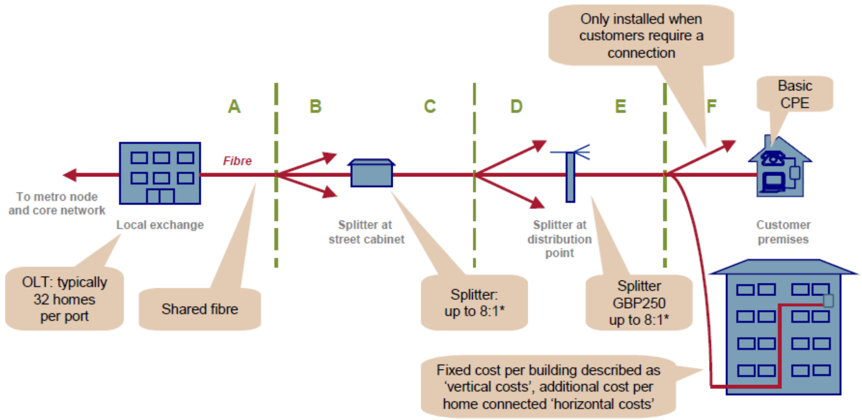

Figure 2-4: Overview of an FTTH access network topology [2.14]

DSL technology

Digital Subscriber Line (DSL) is a family of technologies to provide internet access through data transmission over the local copper loop of the telephone network. Depending on the DSL flavour used, the downstream access speed ranges between 8 Mbps (ADSL) and 100 Mbps (VDSL2), while the upstream speed is between 1 Mbps (ADSL) and 100 Mbps (VDSL2). These speeds are theoretical speeds, and are dependent on the copper loop length. As a rule of thumb, the longer the copper loop, the lower the speed achieved in the field is.

ADSL G.992.1

ADSL technology transmits data over the local telephone network. It operates in full duplex, using frequency division duplex (FDD) to separate the upstream and downstream data flows. For the upstream communication, the 26.075 kHz to 137.825 kHz band is used, and the 138 kHz – 1104 kHz band for downstream communication. With the ADSL standard, the bandwidth can be supported over ranges up to 4km.

VDSL2 ITU G.993.2

The VDSL2 technology allows for higher access speeds compared to the ADSL technology. It uses the 25 kHz – 30 MHz band. However, this implies that the advertised speed deteriorates quickly with the distance to the source. When the copper link is longer than 300 meters, performance degrades as the loop attenuation increases. As copper loops are required to be shorter in order to operate VDSL (or VDSL2), fibre needs to be brought closer to the customer, resulting in an FTTC network.

2.3.2.b Business case evaluation

The standard techno-economic analysis of the FTTC deployment in the UK will follow the methodology proposed in [2.4]. In the UK, COs are clustered into 13 geotypes. These geotypes differ on population density, local loop length and number of connections. The model developed in this dissertation allows to conduct the analysis for all different geotypes. Here, only the results for a typical CO in the London area are described. 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, able to offer VDSL access to 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, the model calculates the necessary amounts of equipment in the local exchange and for each cabinet separately.

Service adoption modelling

Modelling the adoption of the offered services is an important aspect of the standard business case analysis. Customer adoption is the main driver of revenues and variable costs. As such, it has a major impact on the business case evaluation.

While several mathematical models have been proposed to estimate the adoption of services and technologies, [2.15] has indicated the Gompertz adoption curve as the most appropriate approach to model the adoption of telecom business cases as a function of time (Figure 2-5). 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 parameter b, the faster adoption will occur, with $b \in [0,+\infty]$. For telecom cases, values of 4 (a) and 0.3 (b) have been found realistic [2.13][2]. The market potential parameter (m) of 20% used in the case is based on industry insight [2.16].

$$S(t) = m.e^{-e^{-b(t-a)}}[2.17] \qquad (2.2)$$

[2] Actual broadband access adoption data for Belgium was fitted to the Gompertz adoption model using linear least squares.

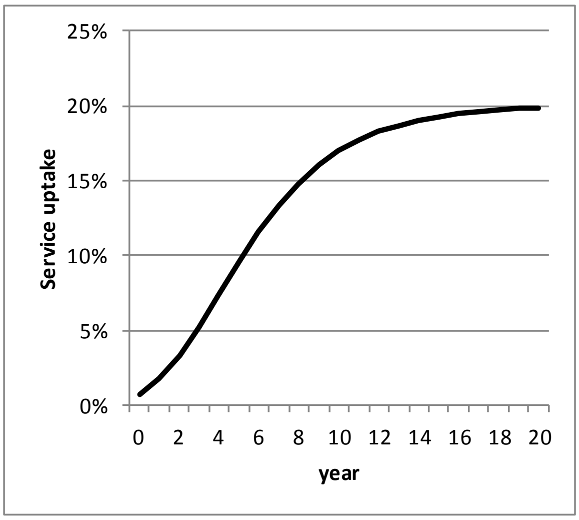

Figure 2-5: Gompertz based FTTC service uptake prediction in London

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 (see Figure 2-3). 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 [2.14]. From the estimated customer adoption, the necessary amounts of equipment in the CO and for each cabinet can be derived (Figure 2-6). The technical dimensioning and equipment model are thus important input for the cost modelling performed in the next section.

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 [2.18], but it is important to link the design to the expected revenues, as has been shown in [2.19].

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. The cable and duct costs also comprise costs for trenching, if required.

In the rollout of FTTC or FTTH networks, cable and duct costs are generally the largest expense [2.13]. 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 [2.14]. The dimensioning of the fibre cables depends on the rollout scenario chosen by the operator. For the small cabinet scenario, the operator estimates that providing for a migration of 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 can be migrated in the cabinet, 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 Gigabit Ethernet (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. The installation of this equipment is demand driven, and only installed when necessary. An overview of the equipment model can be found in Figure 2-6, while cost figures, based on industry insight, can be found in Table 2-1.

Table 2-1: Cost of the different hardware components [2.14]

Hardware component	Remark	Cost (GBP)
Street Cabinet	Small – 144 households	1.250
	Large – 336 households	1.375
ODF	1.440 subscribers	935
GigE card	24 DSLAMs	3.500
Chassis	16 cards	6.000
DSLAM	Cost per port in small cabinet	60
	Cost per port in large cabinet	120
CPE		200
Installation cost CPE		100

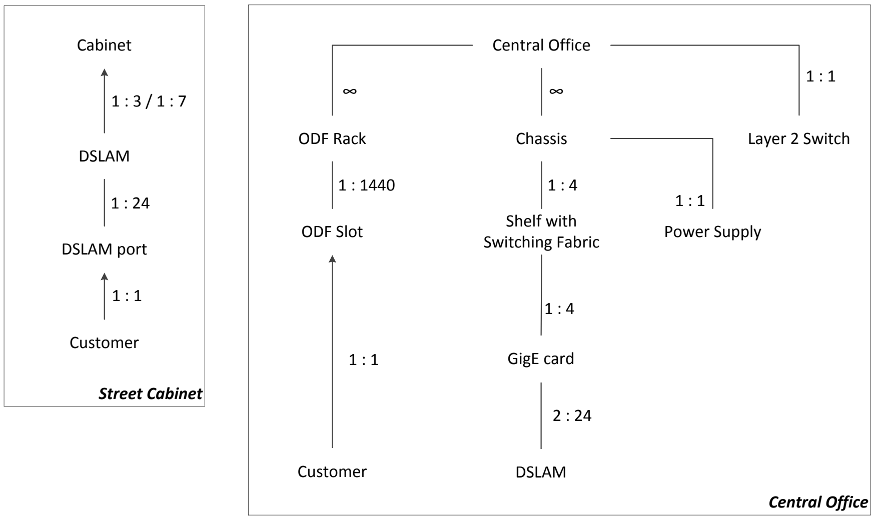

Figure 2-6: Equipment model for FTTC network

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 [2.20], [2.21] but the fractional approach was chosen here to not overcomplicate the analysis. Two main OpEx categories were identified, namely 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.

Revenues

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

2.3.2.c Business case evaluation

Above, the first two steps of the techno-economic methodology from [2.4] were performed. The scope of the problem was defined, gathering information on the technical solutions, network topology, expected customer uptake, etc. From this input data, a detailed model can be built. A model was built to calculate the required equipment installation, estimates on operational costs were made and an indication of the expected revenues per customer was given. With this input and the provided models, the evaluation of the case can be made. This evaluation indicated that the installation of an FTTC network is a financial viable investment. As both a small cabinet and large cabinet installation was considered, we could also conclude that the small cabinet installation offers a higher return. The detailed evaluation can be found in Chapter 3, where we discuss the quantification of objectives.

2.3.3 Installation of an FTTP network in Ghent

In the Brownfield migration, the upgrade of the ADSL network towards an FTTC network was discussed. In this section, a network design with fibre brought even closer to the customer is discussed.

Two different approaches can be identified to build an FTTP network. The first approach consists of installing a dedicated fibre between the CO and the household. This network is called a point-to-point (P2P) network. In the other approach, no dedicated fibre is provisioned, but sections in the network are shared between different users. These networks are called point-to-multipoint (P2MP) networks.

2.3.3.a Technology overview

In P2MP networks, the fibre capacity is shared between multiple households. The shared section consist of the fibre deployed between the CO and the street cabinet, while each household has a dedicated fibre running between the premise and the street cabinet. Such networks are Passive Optical Networks (PON), as optical (1:N) passive splitters are deployed to power-split the signal from one source into N equal signals towards the households. In the other direction, the signals are coupled by the splitter into one signal. In PON networks, all active equipment is located in the CO, and the street cabinets contain the passive splitters. As a result, the OpEx for the street cabinets decreases significantly, as no cooling equipment or power connection is required. As the fibre is shared between the CO and the street cabinet, PON networks also decrease the number of fibres deployed in the network, and thus the maintenance cost for fibre. However, PON networks also have a main disadvantage, since they only offer a limited flexibility in allowing open access on the network, and thus competition.

P2P networks are also called active optical networks (AON). As was already indicated, in these kind of networks, customers are connected through a dedicated fibre to the CO. As a result, there are no intermediate splitters and bandwidth is not shared between customers. Depending on the location of the active equipment, a further distinction between Home Run Network (HRN) and Active Star (AS) can be made. In the first, the equipment is located in the CO, while in the latter the active equipment is installed in the street cabinet. Because of the higher fibre count in these networks, such a topology is more expensive than a PON deployment, but it is more flexible in allowing open access and competition. For both technologies, an equipment tree is provided below (Figure 2-7 and Figure 2-8).

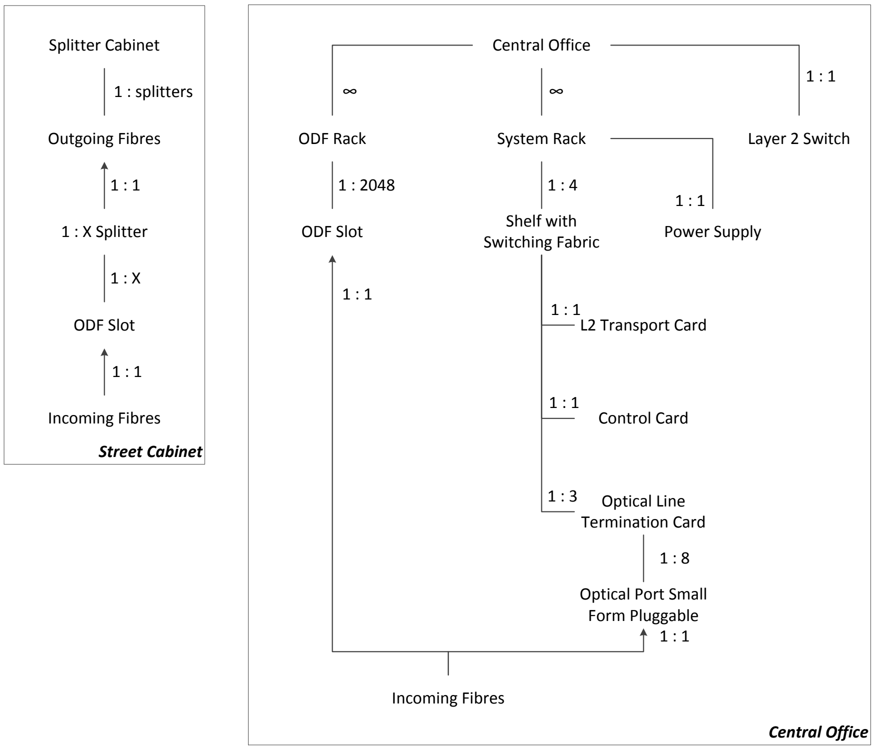

Figure 2-7: PON equipment model

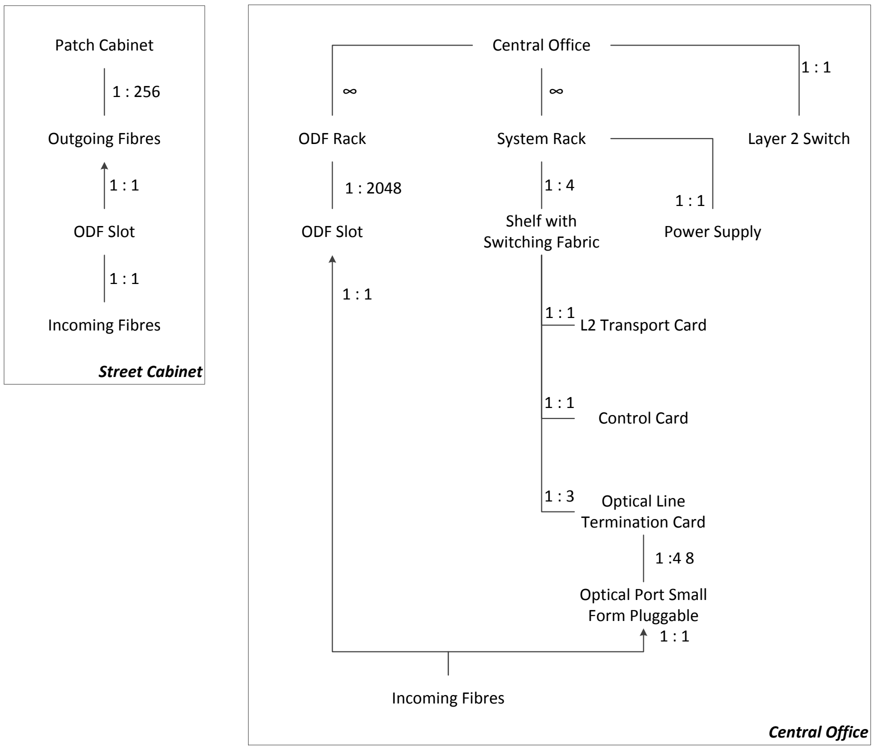

Figure 2-8: P2P equipment model

2.3.3.b Cost and revenue modelling for the deployment

In contrast with section 2.3.2, this case focuses on the Greenfield deployment of an FTTP network in an urban area, the city of Ghent. Here, it was assumed that the project is being executed by the municipal government. Since this player does not currently have a broadband access network, a Greenfield deployment is to be considered.

The city of Ghent is located in the Flemish part of Belgium. It is Belgium's third largest city by number of inhabitants, counting 243,366 inhabitants (as of January 1st, 2010) [2.22]. Apart from these inhabitants, Ghent hosts about 65,000 students in its University and other higher education institutions, of which many reside in the city during the week. These residents are not taken up in the official statistics. The municipality of Ghent (i.e. the city itself and 11 surrounding communities, see also Figure 2-9) covers a surface of 156.18 km², and comprises 134,041 households.

The cost and revenue modelling is conducted in a comparable way as for the previous case. Starting from adoption predictions, the required equipment is dimensioned, and the network topology drives the costs for fibre deployment and trenching. Concerning the revenues, the current used prices for broadband access were used. An average monthly ARPU of €37.7 was used.

As is to be expected, due to the large outside plant investments, the techno-economic analysis indicated that a deployment of FTTP in this area is a costly undertaking, with a long payback period. This payback period is very depending on estimated take-up rate. The higher cost for a P2P network deployment compared to a P2MP network is also reflected in the results of the analysis.

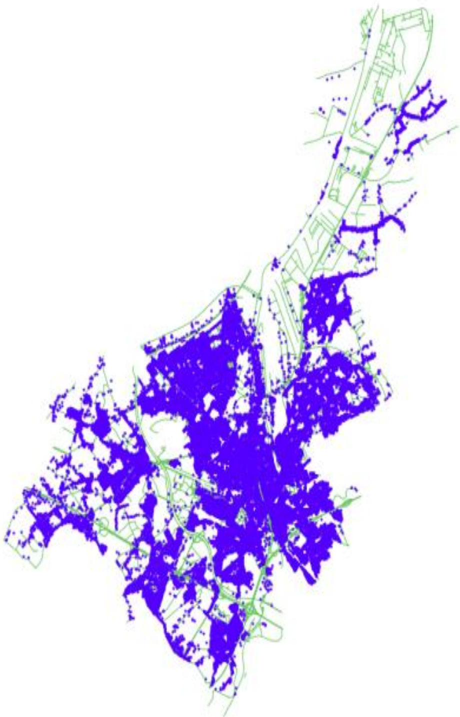

Figure 2-9: The Ghent area, with household location indication

2.3.4 Shortcomings of the analysis

In the techno-economic analyses conducted above, it should be noted that any results obtained are depending on the initial assumptions made. Three important aspects are currently absent in both case analyses, and should be taken into account.

First, both in the FTTC and in the FTTP case, the impact of uncertainty and flexibility was left out. In case of the FTTC migration in the London area, it was assumed that the estimated uptake was correct. However, deviations from this uptake could have a large impact on the outcome. In addition, an average uptake of 20% for the entire London area might be a correct estimate, but no differences between cabinet areas were taken into account. In reality, one area could have an uptake as high as 50%, while another only reaches 5 or 10%. And as the equipment model from Figure 2-6 shows, customers drive the required installation. In addition, in case uptake is higher than expected, the small cabinets could be saturated at a certain point in time. As no extra customers can be connected in this case, this will result in a loss of potential revenues. However, the operator has the flexibility to counter this potential loss by making extra follow-up investments when required. Possible future installations cover the provisioning of an extra cabinet to serve the extra customers, but the network could also be upgraded towards an FTTH network to have extra capacity.

Secondly, no impact of competition is taken into account. When a new FTTP network is deployed in an urban area like Ghent, this new network will be in competition with the existing broadband infrastructures. In this area, both a Hybrid Fibre Coax and FTTC network have already been deployed. The newly deployed FTTP network will thus have to churn customers from these networks. But these networks can execute counter strategies to decrease this churning. Again, the impact of uptake on the dimensioning and equipment modelling will need to be taken into account.

The third aspect covers the objectives captured in the analysis. In the FTTC case, the operator is a private player, so using financial objectives is the correct approach to value investments. However, the second case discussed the network rollout of a municipal player. Here, this player aims at additional objectives, next to financial viability. Universal access, decreasing the digital divide, increasing competition, etc. are only a few other objectives. These objectives should also be captured in the techno-economic analysis.

2.4 Conclusions

Increasing interactions and uncertainty in the current economic environment has an impact on the investment decisions companies need to make. However, the tools these companies have at their disposal fail at incorporating and valuing the impact of both aspects. The migration towards FTTC and FTTH was introduced as case study to indicate how traditional techno-economic analysis is conducted. The results of such an analysis give an indication on the economic viability of the project, but this conclusion is depending on initial assumptions made. A change in an input factor will be reflected in the final result.

In addition, the analysis only captures the financial objective of the decision maker. In reality, as was also indicated in the case study, this decision maker has additional drivers, which cannot be captured through an economic assessment. This dissertation aims at providing insight in the available extensions to techno-economic analysis, incorporating the value of uncertainty, flexibility and competition.

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3
Actors and their Objectives

"Management by objective works – if you know the objective. Ninety percent of the time you don't", Peter Drucker

The need for advanced evaluation techniques in techno-economics was introduced in the previous chapter. It was indicated how competitive and cooperative interaction must be taken into account when making decisions, as these interactions influence the viability of the investment decision. Not only does customer uptake impact the revenue potential, it is also the main driver for the network dimensioning and equipment modelling. However, before these competitive influences can be identified and captured, it is required to know the impacting actors. In this chapter, the basics of multi-actor analysis will be introduced.

A multi-actor analysis serves a double purpose. First, it helps at defining the different roles that must be taken up to produce a good or offer a service. From these role definitions, a detailed cost-benefit model can be built, starting from the underlying technological requirements. Secondly, by sketching the broader picture of the environment in which the company is active, other actors can be identified. Cooperation possibilities and competitive interactions can be indicated in this value network. Following this introduction, some of the important actors in the telecom environment will be discussed.

Building upon the qualitative description of the value network, the detailed quantitative modelling is performed. For this modelling, it is important to have a clear view on both the financial and non-financial objectives of the different actors. For financial objectives, there exists a plethora of metrics. The translation of non-financial goals is more challenging. Specifically for the fixed broadband market, a composite index was developed to measure the regulatory and policy goals.

3.1 Identifying roles and interactions

Before conducting a quantitative analysis of a new investment decision, it is important to identify the possible interactions with other market parties and have a clear view on the scope of the project. The first aspect allows to assess the impact of other players on your own case, while the second aspect serves as input for the delineation of the investment problem, making sure all roles are incorporated. Different models exist to perform such an analysis. We will introduce four models, the Porter five forces model, the Osterwalder model, the PEST analysis and value network analysis.

3.1.1 Porter five forces model

The five forces model was introduced by Michael Porter in 1979 [3.1] (Figure 3-1). It was built as a model for industry analysis and strategy development. The framework introduces five forces that shape competition within a market. Typically, competition focuses on the existing competitors in the industry. The more competitors within your industry, the less attractive the market is. The incumbent telecom operators were and still are operating in a market with few competitors. As they owned and operated the sole network infrastructure, customers had no choice but to buy services from them. However, regulation has stepped in to decrease their power, introducing competition by enforcing local loop unbundling at regulated prices. However, limiting the analysis to only include existing competitors narrows the problem too much and risks a misevaluation of the attractiveness. Therefore, Porter identified four other forces shaping competition. In addition to the existing competitors, two other horizontal forces are included in the framework, namely the threat of new entrants and substitutes. If the market is very attractive at the moment, and no or only low entry barriers exist, the threat of new players entering the market is high. In telecom, such cases are e.g. present in application development. Substitutes pose an analogue threat. These players do not offer the exact same product or service, but one with similar functionalities. Again, the more possible substitutes, the less attractive the market is. For example, if your own product or service is priced too high, customers will look for substitutes offering more or less the same functionality. This behaviour can be noticed in the mobile telephone market. The

emergence of data based services, like Skype for voice telephony or WhatsApp for messaging has churned customers away from the traditional operators.
Next to the three horizontal threats, i.e. industry competition, new entry and substitutes, Porter also identified two vertical threats, the bargaining power of suppliers and consumers. If there is only one company supplying the input you require, you have no other choice than to buy it from him. This puts the supplier in a strong bargaining position. A mobile operator can only acquire a spectrum licence from the government. The same rationale can be followed for the consumer power.
Conducting a Porter five forces analysis offers an indication to the possible interactions between different market parties, but it does not allow a clear view on the detailed breakdown of the roles you need to perform to bring your product or service to market. As such, it offers no guidelines for the quantification required in techno-economic analysis.

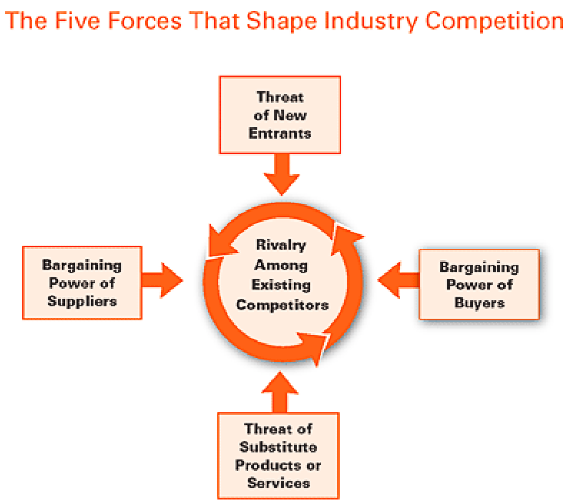

Figure 3-1: Porter five forces model [3.1]

3.1.2 Osterwalder business model canvas

The business model canvas by Alexander Osterwalder offers a template for describing existing or developing new business models [3.2]. It divides the business activity in four main functional blocks: infrastructure, offering, customers and finances (Figure 3-2).
The model is centred around the value proposition, the collection of goods and services offered to the customer that distinguishes the company from its competitors. Both a quantitative and qualitative value proposition are possible. On the left of the value proposition, the main inputs of this value proposition are found. Clustered under infrastructure, the key partners, activities and resources

are defined. Activities aim at executing the value proposition, resources are required input for the value creation and can be human, physical, financial or intellectual. By identifying the key partners, the canvas allows to indicate the important actors impacting your value proposition.

The value proposition is aimed at customers. Differentiation between customers is included by identifying different customer segments. These segments are differentiated on customer needs. In order to reach the different customer segments, channels are included. These channels can be company channels, but a company can also rely on partners to operate the channel. The third aspect of the customer functional block is consumer relationship. This aims at building a relationship with the different consumer segments. Co-creation, self service or personal assistance are possible relations.

The flow from infrastructure over value proposition to customers are built upon the finance functional block. This block is subdivided in the cost and revenue structure. For techno-economic cases, the cost structure entails the detailed equipment model, operational processes, etc.

Analogue to the five forces model by Porter, the business model canvas allows to identify customers and suppliers for the value proposition. In addition, it offers a basic overview of the cost and revenue structure, which is absent in the five forces model. However, it lacks an overview of the possible competitive impact on the value proposition. Compared to the five forces model, the canvas identifies key activities to perform the value proposition, which are required to solve the second aspect of the research question, building a detailed quantitative techno-economic model.

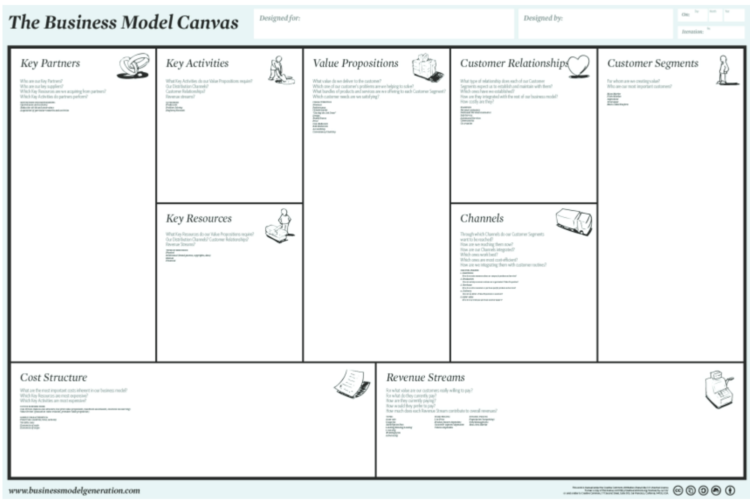

Figure 3-2: Osterwalder business model canvas [3.2]

3.1.3 PEST analysis

The four corner PEST or SEPT model is an extension of the Porter model to capture the business environment. The four dimensions of this model are Political/regulatory, Economic, Socio-cultural and Technological drivers [3.3, 3.4].

The Porter five forces and Osterwalder model focus on industry analysis and business model development, the PEST model has a broader scope to scan for macro-environmental factors. Indeed, such factors could have a clear impact, but are not included in the previous two models. Political factors refer to the degree government intervenes in the economy. Trade regulations, tax laws and privatization moves are examples of such political and regulatory factors. Related to the telecom environment, political and regulatory factors will play an important role. Examples are regulatory intervention in local loop access pricing, spectrum auctioning, etc.

Economic factors encompass macro-economic factors like economic growth, exchange rates, inflation, labour productivity and interest rates. Labour productivity has a direct impact on the cost structure of a company, while interest rates influence the cost of debt capital. In a globalised environment, changing exchange rates affect the cost for imported goods and the revenue for exported goods.

Socio-cultural factors include demographics, like age distribution and population growth. An aging population can result in increasing labour costs, but also in changes of demand for certain services. However, socio-cultural factors are not limited to these demographics. Environmental awareness and consumption habits also fall in this category.

Technological factors cover new scientific breakthroughs, innovation and R&D activity. Again, such factors influence costs, but they can also determine barriers to entry.

3.1.4 Value network analysis

The three models described above each have their own merits and drawbacks, but they fail at offering an integrated view on the entire value network in which the company operates. An approach is required that can indicate both competitive and cooperative interactions, like the five forces model, an identification of the roles and activities (business model canvas) for the quantitative evaluation of the value proposition and the impact of politics, regulation and technology.

Allee [3.5] defines *a value network as any web of relationships that generate tangible and intangible value through complex dynamic exchanges between two or more individuals, groups, or organizations.* Within the scope of this dissertation, we define a value network analysis is a methodology for visualising internal and external value networks. Its building blocks are roles, actors and flows in the environment. Roles are the basic building block of a value network and are defined as the lowest granularity in which an activity can be split up. A role thus refers to an activity with only one responsible. Roles are interconnected, with one role interacting with one or more other roles. These interactions can be information flows, product flows or financial flows. Such a network of roles and their interactions is a value network. For any case studied, there is only one value network.

In the next step of value network analysis, the different roles are attributed to different actors. These actors can be current market parties, but new entrants also need to be considered. This is especially the case when innovative markets are investigated, e.g. the changes in the energy market resulting from a smart meter introduction, as will be described below. While the value network is unique for every case considered, since roles can be attributed to different actors, different value network configurations emerge.

As a value network configuration visualises the different roles taken up by the different actors in the ecosystem, it offers a starting point for the quantitative technology modelling of the business case for the different actors. Additionally, as the value flows were identified, these offer insight in the interactions with other market parties, comparable to what the five forces model offers. However, as different configurations can be identified on the same value network, it can also be used to indicate how competitors address the same value proposition.

3.2 Actors in the environment

In the following section, we will introduce two value network analyses that were conducted during this research. We have chosen for two distinct cases, one in the emerging smart meter market [3.6], one in the Fibre to the Home (FTTH) market. Both cases lend themselves ideally for value network analysis, as both are emerging markets. From the value network introduced, different possible configurations can be built. A comparison of the different configurations can then indicate the pros and cons of each configuration.

Mapping actors on the value network is the key step in building the value network configuration. As such, it is important to have a clear view on the existing actors, but also on possible new emerging actors that can take up roles in the network. In this section, we will introduce the most important actors in both the smart meter and the FTTH market.

3.2.1 Smart meter market actors

The introduction of smart meters in the residential setting is expected to change the existing electricity market value network significantly. Currently, metering at the consumer side is performed using mechanical meters, which are manually read once a year by the distribution system operator (DSO). The meter is also owned by this DSO. The main functionality of smart meters is providing data connectivity between the meter and the backend. As this is the main business of telecom operators (Telco), this actor is also included. The third actor we identify is the energy service company (ESCO). With the availability of a smart meter, companies, like energy providers, but also new non-existing actors, have a direct connection with their customers. This opens opportunities to have tailored offers for different customer segments, steering of appliances, etc. With these three actors, the different value network configurations will be built in section 3.3.1.

3.2.2 FTTH market actors

In the broadband market, different players can be observed. When taking a closer look at the market in e.g. Belgium, the DSL incumbent and the cable operator (CO) are the two dominant players. They are vertically integrated, covering three streams, infrastructure, connection and content and application. The DSL incumbent is the former monopolistic operator, which was forced to open up his infrastructure for new entrants, the so-called other licensed operators (OLO) or alternative network operators (ANP). This decision to open up the network was enforced by the national regulatory authority (NRA). While the other players are typically (partially) private owned companies, the NRA is a government institution. As a result, this player will have clearly different objectives compared to the private players.

In more recent years, different other players have entered the broadband market, trying to claim a share of the revenues. The most well-known players are the over the top (OTT) players. These players have a clear focus on content and applications. Examples are multinationals like Youtube, Google, Facebook, etc.

Since we observe a clear tendency away from vertical integration, the different actors can be clustered according to the three streams, infrastructure, network and services. These actors are the physical infrastructure provider (PIP), the network provider (NP) and the service provider (SP). These actors can be separate market players, e.g. an OTT and an OLO, but can also be integrated in different business units from the same player, e.g. the vertical integrated CO.

There exist a lot of examples in Europe today where new players emerged as PIP actor. In Sweden, municipalities have been the driving force in the deployment of FTTH infrastructure. Other players, like utility providers, can also participate in this role.

The final important actor we want to introduce is the consumer. He is typically the one at which the total value network configuration is aimed. By purchasing services or products, he injects the necessary money flow into the value network.

3.2.3 Interactions between actors

From the description above, it is clear that with different actors active in the same value network, interactions between these actors will emerge. These emerging interactions can be identified through the value network analysis, where value exchanges are indicated between different roles. When actors are mapped on these roles, the value exchanges will be either internal for the actor, or between different actors. In addition, different value network configurations will result in different interactions between actors. By comparing these configurations, it will be possible to indicate the interactions between the different actors and how they impact the value network.

The assessment of the interactions can be performed on four different parameters. The technical design reflects how the chosen configuration impacts the underlying technology of the proposed solution. For example, when the value network configuration requires an open access model, where different players can interact with the underlying product or service, the technical design will require an interface capable of handling multiple players. The business implications of the chosen configuration are equally important. These cover the operational aspects of the interactions. Again, in an open access model, with split responsibilities between different streams in the value network, the implementation of service level agreements (SLA) is a business implication. The third parameter covers the impact on the consumer. The more actors are active in the value network configuration, the higher the possible impact on the customer, especially if he interacts with all these players. Typically, a single point of contact (SPOC) is preferred for the customer. Finally, competitive aspects of the value network configuration are assessed. In a vertical integrated model, where roles are taken up by a single actor, the possibilities for competition are very low. However, when moving towards a value network with multiple actors involved, the opportunities for competition and cooperation increase.

3.3 Selected value network analyses

In this section, we will introduce the value network analysis of two different cases. As already introduced above, the first case tackles the value network of the smart meter market, with a clear focus on the residential level [3.6]. The second case analyses the value network of the FTTH market. By introducing two distinct cases, we aim at indicating the value network analysis methodology in practice. As roles are the basic building block of the value network analysis, the value network configuration offers insight in the required building blocks for modelling the actor in a detailed quantitative techno-economic cost-benefit analysis.

3.3.1 Consumer-oriented smart meter value network

The smart meter market is an emerging market, and is the extension of the typical mechanical metering of electricity streams as performed by the DSO today. Such a mechanical reading reports only aggregate consumption data based on the consumption of the different circuits, and thus appliances, in each house. The data is reported annually by the customer via phone, Internet or post, or by a technician coming to your premises. This legacy scenario is the ‘as-is’-scenario where intelligence and communication ability is not implemented in the meter or in the appliances present in the household.

A smart meter extends the existing electricity provision and mechanical metering role with two extra streams, namely a telecommunication stream and a data stream. These extensions of the existing value network at household level are presented in Figure 3-3. This figure depicts the translation of a value network towards a technical architecture. The technical parts, e.g. electrical meter, communication module, etc. can however be directly mapped to the underlying role. For the electrical meter, this is metering of electricity production and consumption, for the communication module this is providing communication. The three named arrows on Figure 3-3 (P1, P2, P3) are the names of the interfaces of the communication module towards the three connected roles. To not overcomplicate the model, abstraction was made of the higher layers outside the customer’s premises (telecommunication infrastructure for the telecommunication stream, central control server with data repository and smart meter switching capabilities, and hardware and software developments in the data stream) in the model.

The first additional stream towards smart metering is the telecommunication stream. This comes down to extending the value network with two roles, the implementation of a communication module and a gateway, allowing a two-way communication between the household and the central repository system. These two modules combined, the metering and communication module form the smart meter. Secondly, to move towards a real smart energy management system, intelligence needs to be included in the meter. A home energy controller (HEC) is a gateway with software capable of aggregating information and controlling the different appliances within the household in an intelligent way, based on the different signals the smart meter sends to or receives from the central control system. The functionality of the HEC can be installed on different locations: within the smart meter, the telecom router, a separate device in the household or even a cloud based solution. It only needs to be able to communicate with the sub-meters and appliances within the house. External devices such as a stand-alone display or a web-based platform can be used for visualisation of the consumption and production patterns in all of these settings. It may be clear that the choice of value network configuration will impact the technical design, and thus the modelling of the technological requirements.

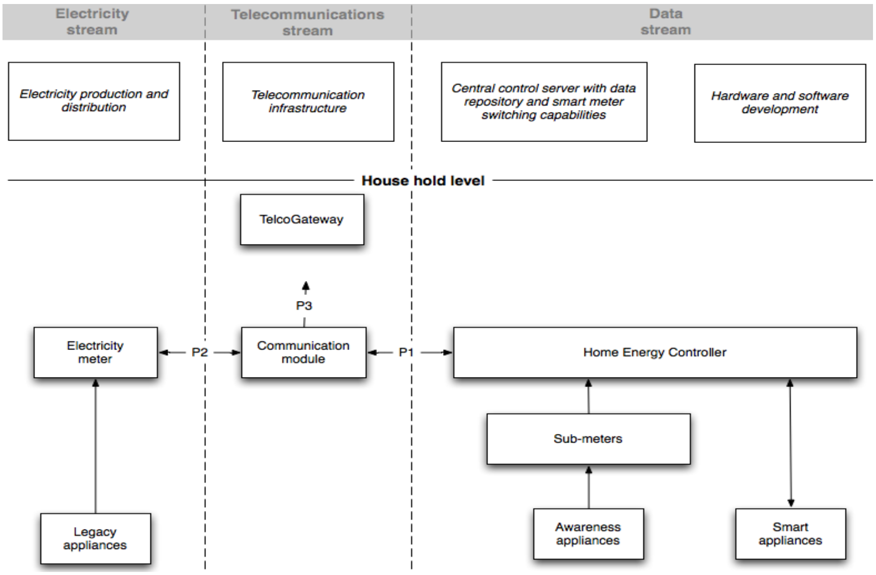

Figure 3-3: The consumer oriented smart meter value network

As already indicated, when different actors take up different roles, other value network configurations emerge. Three different models are described here, the DSO centric model, a Telco model and the ESCO centric model. Additionally, as different configurations result in different interactions between the different actors, the value network configurations can also be assessed on four parameters, their technical design, the business implications, the impact on the customer and the level of competition possible.

3.3.1.a DSO centric value network configuration

In this DSO centric value network configuration, the DSO takes up all roles concerning the smart meter: metering, communication and HEC functionality. This vertical integrated model is the most straightforward model (Figure 3-4). The DSO can take up the role of communication as he can use power line communication (PLC) on his infrastructure to send the meter data. The implications of such a vertical integrated model are discussed below.

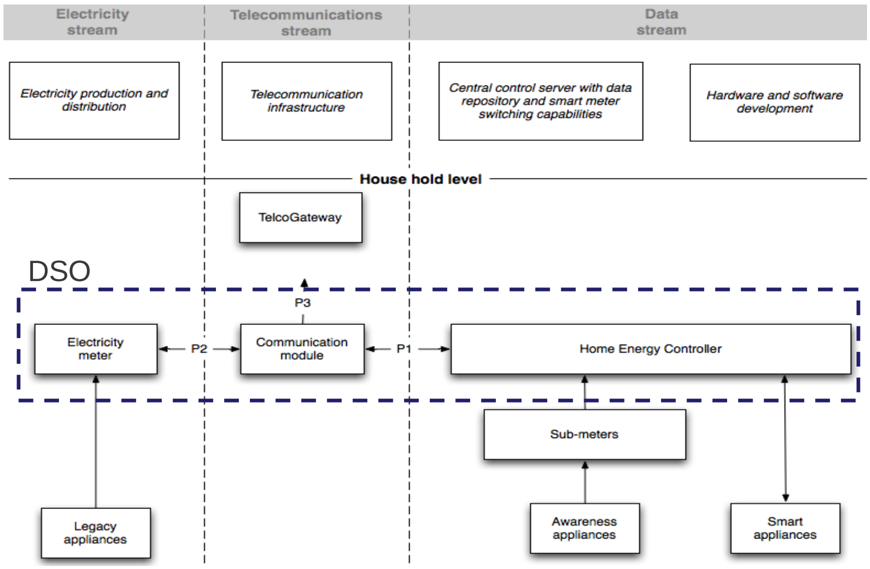

Figure 3-4: DSO centric value network configuration

***Technical**:* As the meter comprises all functionality, i.e. the mechanical meter, communication component and HEC software, installation of this system is relatively easy. However, as an integrated solution is provisioned, it is required that the installation of the meter is performed by a recognised electrician. In terms of operational processes, the existing meter needs to be decoupled and replaced by a smart meter (including communication module), thus the meter data needs to be re-updated in the back office of the DSO, as well as some other administrative issues need to be changed and updated. When problems occur with the meter, such as the replacement of communication module for a new technology, the recognised electrician will need to come down to each house, shutting down the full smart meter including the electricity component, making the replacement and resetting the system. This will require a lot of additional administration in the back office.

In terms of communication, the DSO can make use of its own electricity network to connect the smart meters to its own telecommunication infrastructure via PLC. Additional investments are required in the access network installing amplifiers and connections points in order to cope with all the data (two-way) taking into account a low delay and latency. One of the questions will be the openness of the smart meter, thus what are the ways or standards in which other companies and devices can communicate with the smart meter, for instance in the case of automatically switch on/off devices in the house.

Business: As the DSO is taking care of all activities, everything can be arranged in a more organised and efficient way. He also acts as the SPOC for the end customer. When faults would occur in the network, either in the electricity, telecom or HEC component, the DSO is the only responsible party. This states that all required competences for all these components are available within the DSO organisation. Also a new monopoly is created with control over the smart meter. No innovation is stimulated for services inside the house e.g. additional displays with consumption information, savings on energy, apps, etc. It all depends on the possible interfaces the smart meter offers to the external parties. As the regulation moves towards the energy supplier as SPOC for the end customer, this would require that all the information retrieved from the meter is available for the supplier as well in an open way. The major question is if this kind of service provisioning is a role for a party who offers a public service. As recent regulation required a division between network and services, this vertical integrated model could result in a re-integration.

Customer: For the end customer a single solution with one SPOC would be preferred. Disadvantages are the low possibility of innovation by other parties, the forced placement of the meter and the idea of needing to pay for a service which is enforced by the DSO and with a low (perceived) potential for the end customer. All consumers would be offered the same service, independent of the segment that offers them the highest benefits.

Competition: The level of competition is very low. The DSO is monopolist and controls the ports / interfaces of the smart meter and thus the introduction of innovative services by other actors.

It was indicated that the DSO can use its existing electricity grid as data communication network. However, this would require large investments in these networks. In addition, in most Western European countries, nearly all households have access to either a fixed or wireless broadband access network. A solution to decrease the investment cost for the DSO in the telecommunication stream would be the outsourcing of the communication module. However, this would require some changes in the meter architecture. The existing integrated meter should be changed towards a modular meter, with the two important modules being metering and communication. With such a kind of plug-and-play communication system, maintenance and replacement of the communication module will have no effect on the meter component, reducing the need for a recognised electrician to perform these actions. Additionally, as the meter itself will not have changed, the administrative overhead would also be avoided. This alternative model could thus benefit in many ways. It should be noted that the

DSO still takes up all roles in the value network, and a preferred Telco partner is selected by the DSO.

Technical: Splitting up the electricity and telecommunication streams between separate operators will benefit those actors mostly in the operational phase. Mechanical electricity meters have an average lifetime of over 25 years, while the lifetime of typical telecom components is considerably shorter. This shorter lifetime is mainly driven by a shorter mean time between failure (MTBF). In addition, technological evolution could push operators to replace the communication module with a new module supporting a new communication technology. As mentioned before, if the electricity component needs to be stopped for changing the communication component, this is very costly and causes a lot of administrative issues. When this could be done separately with a modular meter system, this would benefit the customer and the DSO. This change can be done by everyone, not only by an electrician, which would be more convenient and cheaper.

Business: As the cost of the communication module could be paid by the telecom operator, this would lower the total investment cost of the DSO. A fee for data communication can then be paid to the telecom operator on a monthly basis based on the type of network used, also covering the communication module cost. As mentioned above, this would not lead to additional operational processes and costs. The total investment cost of the smart meter (split mechanical electricity en communication module) is more expensive than the fully integrated meter, but in operational costs it is more beneficial. When comparing the total cost of operations over 25 years, it shows a better and cheaper solution compared to a fully integrated solution. In our analysis, we have found that the total initial investment expenditures for a modular meter are about 8% higher compared to the integrated meter for a full rollout in Flanders [3.6]. However, this initial cost is completely offset by the operational costs over the total meter lifetime. When taking only the reduced wages for the personnel making the repairs and the cheaper hardware costs, since only a communication module is required, the modular meter turns out to be 45% less expensive. In total, this comes down to a gain of 6% in the total cost of the smart meter project [3.7]. When taking the reduced administrative overhead into account, even more gains could be achieved with the modular meter system.

Customer: The benefits are relatively the same as in the previous DSO model, as the DSO chooses the telecom operator.

Competition: The level of competition is still very low. The DSO controls the telecom operator and forces the customers to make use of this service. It also controls the ports / interfaces of the smart meter and thus the introduction of innovative services by other actors

3.3.1.b Telco value network configuration

In the Telco model, a telecom operator is introduced in the value network configuration to take up the communication roles. As telecom operator, they are best placed to install and operate the communication module and gateway. In this value network configuration, introducing this actor will require similar changes in architecture of the smart meter as presented above. Historically, the DSO will continue to provide the electricity metering role. However, as communication is not one of their core competences, the communication roles are taken over by the telecom operator (Figure 3-5).

A solution to the communication competences of the DSO would be the outsourcing of the communication module. The difference compared to the model described above, is the ability of the user to choose his preferred Telco instead of the designated operator choice by the DSO.

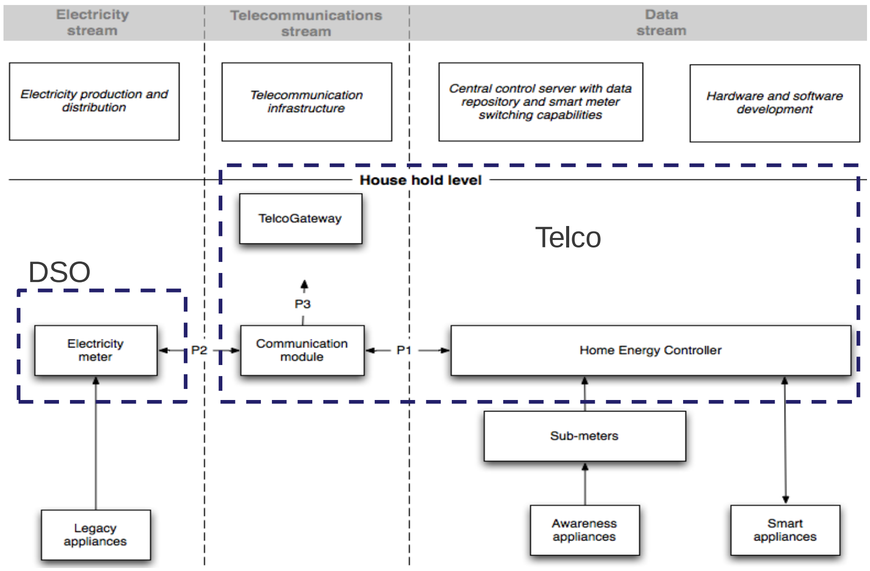

Figure 3-5: Telco scenario value network configuration

Technical: The same solution as described above can be used. The only difference is that all the modules by the telecom operators must be compliant (standardised) with the modular approach of the meter and the data sending format. SLAs must be dealt with in order to guarantee the service delivery. Another option is that the currently available modem of the telecom operator can be reused. For households with an existing internet connection, which consist of

70% of the households in Flanders [3.8], the smart meter signals could travel over this connection towards the central system. When looking at the cost for communication, this could result in lower recurring expenses. For consumers not having an internet connection, Power Line Carrier (PLC) or mobile (GPRS, 3G) communication could be introduced.

Business: The cost of the communication module could thus be paid by the telecom operator, and thus lower the total investment cost of the DSO and its financial risk. A fee for data communication can then be paid to the telecom operator on a monthly basis based on the type of network used. The operational benefits also apply. The risk / SLA lies with the telecom operator, who has the knowledge and competence of offering these communication services, which is advantageous for the DSO.

Customer: The benefits are relatively the same as the model presented in the DSO centric model. Additionally the customer can choose its own preferred telecom operator. In case of issues, the main problem would be the SPOC: who to contact when problems occur: the DSO or telecom operator?

Competition: The level of competition is better. The customers can choose their preferred telecom operator. As different players will be interested in offering this connection from the smart meter to the data centre, lower prices for the end customer could be obtained.

Up to now, the attribution of the HEC role to an actor was not yet discussed. While the previous DSO centric scenario attributed the HEC roles to the DSO, the Telco value network configuration can be adapted to split the HEC functionalities from the metering roles. As a result, the HEC functionality role can be taken up by the telecom operator. In this case the previously installed modem used for regular Internet and IPTV services can be upgraded to be used as gateway for new services such as HEC, aggregating all data from the different devices within your home.

Technical: This scenario poses some additional requirements for the technical architecture. The modem where the HEC is installed on should be able to interoperate with the smart meter, so a standardised interface is required. Additionally, the HEC functionality needs to be open and independent of the organisation sending the signals to the smart meter. We already mentioned the need for SLA in the previous scenario, where the Telco assures the delivery of signals. Here the communication modem should be always on.

Business: The most important issue with this configuration is that Telco operators currently could lack the knowhow of the energy market to offer this type of services. However, offering energy services would result in extra added value next to the existing offer of broadband, TV and mobile and fixed telephony. In addition, Telcos have good knowledge on marketing and advertising to help boosting the customer uptake of energy services. Although it still remains to be seen if the current players on the energy market will allow the telecom operators to enter the market via this model.

Customer: The advantages for the consumer listed in the previous model also apply here. If Telcos would also offer energy services, this would result in a single bill for the consumer for all his services, voice, broadband, television and energy. Also, no additional point of contact will be necessary.

Competition: When different providers could offer comparable energy services to the end consumer, competition on the market should increase, resulting in lower prices. However, if Telcos offer this service, the risk on a digital divide on the smart metering service market emerges, next to the existing digital divide on the broadband market.

3.3.1.c ESCO centric value network configuration

The last scenario we propose is the third party model (Figure 3-6). This scenario is in fact a logical extension of the previous Telco scenario, where the HEC is provided by yet another actor, an ESCO who can be independent of the previous two players or even a device developer who currently is not active on the energy market. In our opinion, this scenario will result in the most competition on the smart meter market, but will also require the most regulation. In addition, each actor focuses on the roles he has the most competences in. Unlike the DSO centric model, the DSO is responsible for the metering and does not move towards the more service oriented roles. This does not mean the DSO has no impact on the signals sent to the households, but they will have to pass via an aggregator party, responsible of combining signals and sending one aggregated signal to the households. The Telco only manages the communication roles and does not interfere with the electricity market specific roles. The HEC role is here taken up by an electricity service company. This could be an electricity supplier, but could also be a currently non-existing company which focuses on specific niche markets. For example, a new ESCO could focus on Plug-in (Hybrid) Electric Vehicle owners or solar panel owners. They could provide specific service to these niche markets like internalising production or charging schemes. In turn, the ESCOs could use their consumer portfolios to offer balancing service to Balance Responsible Parties. Notice that consumer segmentation is clearly implemented in this model.

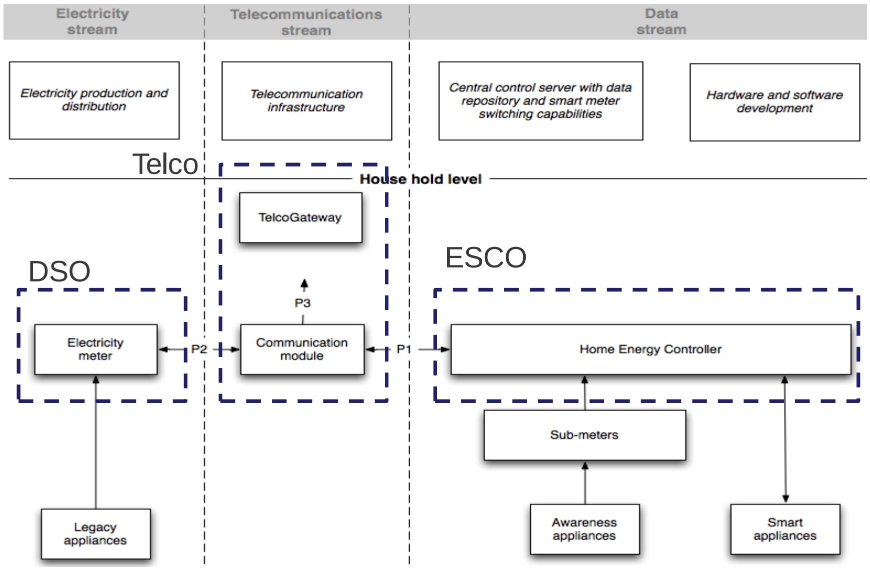

Figure 3-6: ESCO value network configuration

Technical: When the technical issues are considered, they are comparable to the remarks given in the telecom driven service scenario. Standardisation of interfaces will be key, to allow any player who wants to offer the HEC service to communicate with the smart meter.

Business: Since any company interested can offer services via this model, they can focus on niche markets most interesting for them. Different companies with different background and interests will be able to offer tailored services for a specific segment.

Customer: With a broad range of companies offering services, customers can choose the ESCO offering the package most benefiting them. However, this can also have a disadvantage if the number of offers is that large that it becomes very difficult for the end user to pick this best package. This results in inefficiencies for all players. Consumers do not get the benefits they could and companies cannot build the customer portfolio most suited for their offers.

Competition: The third party centric model offers the most possibilities for competition. However, as for the scenario described above, a digital divide on the smart metering market could emerge. Consumers with only low consumption could be deemed uninteresting by the active companies. They would only bear the costs of the smart metering system, e.g. via higher distribution tariffs and no benefits. Regulation could step in here, e.g. by enforcing an actor to offer basic smart metering services, like awareness to improve energy efficiency. This is much like the current social supplier model.

3.3.1.d Smart meter value network conclusions

The development of the residential smart meter value network serves a dual purpose. First, as it allows for a mapping of different configurations, the decision maker can depart from the value network to indicate different possible interactions with other players. Above, this was conducted for three different configurations. In the vertical integrated model, we identified a cooperation possibility between the DSO and a designated Telco. By focussing on their own core competencies, such a cooperation can result in cost reductions for the entire cooperation. When the ESCO configuration is considered, we identified different levels of competition opportunities. The electricity distribution remains a natural monopoly, but competition is possible on both the communication stream and on the data stream. However, this competition will also triggers extra costs for the different actors, so-called transactions costs [3.9]. Transaction costs are costs that occur when an exchange is made. Actors will need to negotiate on contracts, standardised interfaces will need to be developed, etc.

Secondly, as all roles have been identified in the value network, it allows the decision maker to have a clear view on the required roles in this market. As every role represents an activity, it offers the building blocks for the cost benefit modelling. When an actor takes up the TelcoGateway and Communication module role, he will also need to bear the underlying costs, e.g. hardware investment, maintenance of components, etc. The technical design used in the techno-economic modelling can also be based on the chosen value network configuration, like the modular or integrated meter choice introduced above. On the other hand, the data flows mapped on the value network offer an indication of possible revenue flows. Customers interested in using a HEC can be required to pay a monthly sum to a Telco to guarantee connectivity.

3.3.2 FTTH value network

The analogue exercise is performed for the fixed access network case introduced in Chapter 2, more specifically the Greenfield rollout of an FTTH network. By performing the value network analysis, light will be shed upon the detailed activities and their resulting costs and benefits. Secondly, by assessing the case on four aspects, possible cooperation and competition scenarios can be identified. To perform this analysis, existing fibre deployments were investigated to define a set of possible value network configurations and the most suitable and likely ones were identified[3] [3.10].

[3] Within the scope of the TERRAIN project, several workshops with industry and academic experts were organised to analyse the possible value network configurations.

Comparable to the smart meter value network, the FTTH value network is based on three streams: the infrastructure stream, connection stream and content and application stream, indicated on the y-axis of the value network. The *infrastructure stream* includes the planning, deployment and operations of the passive infrastructure: the dark fibre network. The second layer, the *connection stream*, refers to the installation and maintenance of the active equipment, needed for offering connectivity (and thus broadband connection). On top, we find the *content and application stream*, that refers to all additional services that end consumers can subscribe to, like digital television, video on demand, eHealth services, storage services in the cloud, HEC services, etc. These streams already offer a first indication for the required activities and their related costs.

Depending on who takes up the roles identified in the value network, different value network configurations can be subtracted. Typically, the same types of actors take up the roles located in one stream in these value networks configurations: the Physical Infrastructure Provider (PIP), the Network Provider (NP) and the Service Provider (SP). The PIP is responsible for deploying the dark fibre network, and therefore corresponds to the roles in the infrastructure stream. The operations role of this infrastructure stream can be done by the PIP itself or outsourced to the NP, which is a company specialised in telecommunications networks and equipment. The NP will therefore take up all the roles in the connection stream. At the top of the value network configurations, we see the SP, responsible for offering services, contents and applications to the end-user. In the remainder of this section, we will focus on the infrastructure and connection stream.

3.3.2.a Base case: vertically integrated PIP +NP

In the first value network configuration (Figure 3-7), all roles (infrastructure and connection stream) are taken up by one (public or private) actor. The content and application stream is left to service providers. The historic incumbents typically apply this vertically integrated model, and even include the service provisioning roles.

This case is considered as the base case. In the absence of multiple players, no extra negotiation costs between parties are incurred, nor does extra equipment need to be installed to allow multiple network providers to use the same dark fibre connection. However, such costs will be incurred when adding different SPs on the network. Competition is only possible on the service stream.

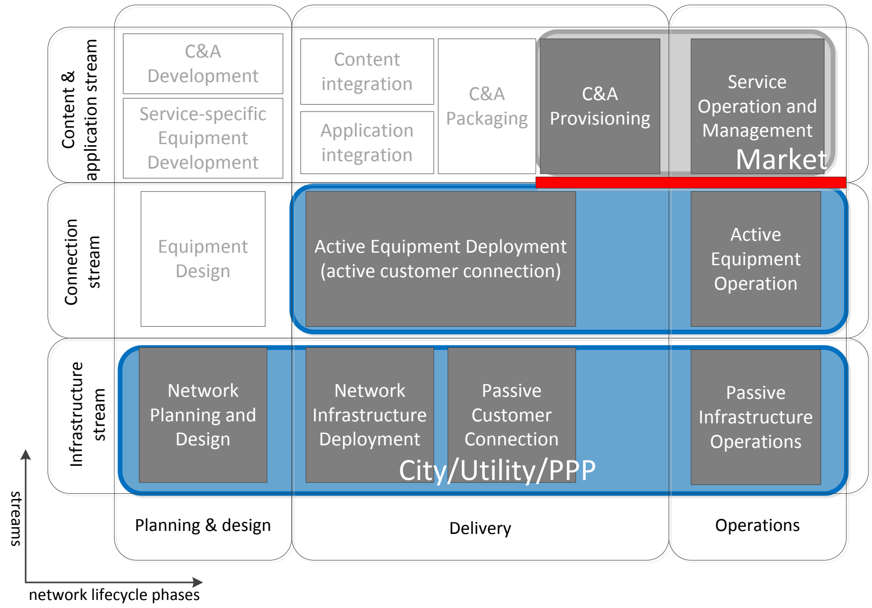

Figure 3-7: Value network configuration 1: integrated PIP and NP

3.3.2.b Separated deployment of passive infrastructure, combined operations

The second value network configuration splits the integrated actor in an actor responsible for the deployment of the passive infrastructure and one responsible for the deployment of the active infrastructure, and assumes that the operations of the entire network are in the hands of this entity, namely the NP. A visual representation of this model can be found in Figure 3-8.

This value network configuration was designed to allow non-telecom centric actors (such as municipalities, other utility network owners, public private partnership (PPP) etc.) to take up an active role in the network deployment. This entity gets the responsibility of planning and deploying the passive infrastructure (which mostly comes down to geographical network planning and trenching), while the operational part, for which more technical expertise is required, is taken up by a specialised company. Cooperation between both parties only occurs when “switching” from deployment to the operational phase. Like in the previous value network configuration, competition is only possible on the service layer.

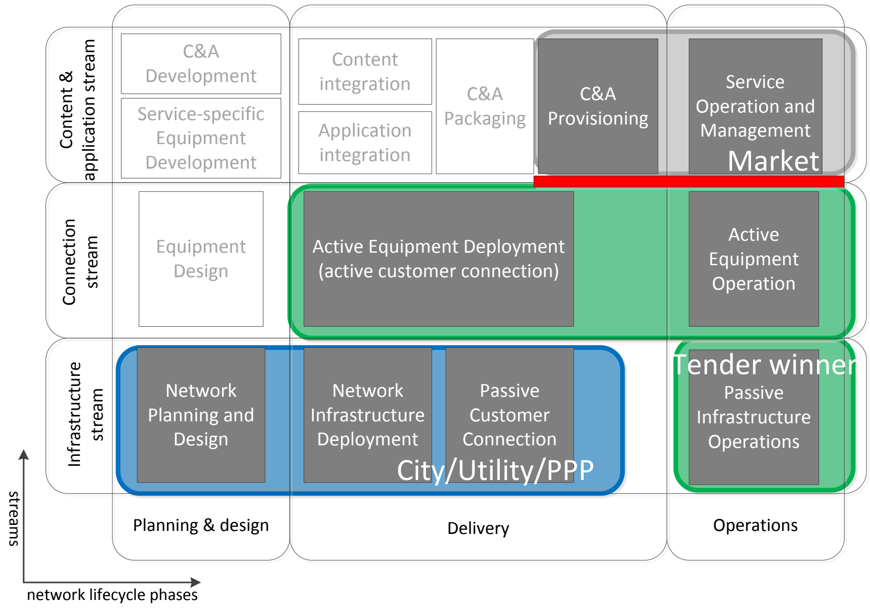

Figure 3-8:Value network configuration 2: Separate PIP, separate NP (taking up the operations in both streams)

3.3.2.c Separated passive infrastructure with operations tender, competition on connection stream

The third value network configuration can be found in Figure 3-9, and includes three different types of actors. At the infrastructure stream, we find one entity that is responsible for the planning and deployment of the passive infrastructure, but once deployed, the operations of the dark fibre network are left to a tender winner. On the connection stream, multiple network providers can install their own active equipment and compete for end customers.

This value network design is the most "open" one, since it allows for competition on both NP and SP layer. However, to allow competition on the NP layer, extra upfront and operational costs are entailed, as extra equipment, i.e. an open access interface, must be installed and maintained. Since this interface connects the different network operators to their respective customers, it should be done by a neutral entity.

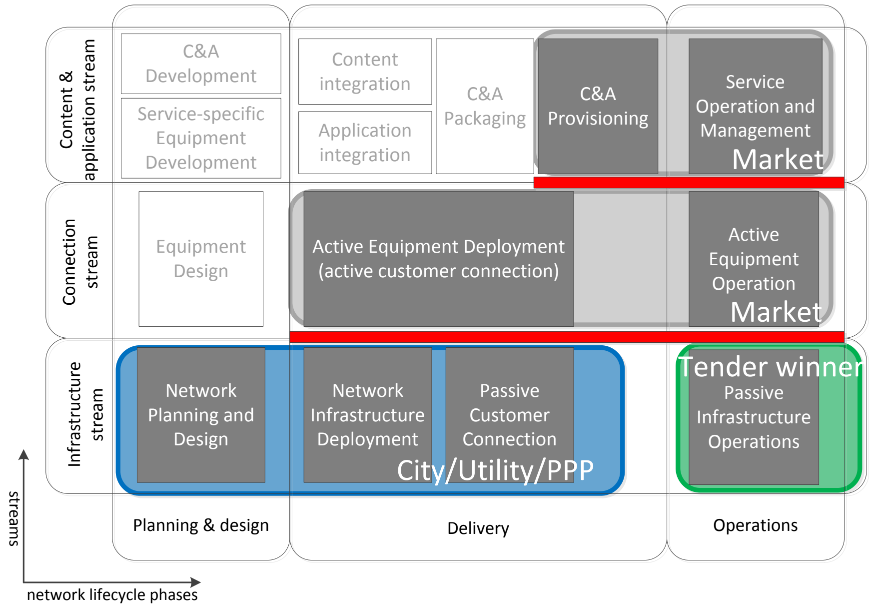

Figure 3-9:Value network configuration 3: PIP with separated operations in a tender, multiple NP

3.3.2.d Infrastructure based competition

In the previous three value network configuration, it was assumed that only one infrastructure is present. In reality, multiple infrastructures have already been deployed. In most European countries, customers can choose between two fixed infrastructures, a copper based DSL network operated by the incumbent and a Hybrid Fibre Coax (HFC) network owned by the CO. On top of these networks, different players are again active, resulting in a value network configuration as in Figure 3-10. Different infrastructures compete, with on top again different NPs and or SPs. We indicated in gray possible vertical integration between the different layers. With infrastructure competition, the same NP or SP can be active on different infrastructures.

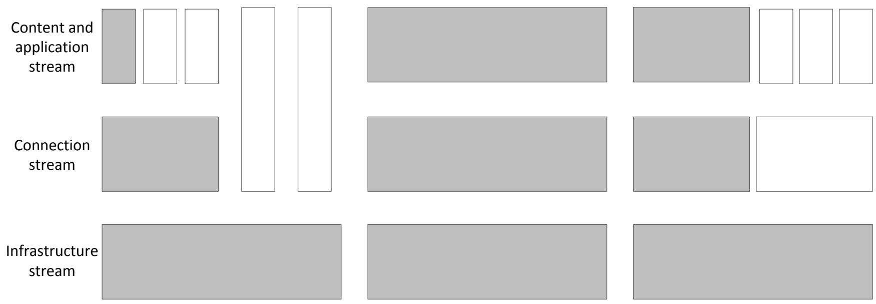

Figure 3-10:Value network configuration 4: infrastructure competition

3.3.2.e FTTH value network conclusions

Designing the value network and building different possible configurations offers important insight in two aspects. By defining all required activities to offer the value proposition, decision makers get more information on the underlying cost models. In the FTTH value network, an actor taking up the infrastructure stream will need to take costs for network deployment and passive customer connection. Choosing for an open access infrastructure has an impact on the technical design of the network. And as important, it also shows which costs not to take into account. While roles link to cost models, the different value streams between roles reflect the revenue streams between different actors. The functional separation between the infrastructure stream and connection stream will result in a revenue stream from the top stream to the bottom stream. The same goes for the streams between the tender winner and the city/utility/PPP. The latter deploys the network and will require a fee from the tender winner.

Secondly, when the different value networks are compared, actors can identify possible cooperation and competition impacts. This was e.g. performed in the PIP with separated operations with multiple NPs. Here, cooperation is possible on the infrastructure stream, and competition between different players on the connection stream.

3.3.3 Why perform a value network analysis?

A value network analysis was performed for two different cases, one in the consumer oriented smart meter market, one in the fixed broadband access network market. Both cases indicated the advantages of value network analysis. Performing a value network analysis has two main advantages. First, it allows identifying all key roles required in offering the value proposition. As a result, the decision maker knows which activities to take into account in the cost modelling, and how they impact the technical design. Secondly, when the different value streams are identified, revenue models can be mapped on the value network. Such a mapping shows from which roles and actors value can be gained, and which actors will need to be paid. Thirdly, from the selected value network configurations, one can identify possible cooperation or competitive opportunities.

3.4 Objectives

When there is a clear view on the value network and the configuration has been identified, the decision maker needs to assess the viability of the project, taking into account the roles identified and the interactions with other actors. When making the analysis, this viability is assessed by checking the impact of the project on the objectives of the decision maker. As different players have different objectives, more detail on these objectives is provided in this section.

3.4.1 Private player objectives

Private players primarily focus on value creation in the long run. This value creation can be measured through different financial parameters. Such parameters include the net present value (NPV), which is typically applied in the standard techno-economic analysis. This analysis comes down to building a detailed model of expected costs and revenues based on the underlying technical design, as was performed in Chapter 2. However, next to NPV, profitability, solvability and liquidity are other factors to take into account.

Private players have other goals in addition to the financial objectives. They can strive for consumer satisfaction, operational excellence or Six Sigma process quality (improving quality by removing causes of defects and minimising production variability). However, most of these objectives are typically directly proportional to value creation. Increased consumer satisfaction will result in higher sales, operational excellence and Six Sigma aim at reducing costs. As a result, these goals can be directly translated in a financial parameter, typically the NPV.

3.4.2 Public player objectives

Determining the objectives of non-profit oriented players is a whole different story. The different public players identified in section 3.2 are municipalities, governments and regulators. Decisions made by such actors are not aimed at generating cash flows, but at increasing social welfare.

When taking the example of broadband performance, the European Commission has made an effort to indicate the different objectives in the Digital Agenda for Europe (DAE). The implementation of its 101 actions in seven priority areas are expected to stimulate innovation, economic growth and improve the quality of life. As such, the DAE is an action list to get the most out of digital technologies and aims at delivering sustainable and inclusive growth [3.11]. To achieve the digital transformation, 13 specific goals are put forward, of which progress is annually measured in the Digital Agenda Scoreboard. For example, full broadband coverage with minimum speeds of 30Mbps and 50% of subscribers having speeds of 100Mbps are two main targets for 2020. For 2015, the Digital Agenda targets look to stimulate internet use, by setting targets for the use of eServices like eCommerce or eGovernment. For 2013, focus is on full broadband coverage. Here, broadband is defined as speeds equal or higher than 144 Kbps. It may be clear that such goals can no longer be measured in financial terms. As such, other tools are required to quantify these parameters.

3.5 Quantifying financial and social objectives

The quantification of the identified objectives is the next step in the techno-economic analysis. With such a quantification, the decision maker can assess if conducting a project is profitable (e.g. NPV) taking into account the required return on investment. In addition, the quantification allows ranking different alternatives. First, the background on quantifying financial objectives is given. This is an established field, and several metrics are available. The exercise is more challenging when social objectives need to be quantified. A composite broadband performance index was developed in this work to quantify and rank broadband objectives [3.12].

3.5.1 Net Present Value

The goal of an NPV analysis is to indicate the economic 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 minimal 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 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 (eq. 3.1). As the name says, it returns the present value of the future cash flows (CF) based on a given minimum return (*r*). The NPV thus reflects the cumulative discounted incoming and outgoing cash flows. 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 [3.13][4]. The formula for the NPV calculation is given below. All cash flows of the project are discounted with the minimum return *r* and summed up.

$$NPV = \sum_{i=0}^{n} \frac{CF_i}{(1+r)^i} \tag{3.1}$$

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.
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.

3.5.1.a Business case evaluation: standard NPV analysis

In Chapter 2, a detailed cost and revenue model was built for the rollout of an FTTC network in London, starting from a network and equipment model. With this input, the NPV analysis can be conducted. 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 bill of material 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

[4] The required return on investment is typically based on the average cost of capital, taking into account required returns for equity and debt.

factor of 10%. This discount factor reflects perceived financial risks and hence the required returns, and is based on industry insight. 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 a central office in London, both installation scenarios prove to be highly profitable, but the small cabinet FTTC rollout scenario turns out to be the best choice (Figure 3-11). Due to the lower cost for the small cabinet and the lower 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 cost difference is limited, the curves remain close together. The initial investment in cabinets and fibre outside plant 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, it should be noted that this conclusion is completely dependent on the initial assumptions concerning customer adoption.

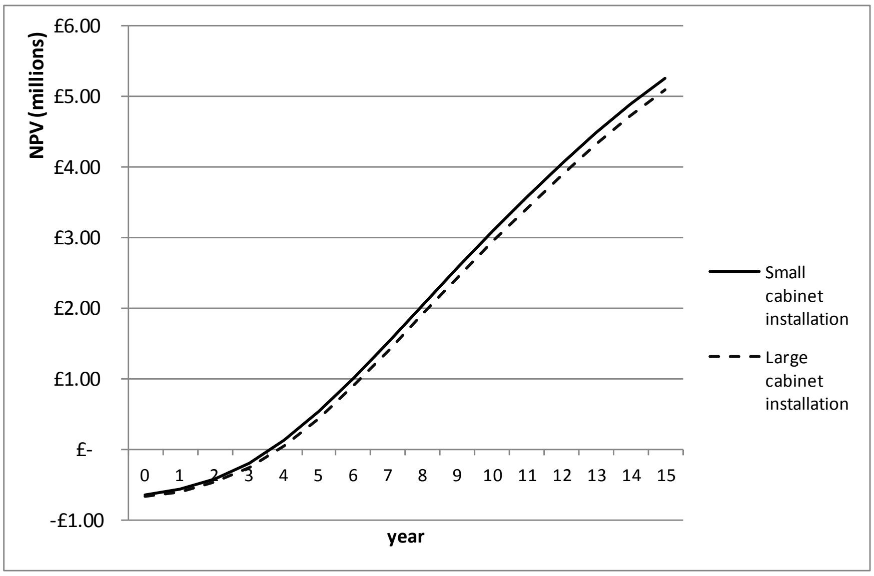

Figure 3-11: NPV analysis for an FTTC rollout

3.5.2 Other financial parameters

Different other aspects were already identified above. Liquidity, solvability and profitability are three other parameters companies strive for. Liquidity is the level at which a company is able to mobilise cash and fulfil short term expenses. As such, it is very important for creditors on the short term. Indeed, if the company has no available cash, these cannot be paid. Different ratios exist to measure the liquidity of a company. The average number of days of customer and suppliers credit, or stock rotation are just a few existing measures. The liquidity ratio is defined as the total value of current floating assets on the short term debt capital (eq. 3.2). Current floating assets are assets that can be converted into cash in short time, while the short term debt capital represents debt the company needs to repay within one year. The higher this ratio, the higher the liquidity of the company. If it is above 1, the current floating assets suffice to pay back all short term debt capital.

$$current\ ratio = \frac{current\ floating\ assets}{short\ term\ debt\ capital} \tag{3.2}$$

Solvability refers to the capability of the company to repay its financial debts and the resulting interest payments. It can be expressed by the ratio of debt capital on shareholders' equity (eq. 3.3). As such, it reflects the amount of debt capital per 1 euro equity. The higher this ratio, the lower the protection for creditors is.

$$degree\ of\ debt = \frac{debt\ capital}{equity} \tag{3.3}$$

The last ratio reflects the profitability of the company. This profitability can be measured in relation to sales, assets or equity. Profitability of equity is expressed by the profit or loss (before or after taxes) on equity (eq. 3.4).

$$net\ profitability\ of\ equity = \frac{profit\ or\ loss}{equity} \tag{3.4}$$

3.5.3 Broadband performance index

A broad toolset exists to quantify financial objectives. When the decision maker aims at other goals, the tools introduced above no longer suffice. A regulator is no profit oriented actor, but executes broadband policy within the regulatory framework. Such a player is responsible for ensuring sufficient competition, achieving broadband penetration, etc. Several indices have already been developed, but the main issue with broadband performance indices is their time dependency. What is considered important today may no longer be required tomorrow. Broadband access speeds are an example of this trend. The definition of broadband is continuously evolving, together with technical breakthroughs in this field. Only ten years ago, broadband was defined as an access speed of 144 kbps, while new technologies now allow to offer symmetric access speeds up to 100 Mbps and higher. In this section, we introduce an up-to-date composite broadband performance index, capable of capturing several policy goals and translating them into a quantitative index. With such an index available, techno-economic analysis can also take into account non-financial objectives.

3.5.3.a Existing indices

The quantification of policy and its impact on broadband has been challenging researchers for the last decade. Policy makers typically adopt metrics which rank broadband performance, allowing them to compare their performance with other countries. The best performers in these rankings are then selected as best policy makers and other countries copy their policy.

However, this approach has some major drawbacks. Penetration has always been an important metric to compare broadband performance. Penetration, as measured by the OECD, represents the ratio of fixed broadband connections on the population of the country (eq. 3.5).

$$Broadband\ Performance = \frac{\#\ fixed\ subscriptions}{\#\ inhabitants} \qquad (3.5)$$

Already in 2007, Ford identified the severe shortcomings of rankings based on this raw metric [3.14]. Next to the applicable policy, other factors influence broadband penetration. Examples are household size, population density, broadband price and income. Excluding these factors in a broadband performance measure significantly reduces the power of the performance indicator (PI). If two countries would have a broadband connection to every household, the penetration rate could only be improved by reducing the average household size in that country. A first improvement of the penetration metric is thus correcting penetration for household size (eq. 3.6).

$$Broadband\ Performance = \frac{\#\ fixed\ subscriptions}{\#\ households} \qquad (3.6)$$

In his 2007 paper on broadband performance, Ford performed a linear regression to estimate the impact of different socio-economic parameters on broadband penetration [3.14]. With the resulting coefficients, he constructed the Broadband Performance Index (BPI), allowing to calculate the expected broadband penetration based on socio-economic factors. When comparing the expected with the observed penetration, one can indicate if the country over- or underperforms. This divergence is mainly driven by policy, and should thus be used to identify good policy. In more recent papers, Ford proposed other PIs, e.g. the Broadband Adoption Index and the Broadband Efficiency Index, all based on the same rationale, namely penetration is not only driven by policy, but also by socio-economic parameters [3.15], [3.16].

Filtering broadband penetration for socio-economic aspects offers interesting insights, but the question today has shifted from “Do you have broadband?” towards “What is broadband, how fast is it, and how fast is fast?” Quality metrics should be included in measuring broadband performance of regions. The Broadband Quality Score (BQS) tries to formulate a solution [3.17]. The BQS expresses the quality of broadband as a weighted sum of download speed, upload speed and latency. These indicators were normalised using Min-Max, as proposed in [3.18]. In the initial proposal, over 50% of the weight was driven by the download speed, but the authors already suggested that the weights should be constantly adapted to reflect market evolutions. As services requiring a high upload speed become more important, the weight of this indicator should increase in the BQS measure. In order to subtract the broadband ranking of countries, a Broadband Leadership ranking was developed, including penetration and the BQS, each with equal weights.

Quality and penetration are two results of a good broadband policy (and socio-economic factors), but policy makers and regulators aim at much more. Next to adoption, coverage or availability is equally important. People cannot adopt broadband if they have no access to it. In addition, competition on the broadband market is a focus point of all policy makers. A good PI should thus include metrics of all these indicators.

We discuss two different PIs that include these metrics. The first metric is the Broadband Achievement Index [3.19]. Next to adoption and speed, this PI also includes availability, competition and digital inclusion. The last indicator measures adoption dispersion. The EU Broadband Performance Index is the second metric, which was introduced by the European Commission in 2008 [3.20], and has now been replaced by the DAE [3.11]. The EU BPI includes several parameters, very similar to the Broadband Achievement Index, namely broadband rural coverage, competition coverage, price, speeds and dimensions like eService uptake. Although these composite indicators take a lot of criteria into account, still two main drawbacks can be identified. First, there are the definitions used for the parameters. For example, the EU BPI uses speed baskets to diversify between high and low speed. Low broadband speed is defined as offers with a download speed below 2 Mbps, high speed is between 2 and 8 Mbps. While these speed baskets made sense when the EU BPI was initially defined, technological progress has caught up with these definitions. VDSL and cable networks can offer theoretical speeds up to 50 Mbps now, while FTTH networks offer speeds over 100 Mbps. As these are both included in the high speed basket, a shift from VDSL and cable towards FTTH networks would have no impact on the indicator.

Secondly, there is the impact of weight factors. Estimating weight factors always requires a value judgement on the different aspects, and is therefore always subjective [3.18]. While one policy maker finds adoption more important, the other focuses on competition. As a result, a different focus of a policy maker results in a different attributed weight. This drawback can be overcome by different approaches. An equal weight approach is possible, or the weights are discussed with the different involved parties to come to an agreed weight for every parameter. Another approach is used in the Broadband Achievement Index. The authors recognise the arbitrary nature of weight factors, and apply the benefit-of-doubt (BOD) methodology. Using the BOD method, each policy maker attributes the weight factor he wants to each parameter, chosen in such a way that they maximise their broadband performance. Sometimes unrestricted, sometimes restricted, requiring a minimum weight of e.g. 10% for each parameter. The performance indicator is then constructed as the ratio of the individual performance to the benchmark performance, being the maximal performance.

Next to the difficulty with determining the weight factors, obtaining the values for the different indicators is also challenging. All indicators introduced above have their own advantages and shortcomings. Penetration is easy to calculate, as the raw data is provided by several institutes, but it is a less correct indicator of good policy. The EU BPI includes different aspects, but its definitions are outdated. Especially if the PI would be used to estimate the impact of policy ex-ante, the used metrics should be up to date and explanatory of policy. Therefore, we have chosen to adapt the EU BPI towards a Next Generation Access Network (NGAN) oriented BPI. The DAE reflects the current European policy goals, and its definitions are thus transferred to the updated BPI.

3.5.3.b An NGAN oriented BPI

The previous section clearly indicated that a good broadband performance index in which current and next generation technologies and the market functioning (e.g. competition and pricing) are included is missing. During our research, we developed a new broadband performance index for which we started from the original EU BPI and made changes where necessary. We used this newly developed BPI to assess the impact of policy decisions on the objectives of the policy maker. In this section we indicate the different updates made to the original BPI. Each dimension of the EU BPI will be elaborated on, and each change will be motivated.

Broadband rural coverage

The rural coverage of broadband is the first dimension of the EU BPI, with a weight factor of 12.8%. For this parameter, it is important to define both broadband and rural coverage. In the original BPI, broadband was defined as access speeds over 2 Mbps. Currently, most European countries already achieved full coverage according to this definition. It may be clear that the introduction of NGAN will not improve this indicator, while this goal is present in the DAE. In the NGAN oriented BPI proposed here, the rural coverage definition is altered towards NGAN coverage. NGAN is defined as a network offering access speeds over 30Mbps, so it includes both the upgrade of existing cable and copper networks as well as the rollout of FTTx networks. However, while we continue to work with fixed speed to define broadband, a future BPI could include a time independent definition of broadband. This could be based on an equation including the current available access speeds and next generation technologies.

The definition of rural coverage can be maintained, although NGAN rollout will initially focus on urban areas. As such, we relaxed the rural coverage into overall coverage for an NGAN. This means that when NGAN is rolled out in urban areas, this also improves the broadband performance of the area.

Competition

Above, we discussed the importance of a PI taking into account the different policy goals of NRAs. While the DAE leaves out competition, this dimension was included in the EU BPI as competition coverage, weighted at 16.7%. Competition coverage is the combination of two factors, namely the market share of new entrants and national coverage. In this definition, it is important to define what a new entrant is. Alternative Network Providers (ANP) can clearly be seen as new entrants, especially since their total market share in most markets is very limited. However, the EU BPI also includes cable operators in the new entrants segment. While this may hold for most cases, some exceptions should be allowed. For example, in Flanders (Belgium), the cable operator entered the market about 20 years ago and currently holds a market share of around 55% of all broadband users, while the former monopolist only holds 40% [3.21]. In this case, the cable operator should no longer qualify as a new entrant.

This dimension can therefore be altered to only include ANPs. However, these can be players that operate on top of either an NGAN or the existing copper network. Additionally, when NRAs should decide to open up the cable network to ANPs as well, the market share of those operators should also be included in this dimension [3.22].

However, one can argue that this competition measure fails at capturing market concentration. Therefore, the competition indicator can be replaced by any measure of competition. For example, the Herfindahl-Hirschman Index (HHI) is a typically used to indicate market concentration [3.23]. The NGAN oriented BPI can implement different competition measures.

Broadband price

Broadband price is the umbrella covering three different dimensions of broadband pricing, to reflect the affordability of broadband. The first dimension is the median broadband price, corrected for speed (weight = 8.7%). This indicator is retained for the NGAN oriented BPI, with a minor change in the calculation method: the median is changed for the average price, which will allow using this index in more specific smaller scale (e.g. city networks) situations and theoretically abstracted (e.g. with less offers) studies. The two other dimensions of the broadband price are the average price for broadband slower than 2 Mbps and for broadband offering speeds between 2 and 8 Mbps (weights 3.8% and 3.4% resp.). While these were the typical speed baskets when the EU BPI was first launched, technological evolution has resulted in rising access speeds, towards 50 Mbps or even higher. Leaving these speeds out of the analysis would neglect the positive impact of network investments. Therefore, the speed baskets were updated towards more future proof baskets. In the NGAN BPI, the 'low' speed baskets represent all offers with a download speed under 30 Mbps, while all retail offers with NGAN speeds (i.e. above 30 Mbps) are classified in the 'high' speed basket. It should be noted that the NGAN oriented BPI is an evolving PI and that these speed baskets are time dependent and should be updated to keep up with technological evolution. In addition, speed is now defined as (advertised) download (DL) speed. In future work, this could be extended towards including a composite index of speed, much like the Broadband Quality Score [3.17], thus including download speed, upload speed and latency.

Speeds

Coverage, competition and affordability were all covered in the previous parameters of the updated BPI. However, as the introduction of NGAN speeds to end consumers will most likely result in an increased uptake of advanced services, speed is also an important dimension of the BPI, split up in two separate parameters.

The average speed is the first indicator (weight = 9.8%). It may be clear that with more NGAN being rolled out and taken up, the value of this indicator will rise. We therefore choose to retain this dimension in the NGAN oriented BPI. However, the second indicator, the percentage of subscribers with access speeds over 2 Mbps, is no differentiator towards NGAN (weight = 8.3%). For example in Belgium, almost 100% of the country is covered with DSL services, so upgrading the network towards NGAN would have no impact on this aspect. But when translating the Digital Agenda goals, which aim at full coverage of 30

Mbps, the change to this parameter is quite straightforward. The speed dimension in the NGAN oriented BPI now includes both average speed and coverage of 30 Mbps.

Other dimensions

The original BPI also includes dimensions like the take-up of advanced services and the socio-economic context (weights 19.6 and 17.4 resp.). Advanced services was interpreted as the number of customers using eServices, like eGovernment, eCommerce or eBanking. Socio-economic factors include ICT spending and PC penetration. We believe it is important to also include such parameters to assess the impact of regulatory decisions ex-post. However, when using performance indices to predict the impact of regulatory decisions, the quantification of these parameters would come with a large degree of uncertainty and subjectivity. Therefore, these dimensions are left out of the analysis. For a visual comparison of the original BPI and the new NGAN oriented BPI, we refer to Figure 3-12 and Figure 3-13.

3.5.3.c What about the weight factors?

When adapting the composite index EU BPI, the same arguments on the arbitrary nature of the weight factors can be made, as with every composite index. We have chosen to retain the weight factors, as these were the result of discussions between the national regulatory authorities of the European countries. However, since the eService uptake based metrics were excluded, the weight factors need to be rescaled so their sum is 1. In addition, it should be noted that the index we developed is built in such a way that weight factors can be easily changed by the user. This way, the user can differentiate between the importance of each of his objectives.

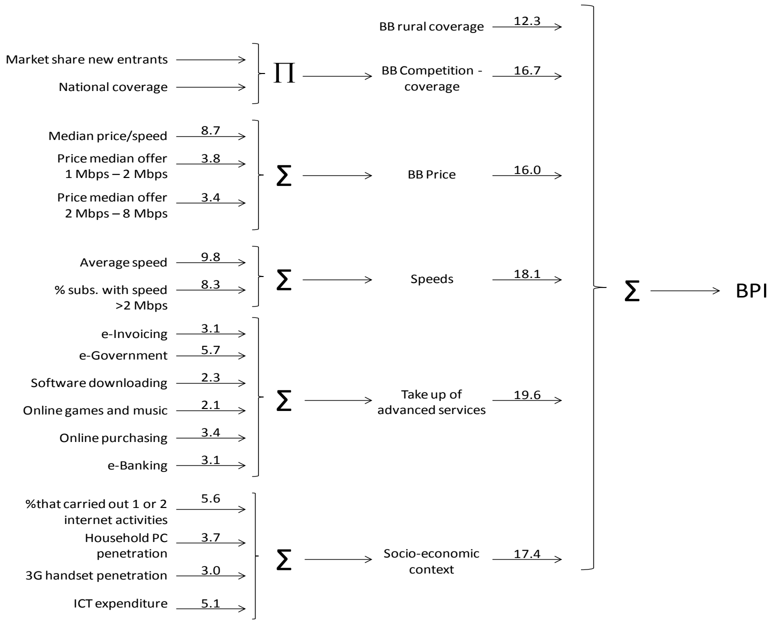

Figure 3-12: From the broadband performance index

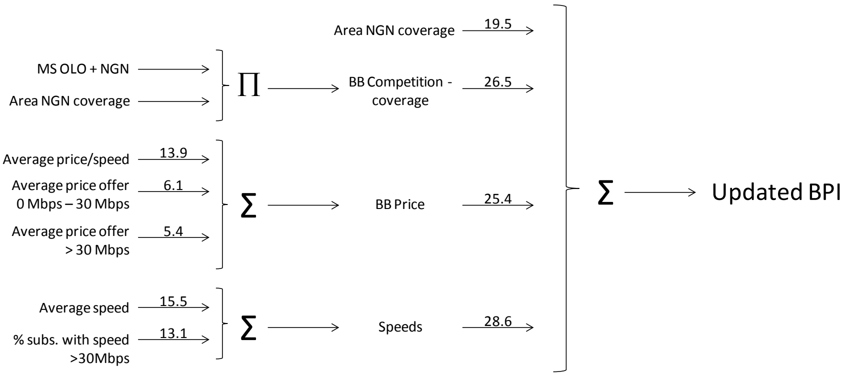

Figure 3-13: To an NGAN oriented BPI

3.5.3.d Comparing countries on NGAN oriented BPI

The NGAN oriented BPI developed serves as a composite index representing the impact of policy or investment decisions on the objectives of public players. In order to indicate how the NGAN oriented BPI works in practice, three countries will be compared in this section. The Netherlands, Sweden and Germany were selected due to their differences in DSL, cable and FTTH coverage and penetration.

The Netherlands

The Netherlands are characterised by a high broadband penetration of 87.3%. Additionally, a strong cable presence (34%) can be observed, but only marginal take-up of fibre (2.7%). For the BPI, speeds and price levels are also required. According to point-topic [3.24], the market share of other licensed operators is around 10%. The values used can be found in Table 3-1. Broadband coverage in the Netherlands is currently 100%. However, this includes VDSL and cable coverage. FTTP coverage is only at 12.8% [3.25].

Table 3-1: Market parameters in the Netherlands

Player	Price Level	Speed (DL)	Market Share
DSL	€35.00	20 Mbps	40.60%
ANP	€35.00	20 Mbps	10.00%
Cable	€36.67	30 Mbps	34.00%
Fibre	€55.32	60 Mbps	2.7%

Germany

Compared to the Netherlands, the total broadband penetration in Germany is considerably lower (66.1%), with the largest market share for DSL. Fibre only accounts for 0.1%, and the presence of cable is also smaller than in the Netherlands. Coverage of FTTP in Germany is at the moment around 2.6%, while NGAN coverage is at 41.5%. On the DSL market, the incumbent still has a strong presence of over 50% [3.24]. The values used in the calculations of the BPI can be found in Table 3-2.

Table 3-2: Market parameters in Germany

Player	Price Level	Speed (DL)	Market Share
DSL	€29.95	20 Mbps	30.00%
ANP	€29.95	20 Mbps	24.00%
Cable	€33.28	30 Mbps	12.00%
Fibre	€40.46	60 Mbps	0.1%

Sweden

Compared to the previous two countries, Sweden has the largest fibre penetration. Coverage is up to 34.8%, and uptake of fibre subscriptions already reaches 15%, five times higher than uptake in the Netherlands. Several reasons for this high uptake can be found. First, DSL and DOCSIS 3.0 coverage is low compared to the other countries. In Germany, coverage of these technologies is around 40%, for the Netherlands this is almost 100%. On the contrary, in Sweden, VDSL coverage is only at 10% and DOCSIS 3.0 just over 25%. As a result, FTTP has the largest coverage, and can thus reach more people. Secondly, fibre broadband services are put at an interesting price level, below the average DSL and cable services (Table 3-3).

Table 3-3: Market parameters in Sweden [3.24]

Player	Price Level	Speed (DL)	Market Share
DSL	€36.81	20 Mbps	26.00%
ANP	€36.81	20 Mbps	7.30%
Cable	€34.00	30 Mbps	12.20%
Fibre	€29.34	60 Mbps	15.00%

3.5.3.e Measuring broadband performance - example

First, we calculated the EU BPI for these three countries. Obviously, due to the small sample and the normalisation method used for the different parameters, the scores will diverge. Normalisation is performed using the Max-Min method [3.18]. With this approach, the highest scoring country receives a 1 score, while the lowest scoring country receives a score of 0. Obviously, due to our small sample, even with small difference between e.g. coverage, the impact on the EU BPI will be significant. For example, a coverage difference of 2% between the highest and lowest scoring country will still result in a 0.123 EU BPI difference. The scores thus indicate a ranking, but no conclusions can be drawn from the differences between the scores. Additionally, one should note that the maximum attainable NGAN BPI is 1, but this does not mean that this specific country could not improve its broadband performance. It only indicates that it is the best scoring country on all metrics.

Based on the current data ([3.11], [3.24], [3.25]), Sweden (0.917) ranks highest on broadband performance, followed by the Netherlands (0.209) and Germany (0.165). Sweden is the best performing country on all but one indicator, namely coverage. However, the country shows a coverage of 97%, so there is little room for improvement. If coverage would reach 100%, the BPI of Sweden would be 1. Based on this analysis, one could conclude that broadband performance in Sweden is already very high, and there is even almost nothing left to do. However, this conclusion is only valid if the old definitions for broadband used in the EU BPI are applied and if the absolute scores would represent broadband performance.

This indicates the importance of evolving metrics, following technological evolution, especially for metrics based on broadband speed definitions. The

NGAN oriented BPI overcomes this issue. The ranking remains the same, with Sweden still outperforming the other two countries, but analysing each metric in detail still indicates room for improvement in all countries. It also unveils one of the greatest shortcomings of using composite indices to measure broadband performance. If all countries score poorly on all metrics, the best scoring country among them will still achieve a high score on the PI. Scores on PIs should therefore not be used as an indication of absolute performance, only of relative performance compared to peers. Only an analysis of the different underling metrics can offer such insight on absolute performance.

It was indicated that the competition measure used in the BPI is flawed as measure for competition, as it cannot distinguish between high competition in a small area and low competition in a large area. We have replaced this metric by the HHI index. However, the results of the analysis stay the same.

3.5.4 The importance of objectives

As Peter Drucker, the founder of management by objectives said: *"Management by objective works – if you know the objective. Ninety percent of the time you don't."* Having a clear view on the objectives of the different actors is thus key when performing a techno-economic analysis. For private players, financial objectives are the most important, as they focus on shareholder value creation. A broad toolset exists to quantify these objectives, of which the NPV is the most widely used. For public players, which have additional non-financial oriented goals, the identification of their objectives is less straightforward.

In the broadband market, a lot of non-profit oriented players are active. Governments and NRAs are two important actors who try to influence the outcome of the market. They aim at coverage, affordable prices and sufficient competition. The NGAN oriented BPI developed in this chapter allows to quantify their objectives. With this composite index, techno-economic analysis can also be conducted for these players. In addition, when private players try to optimise their strategy in light of possible future policies, the NGAN oriented BPI can be applied to indicate the impact of their strategy on policy makers, and vice versa.

3.6 Conclusions

In this chapter, we introduced two important aspects of techno-economic analysis, namely value network analysis and identification of actors' objectives.

Value network analysis offers valuable insight for the quantification steps of the techno-economic analysis. As it identifies roles, value flows and actors, it provides the building blocks for the techno-economic modelling of costs and revenues, an indication of the value exchanges between different roles, and an overview of the possible competitive interactions or cooperation opportunities.

Once the actors are identified, it is important to know the objectives of these actors. Private players typically have financial objectives, but when public players, like governments or regulators make decisions, they do not aim at creating monetary value, but typically at increasing social welfare.
As the quantification of such policy goals is not straightforward, we have developed a composite broadband performance index. This index allows to assess the impact of policy decisions concerning broadband, like open access policy, price regulation, subsidisation, etc. on the objectives of public players.

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4

Real Option Methodology to Quantify Flexibility

"Flexibility has become a modern day value that everyone wants. But flexibility comes with a cost", Maynard Webb

In standard techno-economic analysis, when the actor's objectives are quantified using net present value (NPV) to analyse the financial viability, the investment project is seen as a now or never decision without uncertainty. This assumption does not reflect reality. Initial estimates of customer uptake or operational costs turn out to be over- or underestimated, decreasing the return on investment. When this occurs, it is untrue that the decision maker will do nothing. If possible, necessary steps will be undertaken to increase the return. This concept is defined as managerial flexibility. Decision makers continuously have the flexibility to adapt the course of a project to act on positive and negative events to optimise the outcome of the project. Capturing this impact of both uncertainty and flexibility cannot be done by performing the NPV analysis introduced in the previous chapter. As a solution, options methodology has been introduced for investment projects. Real options (RO) offer a solution to better fit the economic analysis tools for investment problems to the underlying reality. In multi-period planning, the bill of material is calculated over more than one time period. This way, long term effects of the decision can be taken into account. In this approach, building a decision tree for different options is a standard approach. Using real options, the flexibility to switch between different options can be calculated.

Here, we offer an introduction to real option analysis and indicate how uncertainty and flexibility impact the valuation of an investment project, resulting in changing initial decisions made.

Although research on real option theory has been ongoing for over four decades, it is only slowly getting accepted as valuation tool for investment problems in telecom. During this doctoral research, we have classified the existing research on real options in telecom and we have applied this technique ourselves to a plethora of different cases, showing how the real option concept is a natural extension of existing methodologies. These cases include sensor network deployment [4.1], core and access network migration [4.2], [4.3], but also pricing problems in network unbundling [4.4]. This work resulted in a real options tutorial, covering definitions, identification of options and methodologies to value real options in telecom [4.5]. In this chapter, we present the real option methodology, together with two applications of real options theory, namely the migration of existing core and access networks. We show how uncertainty impacts the business case valuation, and how real options can capture the value of managerial flexibility.

4.1 Identifying flexibility in telecommunication

The rollout of a new broadband access network, as analysed in detail in Chapter 2, offers a broad range of flexibilities to the network owner in future stages. One flexibility we already indicated was the possibility to install extra capacity when the initial installation reached its limits.

However, several other types of flexibility are present, and these can already be identified during the planning phase. The rollout of a new broadband access network requires large infrastructure works, which are typically spread over time. During the planning phase, operators will focus on rolling out first in areas where costs are low and expected revenues are high. As these areas are being connected, the operator gains insight in performance of the network in the field and customer uptake. Based on this progressing insight, the operator can adapt its initial deployment plan. New areas can be installed faster than initially planned, while other installations are postponed.

Next to flexibility during the deployment phase, a network also offers opportunities once it is installed. As already indicated, extra capacity can be installed, serving multiple purposes. The extra capacity can be used to connect new customers in the same area, or users can be offered higher access speeds. Incumbents have upgraded services from dial-up to VDSL and higher. Cable operators followed the same track, upgrading to subsequent generations of DOCSIS.

And by using the same network, operators can offer additional services to their customers. While the copper infrastructure was originally used for telephony, operators extended their product portfolio towards data and television. And they now not only offer residential services, equipment has been installed to support local loop unbundling. As a result, other operators can use the incumbent's network to offer their own broadband services.

It may be clear that in telecom, there is a long history of players having and exploiting the flexibility the technology and equipment offers. Flexible deployment planning, subsequent technology upgrades or new services are all examples of telecom operators acting flexibly to changing opportunities. However, the question arises how to incorporate this flexibility into the techno-economic analysis. Real options provide a solution.

4.2 An introduction to real options

4.2.1 Real option basics

For telecom projects, the feasibility of new project proposals is assessed through a techno-economic analysis, introduced in Chapter 2 and an NPV analysis, as performed in Chapter 3. To implement the value of flexibility, the real option concept was derived from financial literature. An excellent definition of real options is given in [4.6]. *"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 (RO) 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 categorised 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.

The value of an option is dependent on several aspects. The first is a time component. During the time period before (possibly) exercising the option (at the strike 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 has not expired, the underlying asset can go up in value. This probability of $S > X$, or the option being in the money, before 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 the 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 [4.7 - 4.12].

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 a Long Term Evolution (LTE) network to be profitable under certain uptake assumptions. These assumptions may have changed after a few years. The static NPV analysis does not allow any flexibility here but a RO analysis offers the possibility to value the possibility to perform a small scale rollout and expand to neighbouring regions later on during the project if uptake exceeds initial expectations. Conducting the RO analysis calculation will result in the value of this option to expand.

4.2.2 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 (Figure 4-1). 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 British Telecom. 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 [4.7]. The different real options categories are summarised in Figure 4-1 and some typical telecom examples are added. The different categories are described in the following paragraphs.

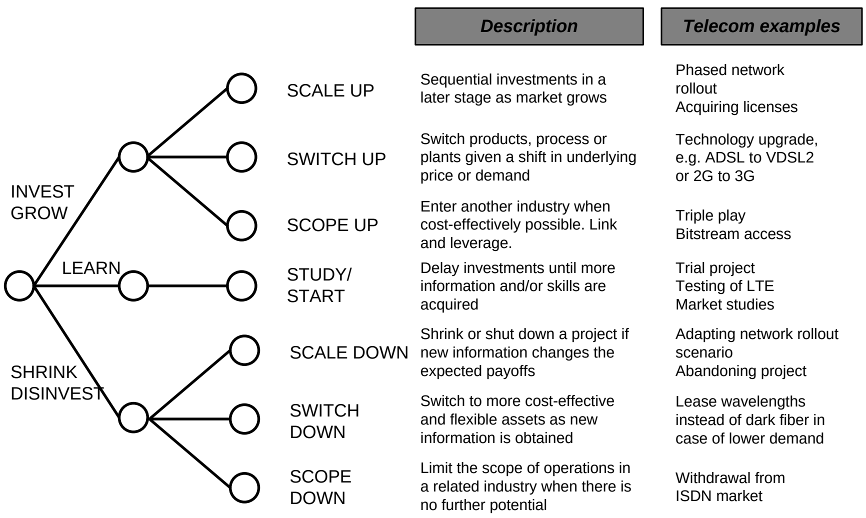


Figure 4-1: Overview of the 7S framework [4.7] and telecom examples

4.2.2.a 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 have been 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 optimise 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 4G licence, management can abandon the rollout of the 4G network in worst case scenarios and put the licence up for sale. The value of such a sale will be very case specific. Selling a spectrum license for which no market existed will have only low value, while the sale of infrastructure with multiple purposes can have a higher value. Buildings are an example of the latter category.

4.2.2.b 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 [4.13]. 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.

4.2.2.c Switch up and down options

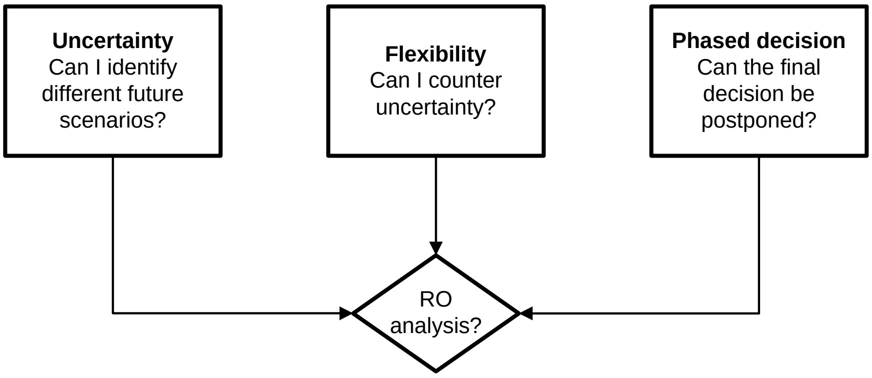
Next to the scale of the project, several other parameters also render flexibility. In a production environment, managers can choose to upgrade machine technology during the project, e.g. to produce better quality products. Changing technology can prove useful during the project lifetime, but results 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.

4.2.2.d 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.

4.3 Real option methodology

In this section, the methodology commonly used to perform real option analyses is discussed [4.8], [4.9]. 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 recognised 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 dissertation, we use the methodology proposed in [4.14], which is based on [4.8] and [4.9]. While a standard techno-economic analysis results in an NPV analysis, the RO analysis methodology extends the techno-economic methodology with three extra steps. The RO analysis thus consists of four steps. First, a standard NPV analysis is conducted. 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. In step four, the actual calculation of the option value is performed. The conditions and methodology are summarised in Figure 4-2. Before indicating how the different steps work in practice by elaborating a simple toy example, more detail is given on the different calculation techniques for real options.



1. Execute a standard NPV analysis
   Perform a regular techno-economic analysis, as if no real options were present.
2. Identify the uncertainties
   Find out which parameters impact the result the most, and how certain their value is. Typical numbers on customer adoption come with a degree of uncertainty.
3. Identify the flexibility
   Use the 7S framework to indicate how the uncertainty in the project can be countered during the project path.
4. Calculate the option value
   Compare the value of the case with the option with the standard case. Different calculation methods exist.

Figure 4-2: Conditions and methodology to perform a real option analysis

4.3.1 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 Cash Flow (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 (eq. 4.1)[5].

$$\text{Project value} = \text{NPV} + \text{Option value} \tag{4.1}$$

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.

4.3.1.a 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 [4.15]. 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 such a 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 licence purchase and the investment in base stations? Another assumption of the Black and Scholes model is that S(t) is a geometric Brownian motion, i.e. $\frac{dS(t)}{S(t)} = \mu dt + \sigma dW(t)$ where $W(t)$ is a Wiener process. Hence, $ln\frac{S(t)}{S(0)} = (\mu - \sigma^2/2)t + \sigma W(t)$ where $W(t)$ is normally distributed with mean 0 and standard deviation $\sqrt{t}$. 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.

In addition, there is an important difference between financial and real options,

[5] The option cost is included in the NPV term of the equation.

which results in the Black and Scholes formula 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. As a result, the Black and Scholes model outcome overestimates the value of the real option. These drawbacks make the Black and Scholes formula less suited for real option valuation.

$$Option\ value = S.N(d_1) - Xe^{-r_f t}.N(d_2) \tag{4.2}$$

With:

$$d_1 = \frac{ln\left(\frac{S}{X}\right) + \left(r_f + \frac{\sigma^2}{2}\right)t}{\sigma\sqrt{t}} \tag{4.3}$$

$$d_2 = d_1 - \sigma\sqrt{t} \tag{4.4}$$

S	= future cash flows
X	= exercise price
t	= option lifetime
σ	= 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 is shown above (eq. 4.2 – 4.4). 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 (eq. 4.5). 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 [4.16].

$$C + PV(X) = P + S \tag{4.5}$$

With:

C = value of the call option
PV(X) = present value of the exercise price
P = value of the put option
S = future cash flows

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. However, we would like to stress again that the underlying conditions for Black and Scholes are not fulfilled for realistic cases.

A telecom operator bought a licence for €3.1 million, valid for 5 years. The expected future cash flows of this fictitious example during this period can be found in Table 4-1. 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 licence 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.

Table 4-1: Fictitious yearly cash flows from licence

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

In the first step, the required parameters are calculated or estimated (Table 4-2). 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, the return on risk free government bonds is typically used for r_f. 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 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.

Table 4-2: Black and Scholes parameters

Parameter	Value
S	€2.975.339
X	€2.000.000
T	1
σ^2	50%
r_f	5%

4.3.1.b 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 [4.9]. The toy example used to indicate the methodology in Section 4.3.2 is an application of the binomial tree model method.

4.3.1.c 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 [4.17].
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 maximising payoff, this procedure 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 sampled from the predefined distributions. 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 allow extending an existing spreadsheet techno-economic analysis with specific uncertainties and conduct the Monte Carlo analysis [4.18]. More information on Monte Carlo basics can be found in [4.19].

4.3.1.d Comparison of the valuation methods

The three valuation methods introduced above each have their advantages and disadvantages (Table 4-3).

Table 4-3: Comparison of valuation methods

Technique	Pro	Contra
Black and Scholes	Simple to use Spreadsheet calculation	Not suited for real options Conditions not satisfied 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	Requires advanced software Estimating uncertainty

4.3.2 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, categorised and quantified. The following investment project is considered. A mobile network operator bought a licence for 100 and has to decide today if he will roll out the network in a large or in a small area. But due to uncertain market perspectives, he does not know exactly how many customers will be willing to buy his product. The entrepreneur believes the probabilities of a small or large market equals 50%. The investment cost for the small area is 50 at t1, while an additional 200 is required to deploy the network in the large area. The expected costs and revenues can be found in Figure 4-3. 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.

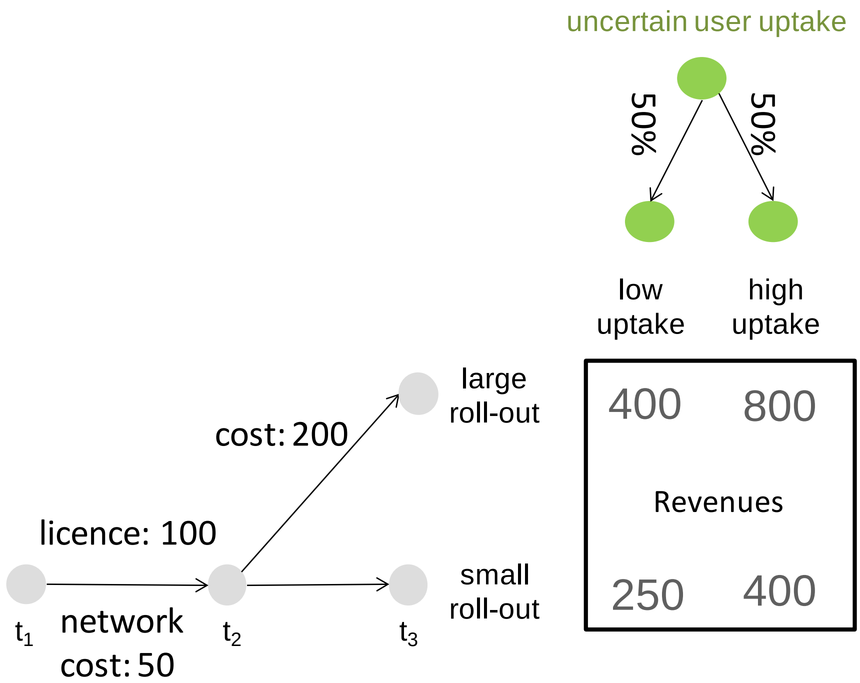


Figure 4-3: Expected cost and revenues for two installation options in the toy example

Uncertainty

The network operator 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 operator has two choices. Either he installs the network in a large area, or he deploys a network in a small area.

Phased process

Looking at this case, we do not see two phases in the investment process. However, nothing forces the network operator to decide today if he deploys the network in the large area. He can decide today to only deploy a small network and expand next year.

The results of the first step of the methodology, the standard NPV analysis, are presented in Figure 4-4. Where the operator installs the large network, his payoff is the weighted average of 50 and 450, or 250. The additional cost for the larger rollout was subtracted from the expected revenues. In the other case he will only gain €175. The standard NPV analysis thus indicates that the operator should deploy the large network from the start, since this maximises his payoff. Notice that in order not to overcomplicate the toy example, the required return was set to zero.

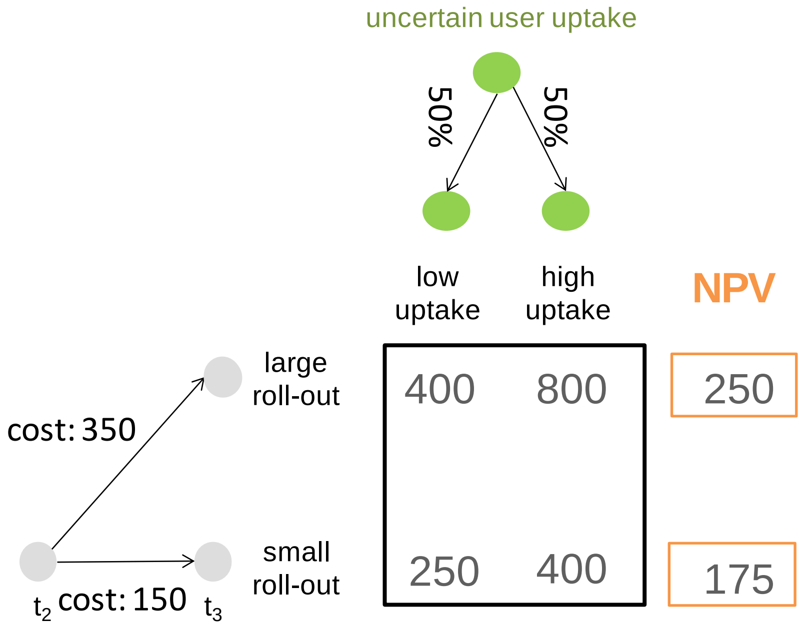


Figure 4-4: A simple example - Step 1: NPV analysis

The second step, identifying the uncertainties in the case, was performed when describing the three preconditions. The operator is uncertain about the customer uptake of his service and on the type of area to cover. When checking the third condition, the operator 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 the small network or expand to the large area. The value of the real option can now be calculated.
We start by analysing the different scenarios under the uncertainty. In case there is a low customer uptake, staying with the small network has the best payoff. In case of high customer uptake, the expansion towards the larger area clearly returns the best result.
Now remember this project consists of two stages. When identifying the flexibility, we indicated that the operator had the option to postpone his 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 expansion. Within the constraints of the example, where no competitive

interaction is present and no revenues are lost, waiting ensures the operator will make the best decision in the future. If he notices a low uptake he will keep his original small network, in the other case he will expand towards the larger area (Figure 4-5). In both the low and high uptake case, he chooses the scenario having the highest payoff. With the option to wait, our operator knows he has a 50% chance on a payoff of 450 and 50% chance on a payoff of 100, or a total value of the project of 275. 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 25 higher. This is exactly the value of the option to wait.

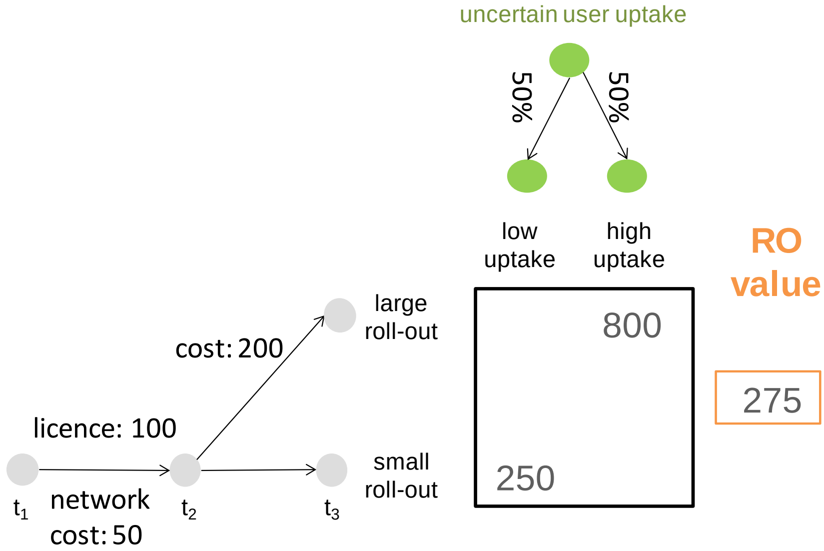


Figure 4-5: Step 4: Value of the option to wait

4.4 Application domains of ROA in telecom

Real options have been applied to a wide range of investment projects from mine valuation to initial public offer valuation [4.9]. Some more telecom related examples are described below. A literature review of real option application to telecom examples can be found in Table 4-4.

Most of the existing literature applies real options to telecom infrastructure rollout [4.9], [4.20-4.23]. 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 optimise 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 [4.9]. 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 [4.20]. 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.

Table 4-4: Real options in telecom literature

Option	Flexibility	Reference	Uncertainty
Scale up/down	Rollout area	[4.1], [4.9], [4.20], [4.22 – 4.23]	Adoption Costs Tariffs
	Speed up/slow down rollout	[4.1], [4.20]	Adoption Costs Tariffs
	Abandon project	[4.9], [4.26]	Adoption Costs Tariffs
Switch up/down	Technology	[4.22]	Firm value Adoption Costs Regulation
Scope up/down	Offering bit stream access		
Study/start	Trial project	[4.21]	Technology Performance Market
		[4.21 – 4.23]	Technology Regulation

Study/start options have also been applied extensively to telecom network problems. In [4.21], 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 [4.24], 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 licences. Dynamic spectrum management, with a two stage assignment through the use of options was proposed in [4.25]. 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. However, the starting position for the deployment of the copper infrastructure was monopoly. Today, this rationale is applicable to the deployment of fibre infrastructure. Operators have the option to wait before deploying new access network infrastructure. Gradually migrating towards more fibre-rich networks also reflects this. In [4.4] and [4.26], 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. [4.27] applied real options to the case of the Belgian rail operator offering internet services on board.

With the real option methodology at hand, the next section will extend on different cases. The first case applies RO valuation to the migration towards FTTC networks [4.3]. In Chapter 2 and 3, this case was already introduced, and a standard NPV analysis has been performed. However, it was already indicated that during this analysis, the impact of uncertainty and flexibility was not taken into account. By extending the analysis with a RO analysis, we show how this uncertainty and flexibility impacts the initial valuation.

The second case studies the migration of core networks from fixed grid networks to flexible-grid networks [4.2]. Comparable to the FTTC migration case, operators here have different options and uncertainty impacts their results. However, this case is particularly interesting, as the extended valuation shows that having the flexibility does not pay off. We included this case to show how options not directly result in an increase of the investment value, but that options sometimes can be worthless. A third and fourth example, researching the option value in sensor network deployment and determining the flexibility value in access pricing, are also included [4.1], [4.4].

4.5 Migrating towards FTTC networks

To indicate the power of real options on realistic business cases, the RO analysis technique will be applied to the telecom infrastructure network project introduced in Chapter 2. The studied case consists of the rollout of an FTTC access network in the UK [4.3]. 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 (Figure 4-6).
In this case, the existing copper access network in London is migrated towards an FTTC network. 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. 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%.

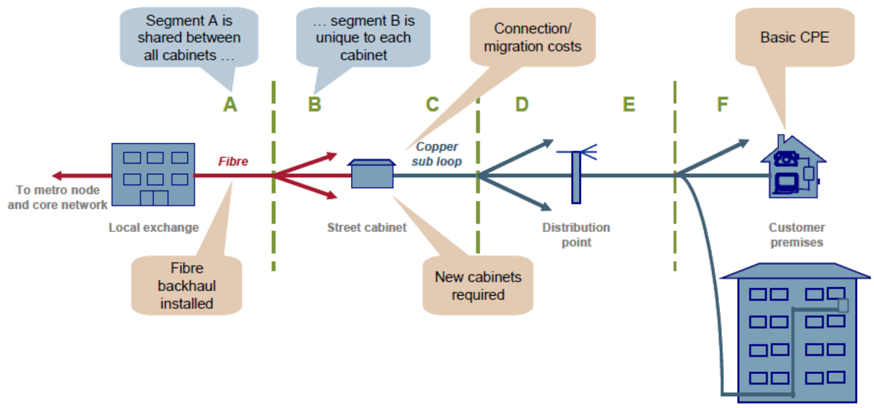


Figure 4-6: Overview of copper access network topology

After conducting the standard NPV analysis in Chapter 3, 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. In Chapter 2, scenario and sensitivity analysis were introduced as methods to capture uncertainty.
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.

Uncertainty

There is undoubtedly a large degree of uncertainty present in this case. The revenues of the project are based on a mathematical adoption model, where the chosen parameters are in the best case “guesstimates”.

Flexibility

There is flexibility present in the choice of cabinet to install. In case the small cabinet is installed in the first phase, the operator has several options once the capacity constraints of this cabinet are reached. The operator can decide to install a second small cabinet, or he can invest in a more future proof access network by migrating towards FTTH.

Phased decision

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 (Figure 4-7). 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.

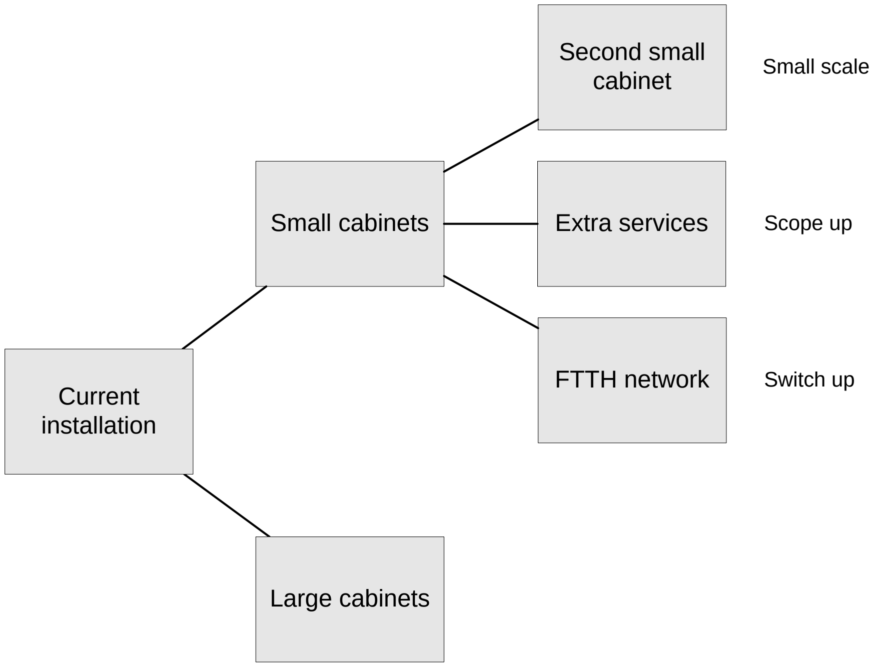


Figure 4-7: Possible installation paths for an FTTC network

4.5.1 Impact of uncertainty on the final decision

The standard NPV analysis identified the installation of small cabinets for the London geotype as the most profitable scenario (Section 2.3). 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 user adoption as the major uncertainty, as this is also the main driver for the bill of material.

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 [4.28]. 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 [4.29]. These models have been translated to mathematical S-curve penetration models, from which we have chosen the Gompertz curve in this business case [4.30-4.32]. 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 Figure 4-8. 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. Once over 30% adoption, the small cabinet can no longer host new connections, and these revenues are lost. However, it is still assumed that all cabinets will follow the same adoption evolution.

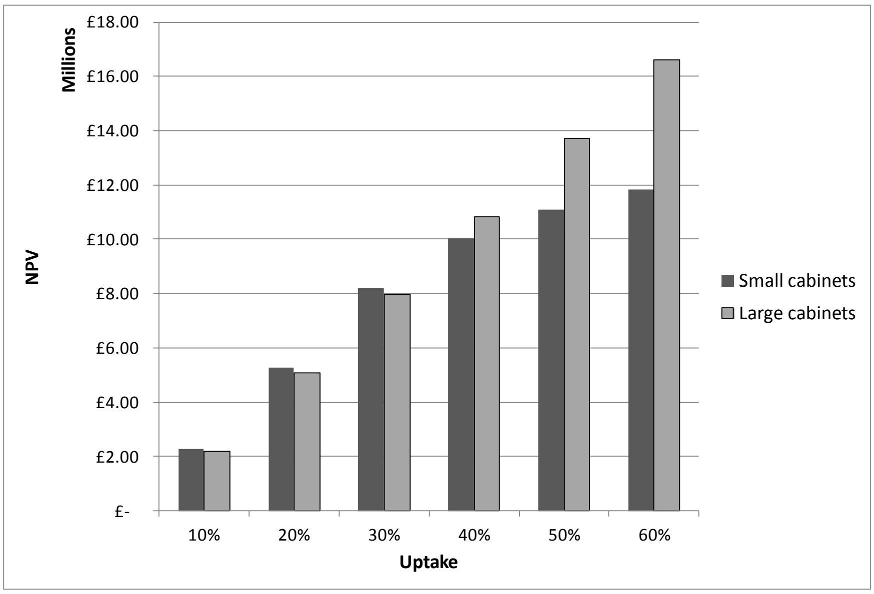


Figure 4-8: Small and large cabinet market potential scenario analysis

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

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 [4.18]. 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 (100.000), resulting in a distribution of the value of the forecasted cells, based on the uncertainty distributions added to the assumption cells [4.17]. 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 (Figure 4-9). 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. Real options thus clearly manage to capture the value of multi period planning.

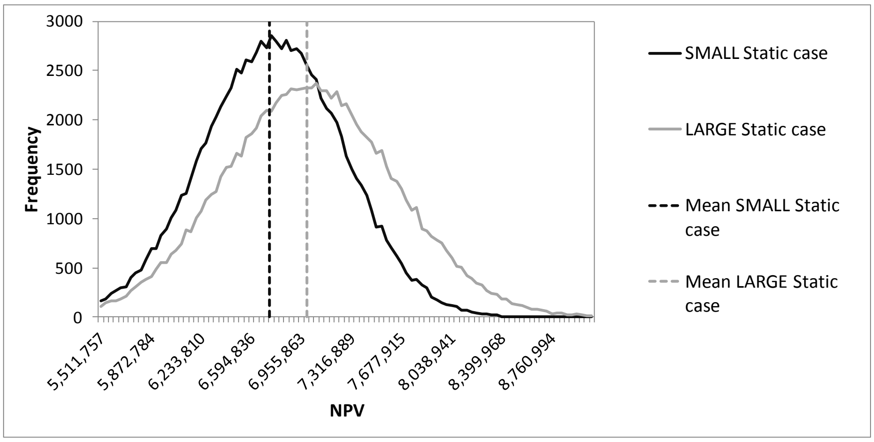


Figure 4-9: Impact of uncertainty on the business case outcome

4.5.2 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 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 average revenue per user (ARPU) per customer by offering extra services to the existing customers, for example by starting to offer IPTV services. Note that at first sight, the option comes for free in this case. No initial expense needs to be made in order to buy the option. However, when taking a closer look at the cost for the small and large cabinet, we notice that a full small cabinet would cost 9.890 GBP, while a full large cabinet costs 18.530 GBP. Or 68 GBP per user in case of a small cabinet and 55 GBP for a large cabinet (see Table 2-1). The higher price per user reflects the price for future flexibility in case of the small cabinet. In this section, we will apply these three options to the business case and show how they impact the previous results.

4.5.2.a 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 exercise price). This capital expenditre also includes the installation costs. 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 (Figure 4-10). 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 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 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.

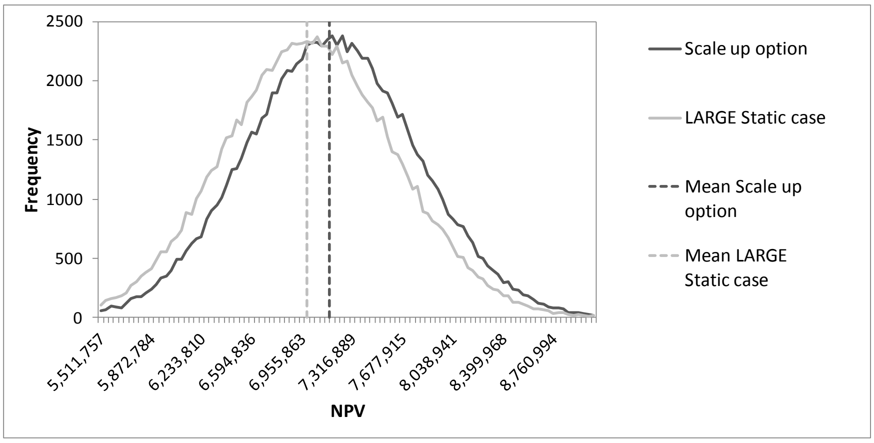


Figure 4-10: Overlay chart large cabinet scenario and small scale case

4.5.2.b 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 4-5.

The impact of the switch option can be seen in Figure 4-11. 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 4-5: Cost parameters for an FTTH deployment [4.33]

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

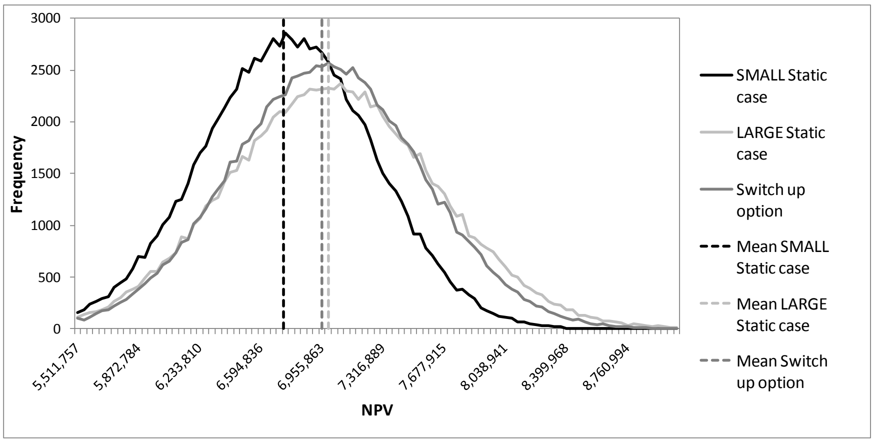


Figure 4-11: Improvement of the business case with a switch up option

4.5.2.c 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 4-6).

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 [4.34] 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 4-7.

The results of this RO analysis can be found in Figure 4-12. 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.

Table 4-6: IPTV cost parameters [4.33]

Parameter	Cost / Revenue (GBP)
Video server	20.000
CPE	250
CPE installation cost	200
Extra ARPU	100

Table 4-7: IPTV Gompertz adoption parameters

Parameter	Value
a	4.667
b	0.366
m	0.405

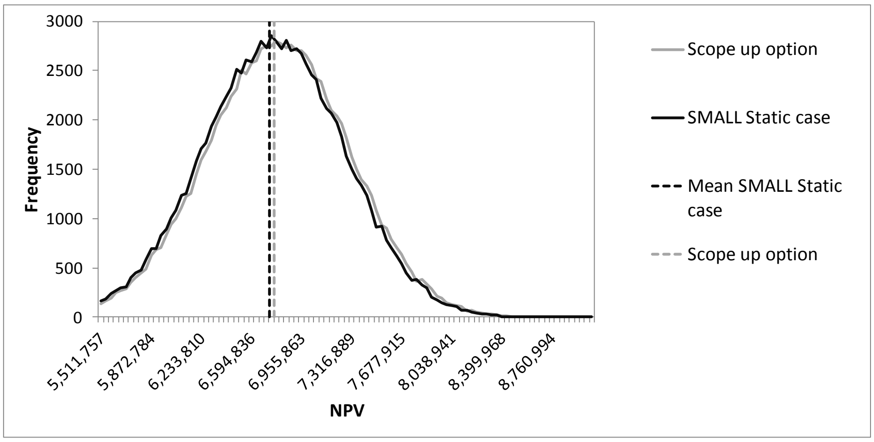


Figure 4-12: Scope up option

4.5.2.d 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 service requires 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 (Figure 4-13).

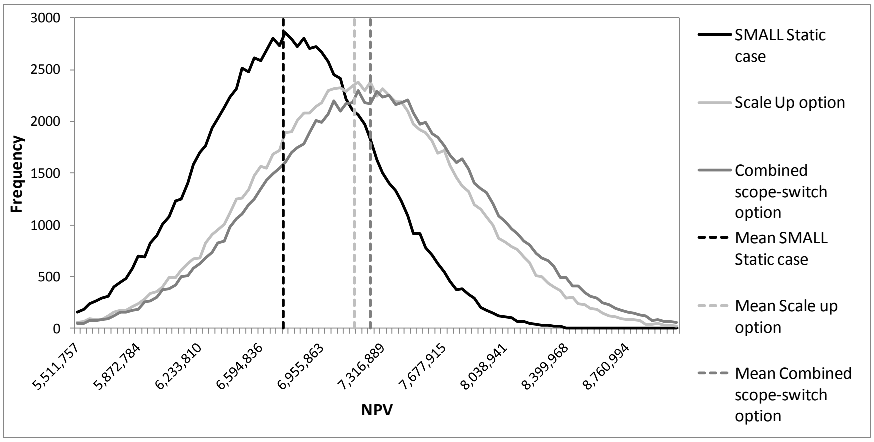


Figure 4-13: Compound options: switch up and scope up combined

4.5.3 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. The scope up option only had marginal value and was almost never executed.

However, in realistic business cases, options almost never occur in isolation. Here we 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.

4.6 Valuing flexibility in core network installation

In this second case study, we will investigate the migration of the existing core networks. In these networks, network demand is continuously growing, especially with the adoption of more bandwidth hungry applications by users in the access network, which obviously also translates in an increase of traffic in the metro and core networks. However, this increase in transported bits is not reflected in the revenues for network operators, since the average revenue per user remains flat. To maintain profitability, there is a pressure on network operators to decrease the average cost per transported bit. Typically, this cost reduction is achieved by installing cost efficient equipment and network architectures. Currently, in the core network, Dense Wavelength Division Multiplexing (DWDM) equipment tuned to the 50 GHz ITU grid is used. However, with increasing traffic, higher line rates per channel will be required. In addition, the underlying assumption that spectrum requirements pose no restriction has been challenged. This will result in networks where the capacity in the core falls behind demand.

To meet the increased demand, the channel capacity will need to be increased beyond the current 100G per channel, together with an increase of spectral efficiency. Additionally, the dynamic functionality of networks should be increased, allowing for dynamic re-optimization.

To achieve the goals stated above, spectral flexibility – or flexible-grid – has been identified as the key type of expected flexibility within DWDM systems. Present day DWDM systems operate under the Fixed Grid – or ITU G.694.1 grid, introduced in 2002 [4.35]. Multiplexers, optical network nodes and transponders are all tuned to this grid. The core network is based on IP offloading, transponders with fixed bit rate and modulation format. But traffic growth would require the use of several 10G or 40G channels between adjacent IP routers.

Flexible-grid, making the wavelength switched optical network (WSON) elastic by moving away from the ITU grid, can accommodate both sub- and super wavelength traffic. It allows an adjustable use of optical spectrum within a certain granularity. This granularity is the minimum bandwidth slot that can be switched in the optical spectrum (6.25 and 12.5 GHz are possible) [4.36]. This technology is slowly coming available, and operators have to decide whether or not to install this flexible-grid capable equipment in their network.

However, various aspects influence this decision. First, under the current predicted traffic growth patterns, Fixed Grid DWDM equipment is expected to suffice for the next years, until the next replacement investment in the core network equipment. Additionally, since the flexible-grid technology is still in its infancy, an installation today will be expensive or risk poor reliability [4.36], [4.37]. Also, the performance of this equipment might still be lacking the full functionality that may appear later.

In order to make the correct investment decision, a techno-economic analysis is conducted for the future installations in the UK core network, as described in [4.38]. The trade-off between a 50Ghz spaced fixed grid installation and a flexible-grid installation is studied. However, an intermediate installation option exists, where the initial installation is flexible-grid ready. Choosing for this installation reduces the investment in later stages when migration towards flexible-grid would be required. As such, the operator buys the option to wait with the migration to full flexible-grid and the option for a cheaper future migration.

4.6.1 Replacing the UK core network equipment

To assess the flexible-grid installation investment decision, a techno-economic case study analysis is conducted for the UK core network (Figure 4-14). This network consists of 27 nodes and 40 edges. There is a distinction between the gray and white nodes in Figure 4-14. The gray nodes represent the current core network nodes, while the white nodes are metro network nodes that have been incorporated in the analysis. In the model, the current traffic matrix of the UK core network is entered, together with a yearly traffic growth prediction of 37% for the entire network [4.39]. As a result, the model calculates the traffic for each source-destination path for the entire time period assessed in the model. Routing the traffic through the network allows to assess the required equipment in the different nodes, taking into account optical bypass. Since the typical replacement period for equipment is five years, this is the period we are interested in. Initially, two distinct scenarios can be assessed, analysing the investment in the WDM layer (Figure 4-15). The first scenario evaluates the installation of a fixed grid core network, while the second studies the flexible-grid capable installation.

However, these two installation options result in a loss of flexibility for the operator. When installing a fixed grid network today, the initial investment is low, but the operator risks either losing money, since he is not able to route all traffic, or he will be putting in a next generation DWDM network (presumably flexible-grid this time) earlier than he would have expected to based on the original planning and demand requirements, also leading to additional costs (fixed grid migrate scenario) under high traffic growth. On the other hand, he can opt to install a full flexible-grid network today. The advantages of such an installation are clear, under any future traffic growth; the operator is ready for it. However, under low traffic growth, a lot of money will be spent in vain, since the installed network equipment is overqualified for the current traffic matrix. Additionally, as was already indicated, the performance of current flexible-grid equipment might considerably improve during the following years. By installing this equipment today, the operator risks higher maintenance costs. And as the learning curve is followed, this will also result in a decrease of the cost for such equipment in the future.

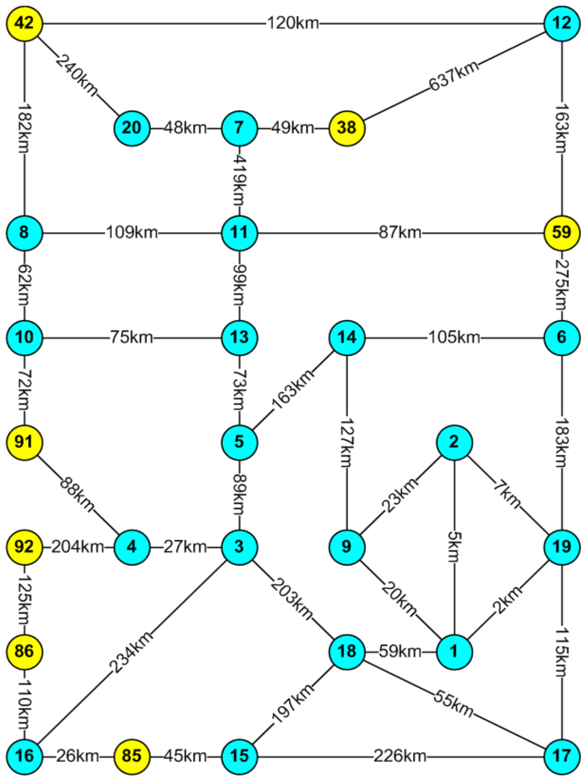


Figure 4-14: The UK core reference network [4.38]

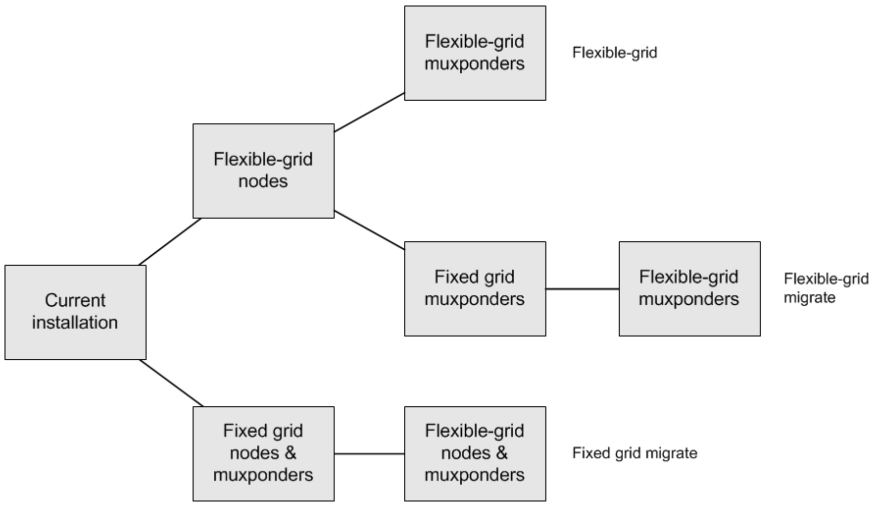


Figure 4-15: Core network installation choices

However, there exists a third installation option which was not explored yet. This intermediate installation path offers future flexibility for the operator (flexible-grid migrate scenario). By installing flexible-grid capable nodes, but using fixed grid DWDM muxponders instead of flexible-grid capable muxponders, the operator buys the flexibility for a cheaper migration towards flexible-grid if necessary. Additionally, since the nodes are used with fixed grid DWDM muxponders, the performance risk linked to the use of flexible-grid and the initial higher capital expenditures (CapEx) associated are decreased. The decision tree now looks as in Figure 4-15.

Next to these three possible installation paths, the operator obviously has many other options. He can overbuild routes or install a fixed grid network with higher channel spacing. When the investment decision is made in practice by an operator, he should take all these options into account. We limit the scope of our study to these three paths, as we aim at indicating the managerial flexibility thinking in telecom infrastructure investments.

Note that under the 37% yearly traffic growth prediction used, no migration to flexible-grid is required during the five year evaluation period. To assess the capital expenditures for both installations, the cost input from the STRONGEST CapEx model is used [4.37], [4.39].

Based on the traffic prognoses, a dimensioning is performed for the nodes and links in the network. As was indicated in [4.38], no standard node model exists for the WDM layer. The node is dependent on the nodal degree N, and this rationale is also applied here. For an N = 2 an OADM, otherwise an OXC is modelled. In addition, based on the number of channels, the building blocks of the nodes vary, and can include Arrayed Waveguide Grating (AWG) or

Wavelength Selective Switches (WSS). Currently the modelled nodes are not contentionless or directionless [4.40]. These nodes consist of wavelength selective switches (WSS) and amplifiers. Their amount is based on the node degree. We refer to [4.37] for a more detailed description of the node model.

Based on the traffic matrix and its expected evolution, the amount of muxponders for each source-destination pair are calculated. For example, a link with a demand of 30Gbps will result in the installation of a 40G (line rate), 4X10G (client requirements), 2500km (reach) muxponder. Traffic of 120Gbps requires one 100G, 10X10G, 2000km and one 40G, 4X10G, 2500km muxponder. With 400G muxponders only becoming available later during the project lifetime, these can only be installed from that year on, in the selected scenarios from above (Table 4-8). This means that once 400G muxponders are available, a link which initially required four 100G muxponders could then have a 400G, 10X40G, 150km muxponder. The operator can thus make the choice between installing an additional parallel 100G path, or replacing the parallel paths with one high capacity path. Here, it is assumed that this migration is performed. Of course, this installation can only be made if the reach constraint of the specific muxponder is satisfied. In addition, when muxponders are replaced by higher capacity muxponders, the initial expense for the first muxponder is not refunded. This calculation results in a number of muxponders required on the start and end node of every link. From this number of muxponders, it is straightforward to calculate the total number of muxponders and wavelengths required per node. The model is extended with three other aspects. As optical bypass is used, regenerators need to be included. For each muxponder, a comparable regenerator is available in the model. Their cost is 1.6 times higher than the comparable muxponder [4.37]. Secondly, amplifiers are modelled every 80 km. The cost of the various types of equipment is expressed in STRONGEST Cost Units (SCU). One SCU represents the cost of a 10G WDM transponder, with a reach of 750km. Notice that for both DWDM and flexible-grid equipment, a cost erosion factor is included. For DWDM, this cost erosion is currently estimated at 10%, while it is put at 15% for the flexible-grid equipment. The cost erosion for amplifiers was considered equally; as this equipment is identical for both systems. This reflects the lower maturity of flexible-grid compared to DWDM. These numbers are based on the extended learning curve [4.41]. It allows modelling the cost evolution of components based on time, and not on the number of units produced. This makes it more suited for the prediction of cost evolution.

Table 4-8: Available muxponders [4.37]

Muxponder	Reach	Year available	SCU
40G, 4X10G (50GHz)	2500	2012	5
100G, 10X10G (50GHz)	2000	2012	13
100G, 10X10G, AUA 40G (50GHz)	2000	2012	16
400G, 10X40G (50GHz)	150	2014	29
400G, 10X40G, AUA 400G, 200G, 100G (75GHz)	500	2014	46

*AUA = Also Usable As

Thirdly, to allow for a fair comparison of the different migration paths, an operational cost for energy was added to the model. The energy use of different muxponders is included, based on industry insight.
In Table 4-9, the total cost (in SCU) can be found for the three scenarios. The total cost of the fixed grid scenario and flexible-grid migrate scenario is considerably lower than the flexible-grid installation, as is to be expected. In [4.37], it was stated that flexible-grid equipment is about 1.3 times more expensive than fixed grid equipment. Here, a full flexible-grid installation is 2.5 times more costly. This difference with [4.37] is driven by the overdimensioning of the flexible grid network for the current traffic matrix. The operator uses higher capacity muxponders from the start, which are considerably more expensive. The flexible-grid migrate scenario is more expensive than the fixed grid scenario, as more expensive nodes are installed from the start. This cost difference reflects the option price.

Table 4-9: Total cost for the installation options

Scenario	Cumulative Discounted Cost
Fixed grid	30.020 SCU
Flexible-grid	75.710 SCU
Flexible-grid migrate	30.663 SCU

When looking at the cost breakdown for different installation scenarios (Figure 4-16), it is clear that the capital expenditures for regenerators and muxponders comprise the largest share of the total cost, around 95% for both scenarios. The cost for nodes, amplifier and energy is negligible.
With this result, the operator would clearly choose to install a fixed grid core network, since this technology choice clearly is the most cost efficient. However, what would happen if traffic growth would be higher than expected? This result

is based on the assumption that no migration from fixed grid to flexible-grid is required, but it was already indicated that traffic growth might force operators to undertake this migration when spectrum becomes scarce. This will be studied in the following section.

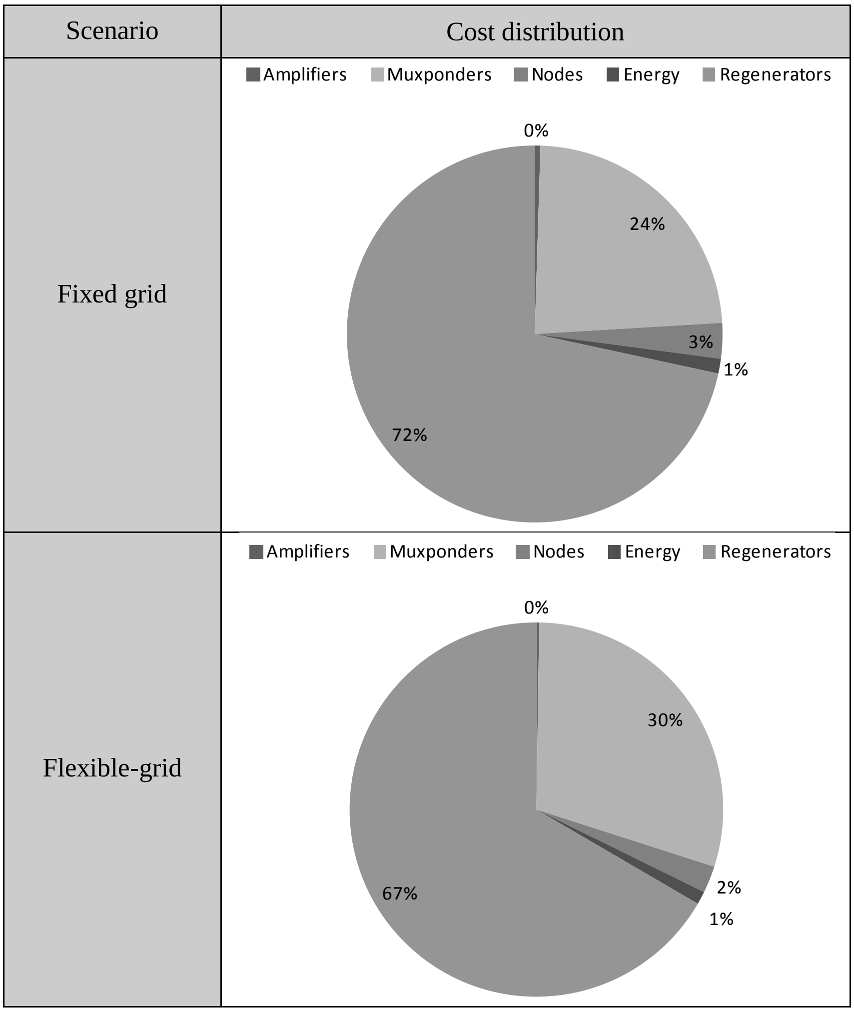


Figure 4-16: Cost breakdown for different scenarios

4.6.2 Checking the three conditions

In order to conduct a RO analysis, the case must meet the three conditions. We will check these conditions below.

Uncertainty

There are various potential sources of uncertainty in the case presented here. These can be linked either to future traffic or the future cost.

- The bandwidth growth evolution is the major uncertainty in this case. The initial traffic matrix is clear, but its evolution in time is bound to an uncertain evolution. What is this expected evolution? And is there any indication of the uncertainty on the expected traffic evolution?
- Current flexible-grid equipment, muxponders and regenerators are still a new technology, and there are still some risks related with using them. For example, it is not very good at distinguishing between wavelengths. The equipment will become cheaper and more trustworthy in the future. As such, the future maintenance and replacement costs of this equipment is uncertain.
- Technological evolution can lead to cost erosion in flexible-grid equipment. While the application of the learning curve can model this cost erosion, it is still required to estimate this yearly cost decrease upfront when making the investment decision.
- Early installation of a flexible-grid network is more expensive, since the equipment has not hit mass market yet.

Managerial flexibility

A graphical overview of the managerial flexibility can be found in Figure 4-15. In case of the migration scenarios, operators have to decide on the upgrade of their core network. Three possible scenarios were taken into account in this study.

- Flexible-grid scenario
  The operator installs flexible-grid ready equipment. If traffic grows faster then expected, the operator is ready for it. If it does not grow fast, a lot of money was spent in vain.
- Fixed grid migrate scenario
  The operator does not install flexible-grid ready equipment. If traffic follows the expected growth path, then this solution will be the most cost efficient, as was indicated in section 4.6.1. If traffic grows faster than expected, the operator will end up either losing money not being able to route all traffic or they will be putting in a next generation DWDM network (presumably flexible-grid ready this time) earlier than they would have needed to, which will lead to additional costs
- Flexible-grid migrate scenario
  The operator buys the option to migrate to flexible-grid by installing flexible-grid capable nodes, but he continues to use fixed grid muxponders and regenerators. In case the traffic grows faster than expected, the operator is ready for it and the investment in flexible-grid ready nodes can be avoided. In case traffic grows at its expected

growth rate, the operator can use the less expensive fixed grid muxponders.

In the flexible-grid scenario the operator looses all its flexibility. The core network is fully upgraded towards flexible-grid, and there is no way back. The same goes for the fixed grid migrate scenario. Under high traffic growth, the operator has no other choice than to install flexible-grid. The flexibility is present in the last scenario. The upgrade towards full flexible-grid can be performed when necessary. In addition, he does not have to decide on this upgrade today, but can do this when the uncertainty surrounding future traffic and flexible-grid equipment is reduced.
Other options are available as well. The operator could overbuild, or install a fixed grid network with larger channel spacing. When an operator performs this investment analysis to indicate its best investment options, these should be included as well. However, we aim at indicating how real options can be identified and applied in telecom infrastructure problems, so we only model the ones presented in Figure 4-15.

Phased decision

Typically an option-based investment is characterised by a phased decision. One makes a small initial investment (buying the option at the option price) which allows a follow-up investment later on leading to additional revenues (exercising the option for the exercise price) or deciding not to go forward with the follow-up investment in case the market conditions do not turn out favourable.
In this case, such an expansion option can be seen in the flexible-grid migrate scenario. The operator makes an additional initial investment, i.e. the installation of flexible-grid capable nodes instead of standard fixed grid nodes. Initially the operator uses standard (cheaper) fixed grid muxponders, but when the traffic grows faster than expected, a follow-up investment in flexible-grid muxponders can be done. In this case, the operator saves the replacement cost for new nodes.
The other option that can be found in this case is the option to wait. By initially installing fixed grid equipment and transponders, the operator can wait and decide at every point in time to migrate to flexible-grid, depending on the bandwidth growth and technological evolution. The longer the investment can be postponed, the higher the value of the option to wait. However, the value of waiting can also be found in the fixed grid – migrate scenario. Here the operator waits with the installation of the flexible-grid muxponders and nodes.

4.6.3 Impact of traffic growth uncertainty

It was already indicated above that traffic growth is a major uncertainty when performing dimensioning studies, and it has a large impact on the expected result. If traffic grows at a faster pace, it would require the installation of additional muxponders and regenerators to provision for parallel paths earlier. As a result, the total available spectrum will be reduced or even run out, requiring a migration towards flexible-grid in case the operator has chosen a fixed grid installation.

Under the expected traffic growth of 37%, this migration towards flexible-grid could be postponed to the next re-installation time, in five years. However, if traffic grows faster than expected, this installation will be required earlier, resulting in an additional investment cost. Here, it is assumed that if total traffic grows by 500%, such a migration would be required, which is in line with the current capacity limits of the UK core network. Although this threshold is inserted artificially, it allows assessing the impact of traffic growth uncertainty. Under the basic assumption of 37% growth p.a., this threshold is not exceeded within the evaluation period of five years for the majority of the links. However, links already currently experiencing high traffic would need to be migrated anyway. The advantage of this migration scenario is that it allows a gradual migration towards flexible-grid, while the operator loses all flexibility in the flexible-grid scenario.

Under these assumptions, the advantages of the Fixed grid migration scenario are clear. Since only a small number of links would require a migration, the cost increase is negligible compared to the investment in a full flexible-grid network. But what would be the impact on the total cost for both scenarios under other traffic growth conditions? When the flexible-grid migration scenario is considered, the same rationale as for the fixed grid migrate scenario holds. However, as the nodes are installed flexible-grid ready, the migration will come at a lower cost, as only an investment in muxponders and regenerators will be required, not in nodes.

To indicate the impact of this uncertainty on the analysis, a scenario analysis for the different migration paths to flexible-grid is presented below (Figure 4-17). It is clear that for the lower traffic growth scenarios, the installation of Fixed grid DWDM equipment is to be preferred compared to the flexible-grid migrate installation, as was also concluded from the standard techno-economic analysis. When no migration is required, the operator would clearly opt for the cheaper fixed grid installation. However, as is clearly visible from the high traffic growth scenarios, the total investment cost for the migrate scenarios rises, while the flexible-grid scenario is traffic independent. Although the flexible-grid migrate scenario offers a cheaper migration in the future, this does not result in a lower total investment cost during the project lifetime. It is thus to be expected that flexibility does not pay off in this case.

In order to indicate the impact of uncertainty clearer on the result, the scenario analysis is extended towards a real option analysis. The traffic growth is now distributed triangularly between 30% and 60%, with 37% as the most likely. The impact of this uncertainty, and the resulting value of flexibility in the migration

decision in time on the results for the migrate scenarios can be found in Figure 4-18. From the cost distributions, it is clear that the traffic uncertainty has a major impact on the cumulative discounted cost (CDC) cash flows evaluation of both scenarios. For both scenarios, an increase in the traffic growth results in an increase of the total cost. However, when comparing both cost distributions, it is clear that the fixed grid migrate scenario remains the most cost efficient. The analysis was also performed for the flexible grid scenario. As the total cost is always significantly higher than the cost for the other two scenarios, they are not depicted on the figure.
Conducting the ROA thus indicated that uncertainty has a clear impact on the CDC evaluation, but there is no value in buying the option for a cheaper migration in the future.

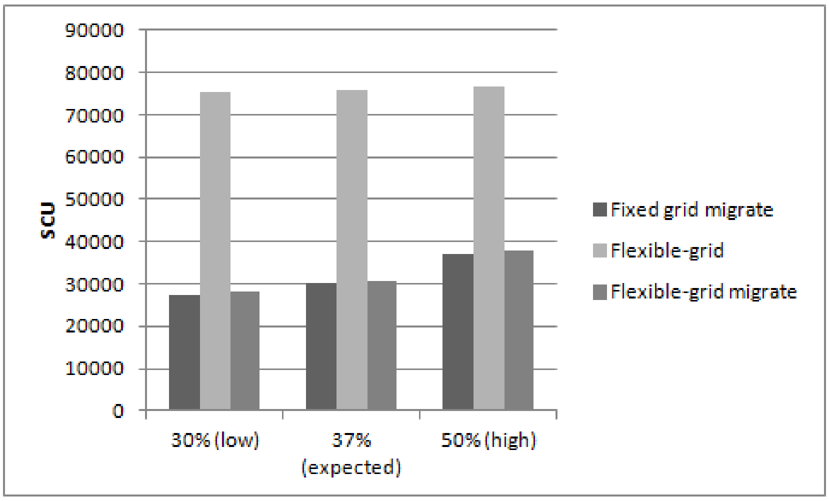


Figure 4-17: Impact of uncertainty on the investment cost

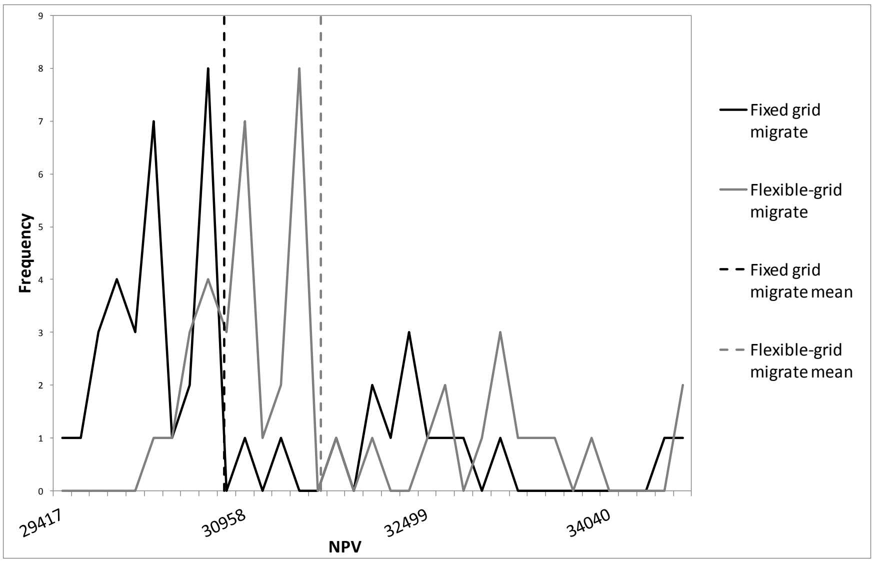


Figure 4-18: Cost evolution under traffic growth uncertainty for the different scenarios

4.6.4 Case conclusions

The translation of high growth in network demand in the access networks is putting pressure on the core networks. In order to maintain profitability, operators are continuously looking to reduce the cost per transported bit. Today, core networks are based on fixed grid DWDM system, making use of parallel light paths between core routers. However, in light of the expected traffic increase, the underlying assumption that spectrum availability poses no restriction is being challenged. As a solution to increase spectral efficiency, the flexible-grid concept has been introduced recently.

As equipment needs to be replaced often, operators will have to make the decision to migrate to flexible-grid within the coming years. This migration decision is based on various aspects, which can have a different influence. Uncertain traffic growth and performance of equipment are only two of those aspects.

Since the operator aims to reduce costs, the translation of these influences on the expected investment needs to be assessed. In this case, such a techno-economic analysis of the replacement investment in core network equipment is performed. It is shown how uncertain future traffic growth evolutions impact the investment decision. Initially, no migration is required, but uncertain traffic growth largely impacts the migration need and the associated total investment cost. However, since operators can flexibly adapt to changing conditions, reducing risk and investment, a real option analysis was performed to capture the value of this flexibility. Flexibility should be taken into account when such an investment decision is made. Although no value of waiting was identified here, the results are case specific and dependent on a broad range of input factors.

As such, the results of the case study only hold for this specific case. The case focused on a dense Western European network. Other network topologies will have an impact on the outcome of the analysis, and on the preferred installation by the operator.

As this cases attributes no value to buying an option, it indicates clearly how option thinking is not an inventive approach to artificially increase the value of techno-economic projects. It is an approach that reflects the possibilities of the decision maker to optimally adapt to the underlying environment and the opportunities it offers.

4.7 Other applications of ROA thinking in telecom

Real options can be applied to a wide range of investment problems in telecom. We will shortly describe two problems here, one on the deployment of a sensor network in a city environment [4.1], the second on access network unbundling [4.4].

4.7.1 Deploying a municipal parking sensor network

Wireless sensor networks (WSN) have multiple applications. They offer possibilities for monitoring all kind of parameters, going from detecting environmental aspects, traffic flow and network control.

Techno-economic studies on WSNs are limited. An extensive study on the current state of research in WSNs can be found in [4.42]. However, most studies, are limited to technical solutions for energy consumption savings and monitoring, rather than the economic viability of the total system. It was studied how opting for an initial phased deployment opens up several future options for the management. The first phase offers learning possibilities, and the speed of the second phase is based on the results of the initial rollout (Figure 4-19). The value of these options is captured with a Real Option Analysis.

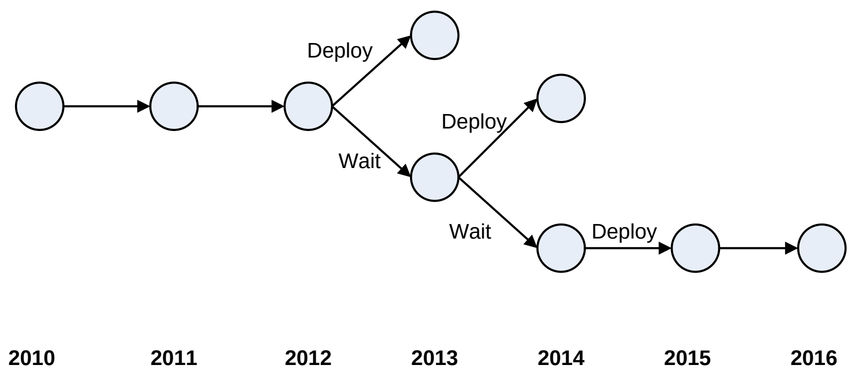


Figure 4-19: Expansion of sensor network to larger area

4.7.2 Flexibility value in access network unbundling

Local Loop Unbundling (LLU) is a method to open the access network connecting the customer to the central office to other operators. Through this open network, other operators can offer services to the end consumers. LLU is enforced by regulators, who also fix the price for this network access. Their main objective is increasing competition in the previously monopolistic market.

Setting the access price is a difficult exercise, as it should suffice to cover the costs of the network owner. With an LLU offer on the market, new entrants have the choice between using the Full Unbundling (FU) or Line Sharing (LS) offer, the bitstream access (BA) offer, installing their own network or not provide access at all to customers (Figure 4-20). It is clear that they have flexibility in their choice. The value of this flexibility should be incorporated in the price setting by the regulator, as the network owner gave up his flexibility when installing the network. Real option valuation can be used to estimate the economic value of this flexibility. It was concluded that the value of flexibility clearly should not be neglected when LLU prices are fixed.

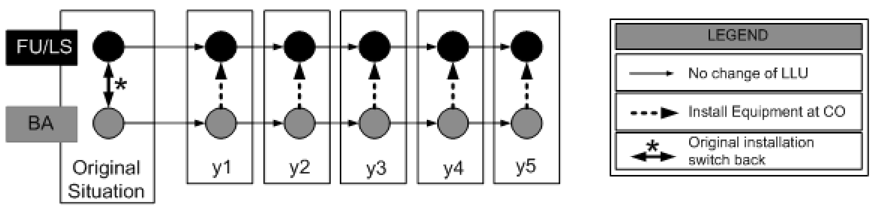


Figure 4-20: A visual overview of the connection options for the new entrants at the end of each year [4.4]

4.8 Lessons learned and shortcomings

4.8.1 Real option analysis guidelines

The practical RO analysis methodology described in this chapter 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 optimisations, 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 network planners to identify the presence of real options in their network plan. Additionally, the 7S framework can help to categorise 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 formalise 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.

4.8.2 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. In addition, the extra value an option generates can be offset by the price paid to acquire the option, as was indicated in the core network migration case.

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.

4.9 Conclusion

The broad range of uncertainties concerning future technological evolution, customer adoption and regulation which is characteristic of the telecommunication sector definitely requires 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 within 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. Here, 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 two cases. The first case studies 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 the second case study the migration options towards future core networks were investigated. We identified different future installation options, but the real option analysis indicated that flexibility in the initial design was not to be preferred, as the cost for the flexibility in the initial installation did not pay off in the future.

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5

Modelling Market Interactions

“Do not hold the delusion that your advancement is accomplished by crushing others”, Marcus Tullius Cicero

The previous chapter detailed how uncertainty and flexibility can impact the decision making for telecom firms. However, the aspect of market interactions was not touched, while this plays a major role in the current environment. Operators, service providers and vendors operate in the existing market environment and need to take into account possible competitive interplay when making investment decisions. But competition is not always the prevailing strategy, as cooperation models also occur. Public private partnerships in network rollout, or alliances in standardisation are just two examples.
In this chapter, the possible market interactions, competition and cooperation, are described. Competition with other players will influence the adoption of the product or service, and in turn impacts the equipment dimensioning and the operational processes and is modelled through a market response model, which is described in [5.1]. By dividing the market, revenues are split between different actors. Cooperation models on the other hand, aim at cost sharing. More detail will be provided on the cooperation possibilities through joint infrastructure rollout [5.2]. By rolling out infrastructure in the same trench and coordinating work, costs can be shared between different utility owners, resulting in reduced total investment cost for every actor involved.

5.1 Strategic impact on market share

5.1.1 Introduction

Two trends have impacted the market structure in most industries today. First, as a result from the liberalisation and deregulation in Western economies, only few industries remain protected. All other sectors are confronted with competition. Examples of such sectors are the energy and telecom market, which have undergone significant liberalisation in the last two decades [5.3]. In the energy market, former monopolies have been opened up to new, possibly foreign entrants. Consumers can purchase energy from different suppliers, while only the transport and distribution networks remain a natural monopoly. In the telecom market, similar trends occur. In the 1990s, the former incumbents have lost their monopoly on voice and data transmission, increasing the dynamism, uncertainty and competition. After the liberalisation wave, the burst of the internet bubble resulted in continuous consolidation in sectors previously populated with many firms, leading to oligopolistic markets. Obviously, compared to other sectors, regulation in telecom and energy still remains high. Although the market has been opened to new entrants, the former monopolists still have significant market power (SMP), resulting in regulatory authorities to introduce policy to reduce this market power. Unbundling of the local loop in telecom access networks or the introduction of nuclear taxes on the incumbent energy producer are only two examples of new regulation. In addition, the uncertainty on the direction of new regulation increases uncertainty for market players. Currently, the future regulation on local loop unbundling in fibre access networks is unclear, resulting in a decreased rollout of such networks.

Resulting from these two trends, liberalisation and continuing consolidation, companies today face strategic uncertainty when making investment decisions. In case of new product or service introduction, the viability of this introduction is typically assessed through a techno-economic analysis. Standardised methodologies exist to conduct a complete techno-economic analysis of investment projects, e.g. the methodology proposed by Verbrugge et al. for techno-economic modelling introduced in Chapter 2. This methodology consists of four steps, gathering input, modelling costs and revenues, evaluating the project and concludes with possible extensions [5.4]. Typically, in the input gathering phase, the future market potential of the new product or service needs to be estimated. While this factor already comes with a great deal of uncertainty, since it is based on guesstimates or market research, it is also the factor with a large impact on the profitability of the project, as it drives revenues and variable costs from the technical model. As was already indicated in the equipment model in Section 2.3, the bill of material is driven by the number of customers (Figure 5-1).

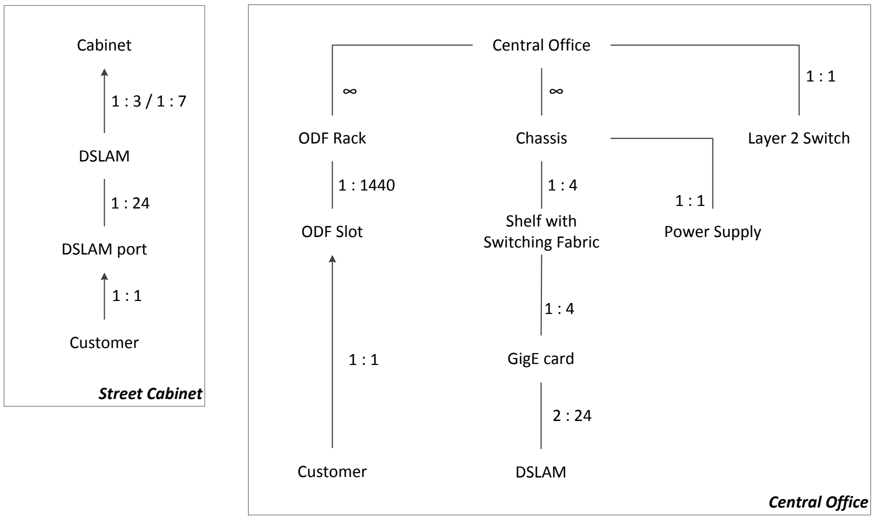

Figure 5-1: Equipment model for an FTTC network

In case of a Fibre to the Home (FTTH) network, the impact of adoption is enormous. The network needs to be deployed to all households, resulting in a large upfront investment cost. This cost is typically in the ranges of €500 to 2.000 per home passed. But in the viability analysis, the cost per home connected is more important. If 50% of the households connect, the cost per home connected is between €1.000 to €4.000. If only 10% connects, this cost rises to €40.000 per home connected. The impact of the underlying technological dimensioning model and the expected uptake on the results cannot be neglected.

In the absence of competition, the adoption is typically modelled using diffusion models, e.g. Gompertz, Bass or Fisher-Pry adoption models [5.5–5.7]. The Gompertz curve was already introduced in Section 2.3.2.b to model the FTTC service uptake in London. However, with strategic uncertainty, the impact of competition with other offers or services comes into play and the estimation of the market potential is much harder. Entering an existing market will have a distorting effect, and it can be expected that this will trigger reciprocal actions by competitors. Price wars are just one example of such competitive interaction. In business case analysis, these dynamics are modelled through game theory [5.8]. Although this theory allows modelling the different strategic combinations in the market and offers tools to find the prevailing equilibriums, an assessment of the market share of all offers is still required in order to conduct the analysis.

Originating from the field of marketing, market response models offer methodologies to indicate the effect of marketing variables on number of products sold or market share [5.9]. These variables include price, promotion, but also competition. As such, they can provide valuable insight in the evolution of market size as basis for techno-economic analysis. However, uptake of these market response models has only been slow by decision makers, mainly due to the high complexity of these models, especially if they are built for specific markets [5.10].

Here we propose a modular market response model. Due to the modular approach, the ease-of-use is increased for decision makers. The model uses generally accepted market parameters, like churn and price elasticity of demand. As a result, it is applicable to different sectors, limiting the need for mathematical modelling and estimation of market parameters and interactions.

In the following sections, we will first introduce some existing market models, indicating their strengths and shortcomings. Next, we introduce the different parameters impacting strategic interaction. As a modular market response model was built, we will go into more detail on these different modules. To indicate how the model works in practice, it is applied to a realistic case, the introduction of FTTH services in the Netherlands. The results of the market response model will prove valuable in the network and equipment dimensioning steps of a techno-economic analysis of an FTTH network.

5.1.2 Existing market response models

Standard diffusion models are the most basic and widespread market response models. Gompertz, Bass and Fisher-Pry curves model the adoption of a new technology, product or service through an S-shaped curve [5.5–5.7]. Initially, the increase in uptake is exponential, but after the inflection point, the penetration asymptotically reaches full penetration. Although these models are widely used in techno-economic analysis and have even been shown to model technology penetration correctly [5.11], some disadvantages exist. While these models can be fitted to observed penetrations of technology ex-post, the ex-ante estimation of the parameters is more difficult. Additionally, the impact of competition with other technologies is typically left out of the analysis. In order to model the competitive impact, more complex market response models are required.

The impact of competition on pricing, output quantity and market share has been a research topic for over 100 years. In Cournot competition, individual firms compete with each other based on quantity [5.12]. Each firm decides on its output quantity independently, without knowing the decision of its competitors. Since Cournot competition states that the number of firms is fixed and they all have the power to influence market prices with a homogenous product, it can be mathematically derived what the output of each player will be. As a result of the Cournot model, players price above competitive price (i.e. they have a positive profit margin). It has for example been applied to local loop unbundling pricing problems [5.13]. In the other case, when players compete on price instead on quantity, the Bertrand model applies [5.14]. In this model, firms compete at competitive price, in contrast with the Cournot model. If the number of players is increased to infinity, the two models generate the same results. These models form the basis of game theory, and will be discussed in more detail the next chapter.

These competition models have been extended and applied to a plethora of different cases. For example, the Stackelberg competition model extends the Cournot model by introducing sequential moves by different players [5.15]. The leader makes the first move, and knows the follower will observe this move. In addition, Stackelberg competition assumes the leader has some sort of commitment power. Such power can be reflected in holding excess capacity, or if the leader was the former incumbent monopoly.

All these models described above consist of a modelling of the competition, and the underlying assumptions, e.g. the homogeneous product, make them less suited for realistic business cases. In addition, they allow to evaluate the output quantity and price of the different players, but the impact on the total market of competitive behaviour is not taken into account.

Approaches from other fields have also been used in order to model market shares of competing operators. The Lotka-Volterra model, also known as the prey-predator model, has been used to study the impact of competition and market dynamics. This model was developed first to study interactions between two species. However, they have proven valuable in economics as well. The Lotka-Volterra equations model the number of individuals of two species in an environment, a predator and a prey. Concerning the prey, it is assumed that it finds sufficient food at all times, while the food supply of the predator depends entirely on the prey. The Lotka-Volterra equations can be found below.

Prey
$$\frac{dx}{dt} = \alpha x - \beta xy \tag{5.1}$$

Predator
$$\frac{dy}{dt} = \delta xy - \gamma y \tag{5.2}$$

The model assumes an exponential growth of the prey population, represented by the first term of eq. 5.1. The second term reflects the rate of predation upon the prey. This term is dependent on both the number of prey and predator. As such, the more predators, the higher the rate of prey population decrease. When the predator population is considered, it is clear that the growth rate depends on the number of prey present in the environment. If there is almost no prey, or food supply, the predator population cannot grow. The death rate of the predator population is modelled through the second term of eq. 5.2.

In telecom markets, the incumbent was modelled as the prey, while new entrants where predators. A new entrant can only increase his market share by churning on the market share of the incumbent [5.16]. Another application can be found in the television market, where new screen technology pushes the older out of the market. The leading CRT technology was replaced by plasma and LCD television [5.17], [5.18].

While the Lotka-Volterra model is well suited to model competitive effects between different actors, it has some shortcomings. First, the carrying capacity of the environment is constant. In realistic markets, markets tend to grow and shrink. The Public Switched Telephone Network (PSTN) market and mobile phone markets are just two telecom related examples. Additionally, in order to model markets with prey-predator behaviour, the market already needs to exist. Finally, one needs to estimate the different parameters upfront, which can prove time consuming for realistic cases and requires historical data.

Other market response models are built upon simultaneous equations models. These models are an extension of the standard regression analysis. Typical regression analysis works with a single equation to estimate a variable based on several parameters. As the name suggests, simultaneous equation models is a data generation process that depends on more than one equation interacting together to produce the observed data. These models require the collection of historical data, like price and uptake, to model demand curves for the different services. In existing markets, such models have proven valuable [5.19], but in emerging markets, the absence of data undermines the usability of such models. In [5.19], such a model was developed for the estimation of the market for cable television. This demand depends on both the supply and demand of analogue and digital cable television.

The different competition models discussed above each have their own shortcoming. Cournot, Stackelberg and Bertrand competition model competitive interaction based on price or quantity. Based on an analytical foundation, they are however less suited for realistic business cases. In addition, their main goal is to estimate the price and output quantity, with less focus on market share modelling. This market modelling is the primary focus of the Lotka-Volterra model. In [5.16], they were applied to a former monopolistic market, where a new entrant appeared. However, the different parameters need to be estimated upfront. As this requires historical data, it is less suited for application to emerging markets. The final drawback these market response models share, is their complexity. While some of them might be easier to use, e.g. the S-shaped diffusion models, it remains difficult for decision makers to translate the parameters to known concepts. Estimating the death rate or inflection point of models is not straightforward, especially since these decision makers are more familiar with concepts as elasticity, contract duration, etc.

As such, market response models based on economic concepts, e.g. price elasticity, churn, cross-elasticity, etc., are more suited to use in techno-economic analysis. The user of the model is typically familiar with these concepts and knows how they relate to his market. In addition, econometrics can easily provide reliable values for these parameters. However, as the typical drawback of market response models is the complexity, which reduces the adoption of such models, a market response model must be accessible and user-friendly. Therefore, we have developed a modular market response model [5.1]. In the following section, we elaborate on the different parameters impacting the market, continuing with the introduction of the competitive market response model. We will also indicate how the different parameters impact the model.

5.1.3 Market impacting factors

The market response model developed in this dissertation aims at estimating the evolution of market shares of competing offers, taking into account the interaction between the prices of these offers. In a competitive environment, different market players compete for market share, typically with even more than one offer. In telecommunications, operators offer basic subscriptions, high-speed subscriptions, triple-play packets, etc. As such, the operators do not only compete with each other, intra-competition between their own offers is also present. For example, an incumbent rolling out a next generation access network, will need to take into account that this might churn the market share of its legacy network. Therefore, the market model presented here allows assigning market shares to different offers, independently of whether they are offered by the same player or not.

The market response model aims to assess the impact of strategies on the competitive equilibrium on the market. Typically, different strategic combinations by different players will have a different impact on the underlying market, which needs to be reflected in the total market size and the market shares of all players. For example, a low average price level for a product will typically result in a higher demand. This is also the reason why broadband price is included in the next generation oriented broadband performance index described in Chapter 2. Additionally, the actor charging the lowest price can expect the highest market share in a normal market, where demand has an inverse relation with price. As such, strategy is the main driver for the market model. The basic strategy used in the model is a price strategy, although price corrected for quality can also be implemented. When an operator offers a higher access speed for a price premium, this can be reflected in the strategy in the market model.

Two important parameters of the market model were already indicated in the short description above, namely the impact of competition on the total market and the impact on the market division. The third parameter that is taken into account is the free market. This parameter indicates the amount of the market that is free to be re-allocated in every year. In reality, not all customers are able to switch supplier at any given moment in time. Due to contract duration, only a part of the total customer base can switch, which is the free market. In the following paragraphs, we go into more detail on the functioning of the market response model. To indicate how the model works in practice, a stylised example will be elaborated on. The example consists of an emerging market, where two suppliers compete for market share. The emerging market is modelled through an S-shaped Gompertz curve, which was already introduced in Chapter 2. The Gompertz curve was chosen, as this has been indicated to be the most appropriate approach to model the adoption of e.g. telecom business cases [5.11]. In the mathematical formula (eq. 5.3), three parameters are required, point (a), slope (b) and market size (m).

Table 5-1: Gompertz curve parameters for the stylised example

Parameter	Value
a	4.0
b	0.3
m	1

$$S(t) = m.e^{-e^{-b(t-a)}} \tag{5.3}$$

For simplicity reasons, price was selected as the only factor impacting consumer choice in this example. To indicate the effect of price changes on the total market and the market division, decreasing prices were chosen. Supplier 1 charges a monthly price of €35, with a monthly price decrease of 2%. Supplier 2 charges a lower price initially, of €30, but only with a price decrease of 1% per month (Table 5-2). The evolution of both prices is shown in Figure 5-2. The prices were chosen in order to indicate how evolving prices impact the final market division resulting from the market response model.

Table 5-2: Market parameters for the stylised example

Parameter	Value
Initial price offer 1	€35
Price decrease offer 1	2%
Initial price offer 2	€30
Price decrease offer 2	1%
Price elasticity of demand	-0.5

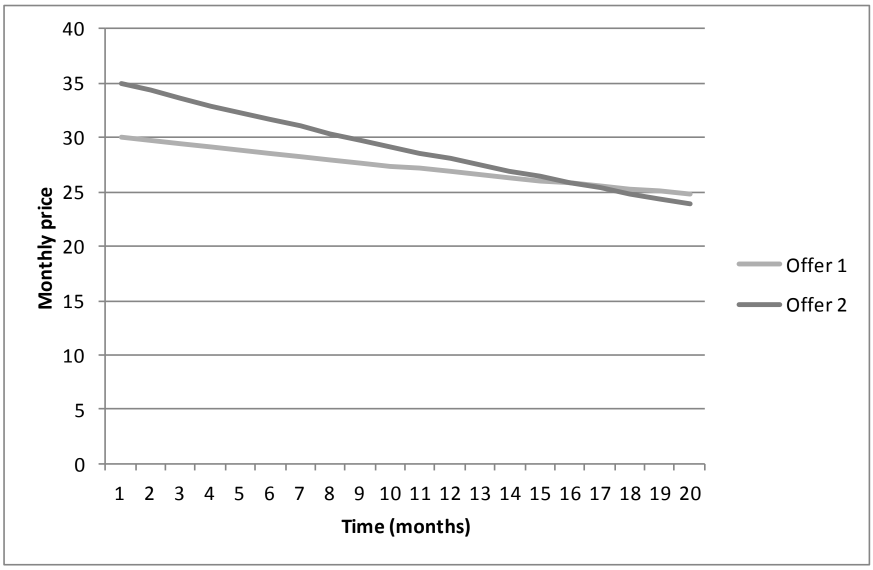

Figure 5-2: Monthly price evolution of both offers in the stylised example

5.1.4 Modular approach

The market model uses a logical stepwise approach to calculate the market share of each offer, linking the three parameters together. These links are shown in Figure 5-3. As input, the model requires the strategies of the different offers, and an initial market. This initial market can be limited to a standard S-shaped adoption curve, but can also include the initial market shares of the existing offers on the market. In the market model, the market is defined by a maximum of four parameters. The expected market potential, together with a minimum and maximum potential over time. These can be growing or decreasing over time. When these are not defined, the model assumes a minimum potential of 0%, and a maximum of 100%. The fourth parameter defining the market is the price elasticity of demand.

By combining an initial market with the strategies of the different players, the total market is defined. For example, this total market is the initially defined market, corrected for the impact of the price elasticity of demand. Next, from this total market, the free market is derived, e.g. based on the yearly market growth. Finally, by defining the market division, the free market can be distributed to the different offers, resulting in the calculation of the market shares for all offers. In the following sections, we go into more detail on the different modules of the market model.

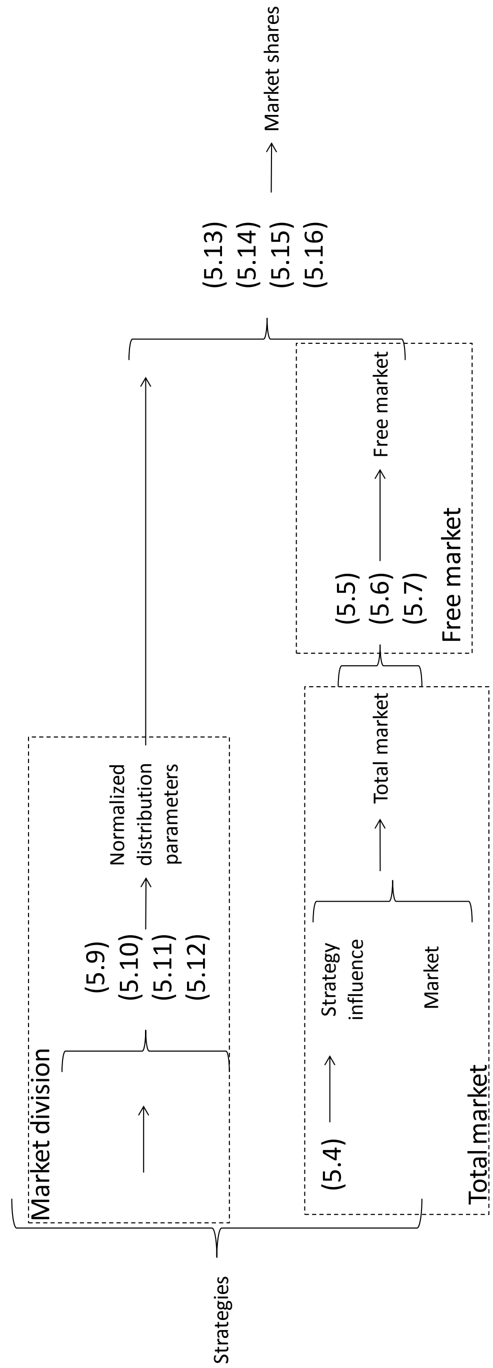

Figure 5-3: General overview of the market model

5.1.4.a Impact of strategy on the total market

In the first step, the impact of changing strategies on the total market is modelled (Figure 5-4). In economics, the elasticity concept is used to model the effect of a change in one factor on another economic variable [5.20]. As the market response model indicates the impact of strategy on the total market, the elasticities of demand are of interest in this model. The price elasticity of demand measures the responsiveness of the total quantity (Q) demanded of a good or service to a change in its price (P). It is represented by eq. 5.4.

$$e_D = \frac{dQ/Q}{dP/P} \tag{5.4}$$

In typical markets, a rising price results in decreasing demand. A price drop for computers, cars or smart phones will have a positive effect on demand, and thus on the penetration rate of these goods. However, for some products or services, it is possible that an increase of the highest price on the market has a positive effect on the total demand (in case of Veblen or Giffen goods) [5.20]. This is typically the case for luxury products, where the prestige linked with the product rises with the price and thus increases demand (Veblen). Otherwise, it can also occur for inferior products (Giffen). A rising price for bread results in a higher demand, since lower income groups notice a large effect of this price on their income, so they start substituting other more expensive food with bread. It should also be taken into account what price impacts this demand change. In the standard formula included in the market response model, this is the average price level. Although this is the most common approach, the market model should also be applicable to other cases. The introduction of a new service at a lower price level can attract new customers, who previously could not afford the service. Therefore, a decrease of the lowest or highest price on the market was also implemented as demand driver. A price elasticity calculator is introduced to model this behaviour. Also notice that the market model works with a range of prices, so the arc elasticities are used, not the point elasticities. The corrected total market then serves as input for the following module, which determines the free market.

In order to apply the elasticity impact module to our example case, an estimate of the price elasticity of demand for the market is required. In this example, a price elasticity of -0.5 is used (Table 5-2). Using the example case from above (Table 5-1 and Figure 5-2), it will be indicated how these parameters impact the total market. The effect of the impacting price will be indicated by choosing the lowest, highest or average price level as demand driver.

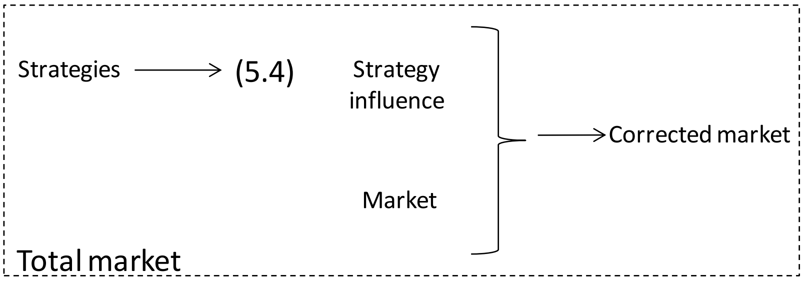

Figure 5-4: Calculating the impact of price elasticity of demand

Price as demand driver

In our example, a negative price elasticity was chosen. As the broadband market has shown to be a market where decreasing price increases demand, it is clear that the price evolution in the example case should result in an increasing market, as can be seen in Figure 5-5. As both prices decrease over time, the total market is expected to increase. The different behaviour from using different reference prices is interesting. When the average price level on the market is used as basis for the elasticity impact, this impact is linear. After 20 months, the expected market will have grown by 11% due to the price elasticity of demand, compared to the case where prices are constant. Since in the stylised example, the highest price (offer 1) shows a faster price decrease, this results in a higher elasticity impact. Once the two prices cross, and the price of offer 2 becomes the lowest, the elasticity impact shows a nod.

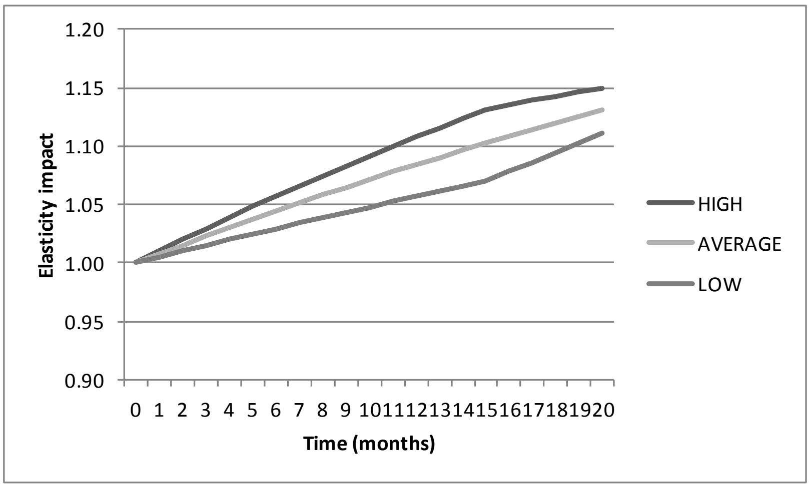

Figure 5-5: Elasticity impact with different reference prices for the stylised example

Price elasticity and its effect on market growth

The effect of the height of the price elasticity will obviously also have an impact on the total market. Figure 5-5 showed an inelastic market, but a higher price elasticity would even enforce the elasticity impact. As the model is built based on time series, it is even possible to have a changing price elasticity over the studied period. Once the impact of elasticity is estimated, it can be combined with the total market. The impact of price elasticity clearly shows in Figure 5-6. The expected market is multiplied with the elasticity impact calculated above. Again, as a negative price elasticity was chosen, due to the decrease in prices, the market grows faster than initially expected. In addition, the introduction of a maximum market potential caps the penetration to 100%.

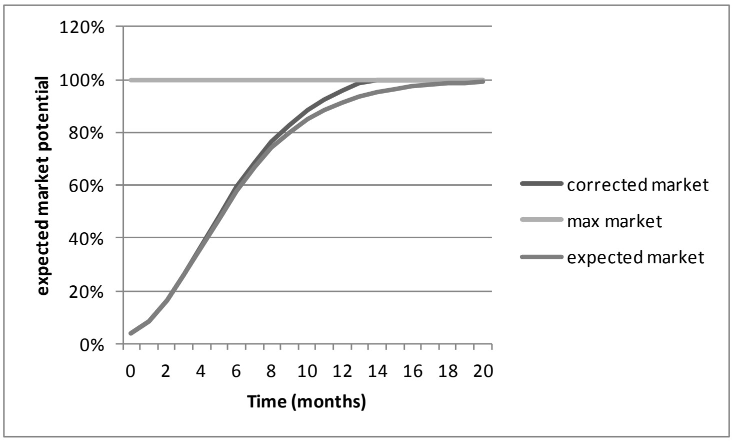

Figure 5-6: Price elasticity of demand increases expected market

5.1.4.b Determining the free market

When a player enters a new market, or decides to change his strategy in an existing market, the effects on the market division will only be visible after a certain amount of time (Figure 5-7). Indeed, at any moment in time, there is only a part of the market that can react to the changed strategy and switch offer. Churn rate refers to the proportion of customers that leave a supplier during a given time period. It is a term used in markets with a contractual customer base. As such, it is very typical for telecom markets, who have a subscriber-based model. At the end of their contract duration, a part of the subscribers will switch provider and leave their current operator.

However, as the churn rate indicates the number of customers actually changing supplier, an important remark needs to be made. In the market model proposed below, the free market is used. In that respect, it needs to be taken into account that not all customers who are at the end of their contract duration will

effectively leave their current supplier. As such, the free market consists of the customers inclined to change (CIC) fraction (eq. 5.7).
In addition to the customers inclined to change, there is a second aspect present in the free market. In a growing market, the yearly growth will also be competed for by operators, and should as such also be catalogued as free market (eq. 5.6). Combining these two concepts results in the total free market per year (eq. 5.5).

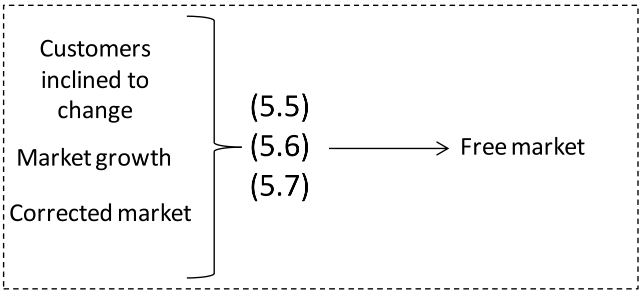

Figure 5-7: Determining the free market based on initial market and CIC

$$\begin{aligned} Free\ market_i &= customers\ inclined\ to\ change_i \\ &\quad + new\ Market\ share_i \end{aligned} \tag{5.5}$$

$$\begin{aligned} new\ market\ share_i &\\ &= Corrected\ market\ potential_i \\ &\quad - Corrected\ market\ potential_{i-1} \end{aligned} \tag{5.6}$$

$$\begin{aligned} customers\ inclined\ to\ change_i &\\ &= Market\ potential_{i-1}.fraction\ CIC \end{aligned} \tag{5.7}$$

With i = period

Applied to the example, it can be seen that it uses the outcome of the previous module as input to determine the free market (Figure 5-7). Here, we have chosen to use a CIC fraction of 20%. The free market in the example is shown in Figure 5-8. Once the market reaches 100%, the free market is solely determined by the CIC.

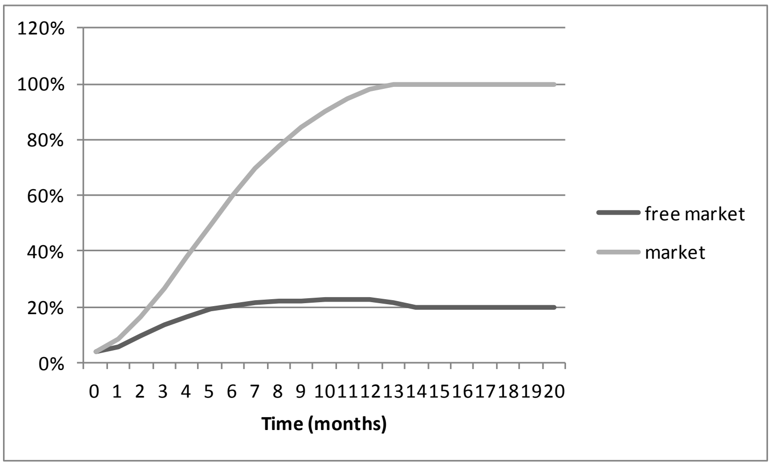

Figure 5-8: Available market with 20% CIC

However, other definitions of the free market are possible. For example, due to contract duration, it is possible that customers are locked in, making it impossible to change supplier during the contract period. This has also been implemented in the market model. After the contract duration, these customers become available in the free market.

5.1.4.c Dividing the free market

The last question remaining is how the free market from the previous module is divided between different offers based on their strategy. The most straightforward division is 'The Winner Takes All'. When using such a market division, the total free market is allocated to the best offer during that time period. The best offer can be defined as the cheapest, highest quality, or even the offer that has been the longest on the market. With the latter, one can model a first-mover advantage.

However, in reality, it is hardly ever the case that one supplier captures the entire free market. It will most likely be the case that the best offer captures most of the market, but all other offers can still attract market share. Still, the demand of each service or good will still be impacted by the price of the other offers. In economics, such an effect is indicated by the cross-price elasticity of demand [5.20]. It is a measure for the responsiveness of the demand of one good to a change in the price for another good. The other good is not necessarily a substitute; it can as well be a complement of the former. Typically, when it is a substitute, the cross-price elasticity of demand is positive. A price decrease of product B will result in a decrease of demand of good A. When both goods are complements, the cross-price elasticity is obviously negative. An increase in the price of good B will result in a decrease of demand in good A. In eq. 5.8, the calculation method for cross-price elasticity of demand can be found. In case of multiple offers on the market, there is a (different) cross-price elasticity between any two offers.

$$E_{A,B} = \frac{dQ_A/Q_A}{dP_B/P_B} \tag{5.8}$$

Competition for the market between different offers is played on different factors. Price and quality of the offer are typical distinguishing characteristics, but competition can play on other facets as well. Marketing, innovation or image can also influence the perceived utility the offer has for the consumer, increasing its attractiveness.

In the example, cross-price elasticity of demand is used to indicate the functionality of this module. Based on the strategies of the different offers, the distribution parameters are calculated (Figure 5-9). However, the modular model allows using different division concepts in a plug-and-play approach. To determine distribution parameters based on cross-price elasticity, the following equations are used (eq. 5.9 – 5.12). Suppose there are *N* offers on the market, each with price P_i, i = 1,…,N. The average price of the alternative offers for offer *j* are then calculated based on eq. 5.9. Assuming a constant cross-price elasticity between two different offers *i* and *j*, the distribution parameter κ_j is defined according to eq. 5.11. For further analysis however, we use the normalised distribution parameters $\overline{\kappa_j}$.

An example of the distribution parameters can be found in Figure 5-10, using a cross-price elasticity of 0.5.

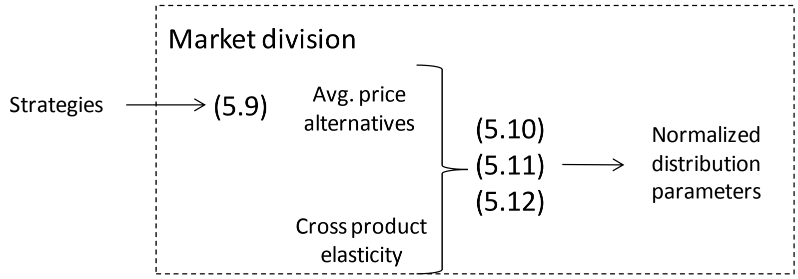

Figure 5-9: Determining the market division

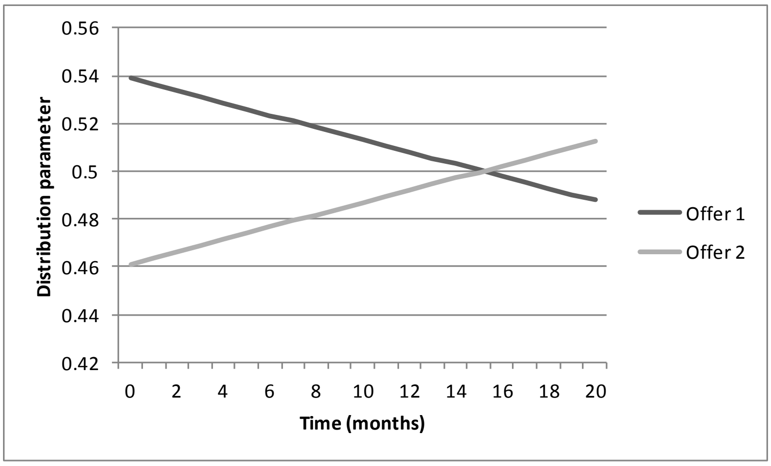

Figure 5-10: Distribution parameters for both offers based on cross-elasticity

$$average\ price\ alternatives_j = \frac{\sum_{\mathrm{i}}^{N} price_{\mathrm{i}} - price_{\mathrm{j}}}{\mathrm{N} - 1} \tag{5.9}$$

$$price\ difference_{\mathrm{j}} = price_{\mathrm{j}} - average\ price\ alternatives_{\mathrm{j}} \tag{5.10}$$

$$\kappa_{\mathrm{j}} = 1 + price\ difference_j . cross\ price\ elasticity \tag{5.11}$$

$$\overline{\kappa}_j = normalize\left[max\left(0, \kappa_j\right)\right] \tag{5.12}$$

5.1.4.d Calculating the market share

The final step consists of bringing everything together to calculate the market share of all offers. To determine the net change in market share of every offer in every year, both gains and losses in market share need to be calculated for each offer *j*. Each offer virtually loses a fraction of his customers calculated from the CIC-fraction (eq. 5.13). The gains are the division of the sum of customers inclined to change of all players with any growth in the market (or vice versa for a shrinking market) (eq. 5.14). This division is based on the distribution parameters introduced ($\overline{\kappa_j}$) above.

All these methods control for negative market share.

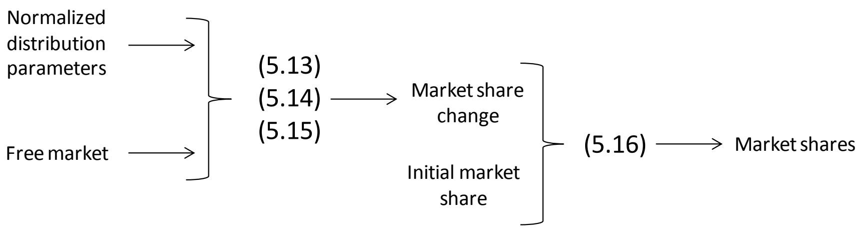

Figure 5-11: Calculating the market shares from strategies and the free market

$$losses_{i,j} = Market\ share_{i-1,j}.CIC\ fraction \tag{5.13}$$

$$gains_{i,j} = Free\ market_i.\kappa_{i,j} \tag{5.14}$$

$$Market\ share\ change_{i,j} = gains_{i,j} - losses_{i,j} \tag{5.15}$$

The total market share for every offer is then given by the formula below (eq. 5.16). It is also scaled to the total market potential.

$$Market\ share_{i,j} = initial\ Market\ share_j \\ + Market\ share\ change_{i,j} \qquad (5.16)$$

Concerning the stylised example, the evolution of the market shares for both offers can be estimated using the above equations. To determine the net change in market share every operator has in every year, both the gains and losses in market share are calculated. Each operator virtually loses a fraction of his customers calculated from the CIC-fraction. The gains are the division of the sum of the customers inclined to change of all players together with any growth of the market (or vice versa for a shrinking market) with the distribution parameters introduced above. As a result, the evolution of the market shares for both offers can now be estimated (Figure 5-12).

Since offer 1 charges the lowest price during the first months, it claims a higher share of the market. Once full penetration is reached, no more large growth is realised for either offer. However, due to the fact that the second offer becomes cheaper than the first, it reclaims some of the market share from offer 1.

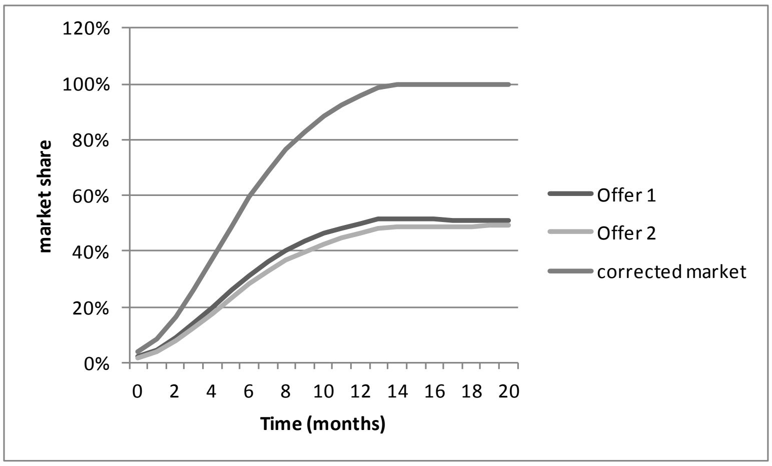

Figure 5-12: Market distribution resulting from market model in stylised example

5.1.5 Application of the market model

In the previous section, the different modules and their interoperation where indicated with a stylised example. In order to indicate the full strength of the model, it will be applied to a more realistic telecom case.

In the liberalised European telecom market, competition between different operators is now present. In addition to this competition, the broadband market also matured. On average, broadband coverage reached 95% in Europe [5.21]. In Belgium, household penetration is currently around 80% [5.22], in the Netherlands it reached 95% in the last quarter of 2012 [5.23].

Although the broadband market can be seen as mature, new technologies continue to increase the quality of the broadband connections. The rollout of FTTH networks will increase speeds to and above 100 Mbps. However, such rollouts require large upfront investment, since the legacy copper networks need to be replaced by fibre. Typical numbers suggest a cost between €500 and €2000 per home passed for initial rollout, depending on the building density [5.24–5.25]. Translating these to the cost per home connected largely depends on the estimated uptake. When combining these costs with the typical average revenue per user (ARPU), this results in a serious pressure on the fibre business case, especially when uptake of the new network remains low. Estimating this uptake is thus of key importance in order to conduct the techno-economic analysis of the fibre business case. Typical uptake estimations leave out the impact of competition by existing offers, and suggest high FTTH uptake levels up to 50% within the next five years [5.26].

However, in regions where FTTH has already been rolled out, these levels are typically not reached. For example, FTTH uptake in the Netherlands currently is at 6.22% [5.23]. Of course, the uptake is lower due to the fact that FTTH is not available in the entire country, but rolled out regions also notice lower uptake than originally estimated.

Here, the effect of introduction of FTTH in the Netherlands will be estimated using the modular market response model. As uptake numbers are available, the results from the model can be benchmarked with the observed uptake. The historical uptake percentages per type of operator and the total penetration can be found in Figure 5-13. It can be observed that the total penetration rose from 75% to just over 95% in 5 years. The majority of the customers connected to the DSL and cable network, while the other licensed operators (OLO) active on the DSL network lost market share. Fibre uptake only grew slowly, with the penetration increasing from 2% to 6.2%.

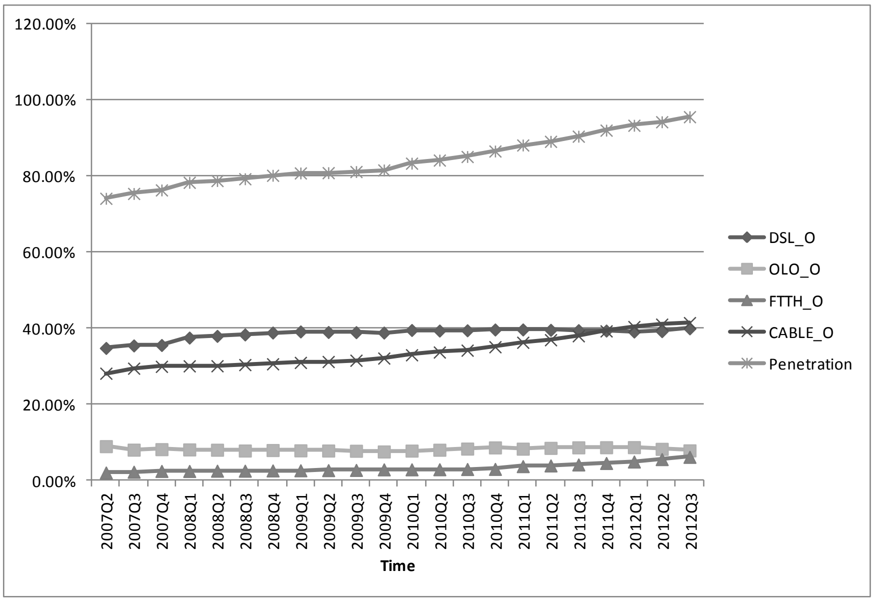

Figure 5-13: Observed market shares per operator in the Netherlands

The parameters required for the market response model are the initial market shares for the different operator, the CIC fraction, cross-price elasticity and the retail prices per operator. The initial market shares can be derived from Figure 5-13 and are depicted in Table 5-3. Notice that the initial market shares are normalised to match a total market of 100%. The retail prices per offer can be found in Table 5-4. However, as current retail prices for the OLO offer and DSL offer are equal, the difference between their respective market shares obviously is driven by other factors, e.g. availability, lock-in effect, etc. The retail prices should thus be corrected to reflect the actual perceived utility. As CIC fraction, 5% was chosen. Typical contract duration is five years, so per quarter 5% of the total customer base is available to redistribute between the offers. As the total market penetration was given per quarter, the observed numbers were used (Figure 5-13). We enforced the modelled total market to match the observed total market. Finally, cross-price elasticity of demand was chosen relatively high, at 2 (Table 5-5). The broadband market has been shown to be very elastic [5.27], with already high cross-price elasticities between cable and ADSL offers. The introduction of a premium FTTH offer is expected to further increase this elasticity.

Table 5-3: Market shares of different offers in the Netherlands [5.23]

Provider	Market share
DSL incumbent	46.97%
Cable operator	38.02%
Other licensed operators (OLO)	12.17%
FTTH	2.83%

Table 5-4: Monthly retail prices for different broadband offers [5.28]

Provider	Market price
DSL incumbent	€35.00
Cable operator	€36.67
Other licensed operators (OLO)	€35.00
FTTH	€55.32

Table 5-5: Market response model parameters for the Dutch fixed broadband market

Parameter	Value
CIC fraction	5%
Price elasticity of demand	0 (observed market growth used)
Cross-price elasticity	2.00

Applying the market model on this information returns the following evolution of the market shares for the different operators (Figure 5-14). It can be seen that the observed and modelled market shares are aligned for all offers. In Q3 of 2012, the largest difference between observed and modelled uptake is 0.42% (for the OLO offer). The introduction of the FTTH offer has no disruptive effect on the total market. Due to the large cross-price elasticity and the retail price difference between this offer and the legacy offers, FTTH only claims a small market share. In the growing market, only the OLO offer has a decreasing market share. As penetration rises sharply during the observed period, the cable and DSL offer notice no market share decline. The OLO offer remains low, as the model takes into account the perceived utility of this offer compared to the other offers, consistent with the current market division.

Differences between the observed and modelled market shares can be explained by the reduced complexity in the model. It was assumed that the cross-price elasticities between the different offers are constant and equal. Additionally, prices are used to model uptake differences as proxy for perceived utility.

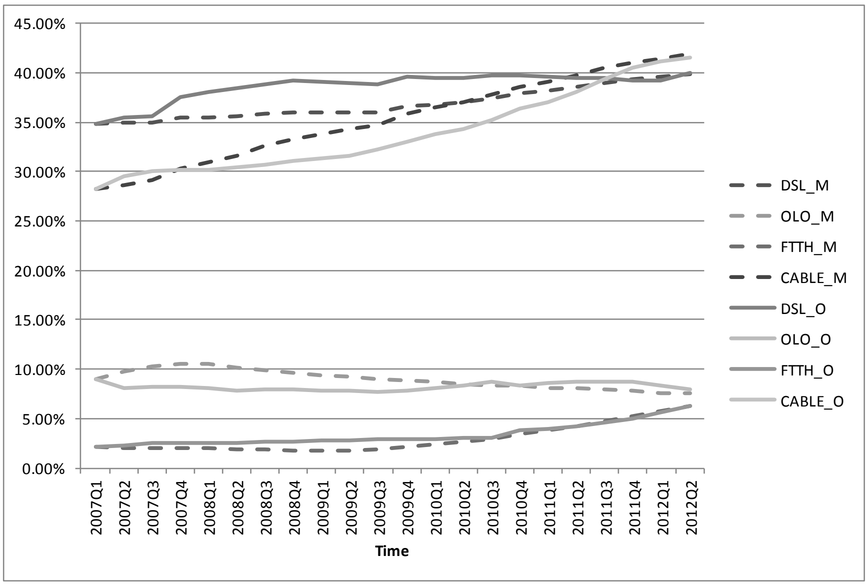

Figure 5-14: Market share evolution of broadband market with introduction of an FTTH offer (M = Modelled, O = Observed)

5.1.6 Conclusion

Due to two simultaneous trends, liberalisation and continuous consolidation, most Western industries are characterised today by a high degree of concentration. When new products or services are introduced in such markets, firms face a large degree of strategic uncertainty.

Typically, the viability of investments is assessed through techno-economic modelling. However, this requires a reliable estimation of consumer uptake, as this is the main driver for the expected revenues and variable costs. The number of customers to serve has a direct impact on the required equipment to install. Diffusion models are used to model this uptake. Although such models can match the observed uptake of new technologies or services ex-post, the ex-ante estimation of the model parameters is harder. Especially since these parameters are difficult to interpret for the decision maker.

As such, market response models have been proposed to offer a more accurate estimation of market share evolutions, based on prices, promotion and

competition. While such models are accurate for the specific cases they were built for, their increased complexity reduces uptake.
Here, a modular market response model is introduced, able of modelling future market shares of competing offers. The main advantage of the modular approach is the possibility to use different modules for different cases, while the complexity of the calculations within each module is hidden for the user. As such, the user only requires simple parameters, such as current market shares, price levels and elasticities. Most of these parameters are typically available for the user, while econometrics allows quickly finding the missing parameters. These parameters are generally accepted economic parameters, and the user can easily link them to his specific case, providing him with valuable input for his network dimensioning and further techno-economic analysis.
While the market response model presented here reduces the complexity for the user, it is still able to accurately predict market share evolution over time, as has been shown by the FTTH case. From the insight gained from the observed and modelled FTTH market shares, questions about the necessity of FTTH can be raised. With only small market shares, the business case for operators will not balance when the large upfront investment costs are taken into account. However, customers will require higher access speeds, driven by the uptake of bandwidth demanding services. As the willingness to pay for network access does not seem to grow with this increased demand, operators will need to look into other options to improve the FTTH business case.

5.2 Cooperation models in telecom

Cooperation models typically aim at achieving cost reductions. In Chapter 2, we already introduced cooperation in standardisation bodies as a possible cooperation strategy. Other cooperation possibilities are also present in the current environment. For example, public and private players can cooperate by forming a new entity, a so-called public private partnership (PPP). Another example was already introduced in Chapter 3, where one entity rolls out the network, while another operates it. Another cooperation model aims at cost sharing between several players through joint operations. This last model will be discussed in more detail in Section 5.3.

5.2.1 Public private partnership models

For large infrastructure works, a public authority cooperates with private players through a PPP, in order to split the investment costs. By cooperating instead of competing, several goals can be achieved. If both players have a customer base, this can be combined, increasing the possible revenues. Referring back to the high initial investment cost of network deployment, this cost can thus be spread out over a larger customer base. In addition, both actors can perform different roles, leveraging their own strengths. However, several guidelines must be kept in mind when a PPP is formed, especially when the rollout of access networks is considered.

In case of access network rollout, The European Commission has forbidden state aid in several regions, depending on the current competitive state. However, as was already described in Chapter 3, the competitive environment might not reflect the desired state of the public authority. For example, in Belgium, no state aid is allowed in broadband access network rollout, as (almost) the entire country is covered by two competing infrastructures. However, none of these are FTTH networks. When a public authority wants to invest in the latter type of network, it must do so under the market investor principle, meaning that they invest under the same terms as a private company would do. An example of such a PPP set up for the deployment of an FTTH network is the case of Amsterdam, where the municipality funded 30% of the initial investment, on the same terms as a private player.

Examples of such PPP models were already introduced in Chapter 3. When the value network analysis was conducted for the FTTH access market, it was already indicated that the actor taking up the role of fibre infrastructure deployment could be a utility or municipality. The daily operation of this network could then be outsourced to a tender winner. Instead of outsourcing, a PPP could also result from this cooperation model. During this research, the PPP model was also applied to the case of a wireless access network rollout in the city of Ghent [5.29]. The municipality and a private player form a PPP to deploy a municipal WiFi network. Both actors invest on the same terms, with the municipality taking a share of 30%. A quantitative analysis of such a PPP can be found in the next chapter.

5.2.2 Split responsibilities

Up to now, the discussed models considered cooperation up to some level in the value network. In joint infrastructure rollout, players cooperated in the deployment phase of the access network, more specifically in the trenching part. In the PPP model, both players invest on equal terms in the partnership, in order to share costs and increase the customer base. Competing would result in a fragmented customer base and duplication of infrastructure, decreasing the viability of the case for each actor. However, cooperation in access network rollout can also be very limited. In the extreme case, one party can independently rollout the network, before selling it to another actor. In this case, the coordination costs present under a tender case are removed, and only the cost linked to the negotiation of the sale remain.

5.3 Cooperation in access network deployment

Competition for end customers was shown above to put pressure on the business case viability for operators. A large part of the investment cost is independent of the number of customers, as each house must be passed in order to be able to offer the service. On the other hand, revenues are driven by the customers connecting. As a result, operators need to look for new approaches to increase viability. We already indicated that the initial investment for the rollout of networks is high, up to €2.000 per home passed in rural areas [5.24], [5.25], [5.30]. The majority of this cost can be attributed to the initial outside plant deployment, driven by trenching and fibre deployment. Research has indicated that the initial installation cost for the outside plant of underground networks represent between 55% and 70% of the initial investment [5.31]. This high upfront investment is one of the main reasons private players have not started the rollout of FTTH networks on a large scale in Europe. The largest share of the investment is independent of the customer uptake. As such, low uptake due to competitive interaction has a negative impact on the viability. The lag in FTTH installation is clearly reflected in the current penetration rates of FTTH in Europe. Compared with the penetration rate of fibre to the building/home in Korea (72.10%), Japan (49.65%) and the United States of America (12.34%), most Western European countries are clearly behind with 4.81%. Only Switzerland and the Netherlands have a fibre penetration over 10%. [5.23]. Focussing on cost reduction in this initial deployment can thus help to improve the business case.

In recent years, a shift in perception can be noticed towards telecom networks, where they are seen as just another utility network, like gas or electricity networks. Several similarities can be identified between these infrastructures. The passive infrastructure of all these networks typically can be found in the same location in the public domain, and the operations in rollout and maintenance of this infrastructure show several similarities over all networks. The initial rights of way, trenching and rollout of the cable or duct is alike for all infrastructures, although differences in the technical limitations exist. Important economies of scope can be gained by combining these operations [5.32], [5.33]. Regulatory practices of one infrastructure can also set the example for other infrastructures. The unbundling of the electricity market, with a structural separation between the infrastructure operations and the electricity production and supply can be successfully transferred to telecom networks [5.34], [5.35]. In the electricity sector, distribution grid operators roll out and maintain the network and sell access to this grid to suppliers and producers on equal terms. In telecom, Swedish municipalities have rolled out and own the passive fibre infrastructure [5.36]. Other telecom operators are given access to this network on fair terms to offer services to end users, which is an open access model for telecom [5.37–5.39].

These two factors, the similarities in the passive network rollout and operations and the comparable regulatory issues, have resulted in recent policy and recommendations towards the joint rollout of infrastructures [5.40], [5.41]. By stimulating the cooperation between different infrastructure owners, policy makers aim at reducing the nuisance for inhabitants and small and medium enterprises (SMEs) by reducing the total work time. The economic impact of road works cannot be neglected. Time losses and extra fuel consumption due to congestion is only one aspect. In addition, especially for infrastructure works in cities, SMEs can be (partially) cut off and are harder to reach for their suppliers and customers, resulting in lost turnover.

Here, we show how cooperation impacts the technical design of the outside infrastructure rollout. We introduce a cost sharing model based on underground location of the infrastructure to indicate that a joint rollout of different types of infrastructures not only results in reduced nuisance and economic losses for the society, but also offers cost saving possibilities for the utility owners compared to an independent rollout. With this model, it is shown that joint rollout drastically improves the business case for an FTTH infrastructure owner. Reducing the initial investment costs can persuade actors to start with the rollout of the infrastructure, raising the penetration of FTTH networks in Europe and helps at reaching the goals of the Digital Agenda.

Section 5.3.1 gives an overview of the typical network characteristics, together with the (ideal) trench model. Next, the cost and allocation model is discussed in sections 5.3.2, 5.3.3 and 5.3.4. We continue with two example case studies, highlighting the impact of a joint network infrastructure rollout on the total initial rollout cost in different areas. Section 5.3.7 concludes, together with some topics for future work.

5.3.1 Underground network infrastructures model

To decrease the existing gap between the Digital Agenda goals and the existing cost issues for infrastructure providers to rollout the network offering the higher access speeds, a joint utility network rollout model has been developed. This rollout model starts from the underlying technical requirements of the underground infrastructure. In Greenfield situations, the opportunities for cooperation during rollout are straightforward. In Brownfield situations, existing utility networks typically require regular pre-emptive maintenance, which can be an opportunity for telecom operators to deploy a new network. Also, the potential large upgrades needed to the electricity networks to move towards smart metering offer opportunities for other actors to coordinate road works[6]. A last example where cooperation in Brownfield installations can occur is the upgrade of existing sewage systems. While these are currently single pipe systems, they need to be upgraded towards split systems for sewage and rain. Several advantages can be expected from such a joint rollout. Reducing the rollout cost for FTTH networks could improve their respective business cases, speeding up the introduction of these high bandwidth networks in Europe. Additionally, other utility providers could profit from such cost synergies. An important advantage for policy makers could be the reduced nuisance for inhabitants and SMEs when all infrastructure works are carried out together, thereby reducing the total work time. However, such a joint rollout can also be expected to result in extra overhead costs. Deploying the infrastructures together will require extra coordination costs. Additionally, existing safety regulation concerning underground infrastructures could result in only marginal cost savings, making the extra overhead costs outweigh the possible cost gains. It is therefore important to identify the level of cooperation between the different utility operators.

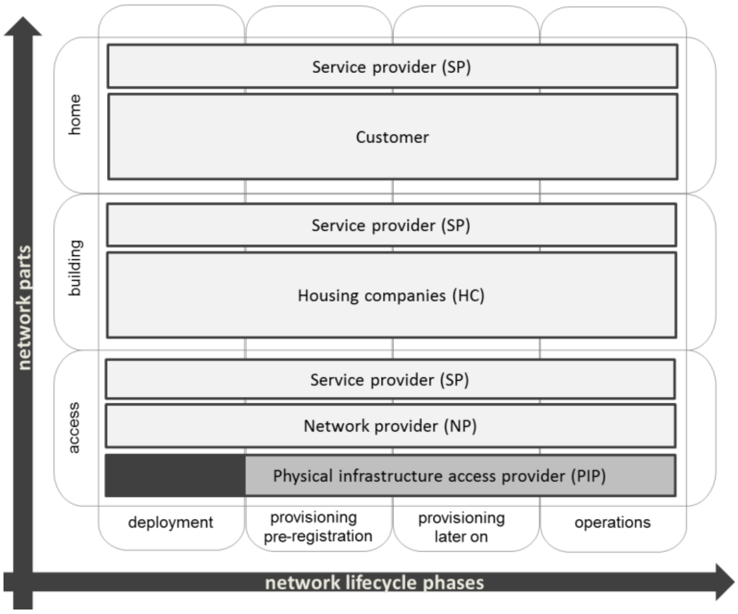

Figure 5-15: Overview of potential utility network synergies

[6] This opportunity only exists in case PLC is chosen as technology to transfer smart meter data. In case of wireless technology, no road works will be required.

Figure 5-15 shows an overview of the different network parts (access, in the building, within the home or apartment) when considering a utility. In the model presented here, an open access network is shown [5.35]. The network is opened at different levels to different actors, as was also described in Chapter 3. The focus in this model is on the physical infrastructure provider (PIP) who deploys and operates the access infrastructure and opens it for all network and service providers on top. More in detail, the PIP actor contains the Right of Way/trenching and duct/fibre role. Since previous research indicated that cooperation offers synergy opportunities in these layers, focus is on the PIP [5.32], [5.33].

In every network part, four network lifecycle phases can be identified on the horizontal axis: deployment, initial and later-on connection provisioning to the customer and network operations [5.35]. As was already indicated, the largest part of the cost of an FTTH network is in the deployment phase [5.31]. For an all buried installation, deployment costs typically result in over 55% of the total costs. Depending on the chosen technology, this can go up to over 70%. Within this deployment cost, 75% can be attributed to the outside plant installation. Even small cost savings in this domain will thus already have a considerable impact on the total investment cost for an FTTH network. For Belgium, the total capital expenditures (CapEx) for a full FTTH rollout have been estimated around €4 billion [5.42]. Additionally, in the deployment phase, the operations conducted by the different utility providers show resemblances. Apart from the technical constraint of the network, e.g. requiring a ring or tree structure, most of the work consists of trenching and deployment of cables and ducts. Therefore, this model will look at the possible synergies in this deployment phase, which includes right of way, trenching, ducts, cables and flexibility points, and indicate what the impact of cooperation is on the total cost for each utility operator.

5.3.1.a Infrastructure characteristics

To indicate the possible synergies in the infrastructure rollout phase, the typical characteristics of each considered network must be taken into account. Typically in a fully buried installation, the following networks can be found underground: telecom networks (cable, copper and fibre), energy networks (electricity, gas and heat), drinking water and the sewage system. An overview of a typical cross-section of a road can be found in Figure 5-16.

Since the liberalisation of the energy market through the different energy packages, the energy network infrastructure falls under the responsibility of the transport and distribution system operators [5.34]. A typical electricity distribution network can be found at a minimal depth of 60 cm. Electricity cables are quite flexible and not many safety regulations apply. For example, the minimal distance between an electricity cable and another network should only be 6 cm.

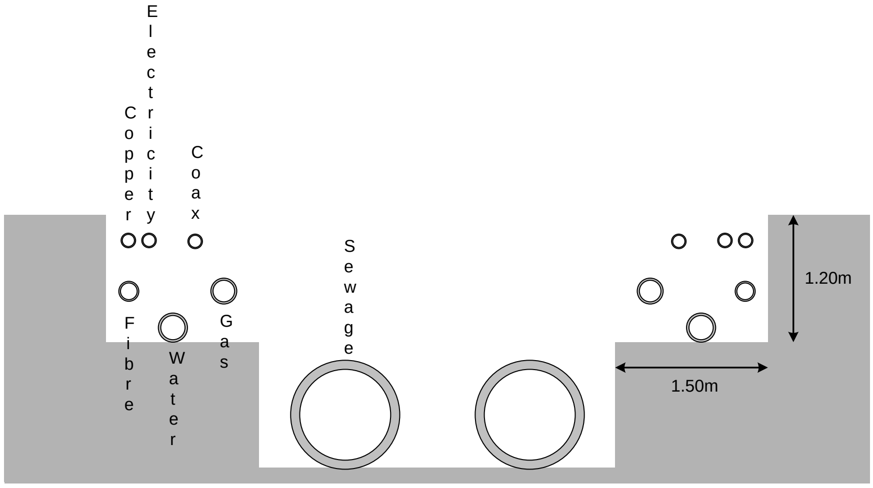

Figure 5-16: Cross section of a typical road

Gas networks require a more rigid duct system, mainly for safety reasons. In addition, a safety distance needs to be taken into account when installing other networks in the proximity of gas pipes. They are typically also installed deeper underground than electricity networks and no other infrastructure can be placed on top or below this network.

Telecom networks, typically the hybrid fibre coax (HFC), copper and fibre network, in a fully buried network, are laying at a minimal depth of 75 cm. At regular distances, flexibility points like manholes and street cabinets are installed. Apart from this, only few requirements are in place for these types of networks. The safety distance between telecom networks is also considerably lower compared with the safety distance for gas networks.

The last two networks considered are the drinking water and sewage system. Like the gas infrastructure, drinking water makes use of a rigid infrastructure and has similar safety requirements. Concerning the sewer system, a separate system is required for rain and sewers infrastructure for new rollouts. Since these systems are typically located in the middle of the road, while all other networks are installed on both sides under the footpath, the sewage system is left out in the analysis. However, when large road works are carried out or contracted by the government, be it federal, regional or local, utility owners could benefit from the road works to roll out their infrastructure while the road is open since no or only limited additional digging would be required [5.40].

5.3.1.b Standard trench

It was already indicated that most underground infrastructures, apart from the sewage system, are located in the same area on both sides of the street. The combination of all limitations, namely the existing safety regulations on required coverage, distance between infrastructures and minimal distance to the walls of the trench (Table 5-6), has resulted in the description of a standard trench (Figure 5-17) [5.43]. In addition to the requirements inside the trench, extra safety requirements are imposed. A minimal distance of 1.10m to buildings should be saved for Greenfield situations. For the same reasons, the trench should not exceed the dimensions of 1.10m width and 1.20m depth.
Based on these requirements, a cost model tool was developed to minimise the cost of deploying different infrastructures. After optimising the dimensions of and locations in the trench, a cost allocation model allows to calculate the impact of a joint rollout on the total costs per utility operator.

Table 5-6: Proposed standard trench parameters [5.43]

Infrastructure type	Depth (m)	Distance to trench wall (m)	Distance to other cables (m)
Electricity	0.6	0.05	0.06
Gas – low pressure	0.8	0.1	0.2
Gas – medium pressure	1	0.1	0.2
Telecom	0.75	0.05	0
Drinking water	1.10	0.1	0.2

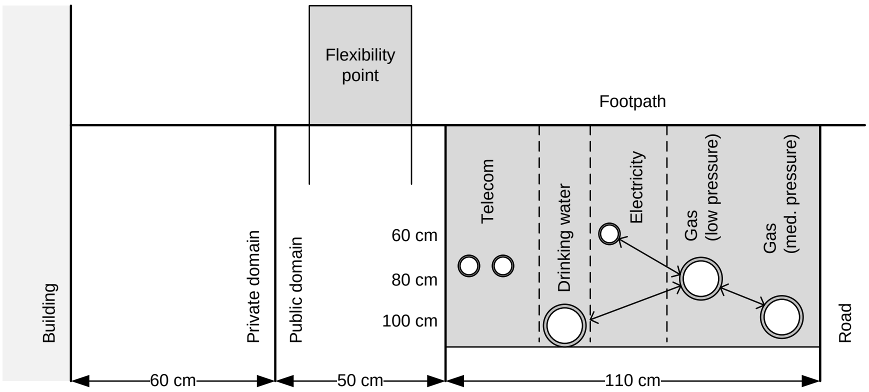

Figure 5-17: Standard trench description

5.3.2 Trench optimisation model

The standard trench proposed by one of the Belgian distribution grid operators Eandis [5.43] offers a first guideline towards a theoretical optimised trench, but in practice, rolling out a new network will probably not be executed in a Greenfield situation. The location of existing infrastructures and space limitations should all be taken into account. Therefore, the spreadsheet model developed in [5.44] was extended towards an optimisation model in java code. When developing the model, two challenges were encountered.

The first challenge is identifying the parameter or function to optimise. The distribution net operator [5.43] indicated both width and depth of the trench as important drivers for the total cost of the infrastructure deployment. This is reflected in the cost for opening and repairing the pavement (surface dependent) and the cost for digging (depth dependent). In this model, the total volume of the trench is optimised to minimise costs. However, the model can easily switch to other functions to optimise. The total width of the trench could be a more important factor, for example if the repair cost of the surface is very high. Optimising width or depth separately has therefore also been implemented in the model. Other functions can easily be added to the model.

A second challenge towards the implementation of an optimisation algorithm is the presence of distance constraints between different infrastructures. Simple Linear Programming (LP) software and algorithms can therefore not be used [5.45]. To counter this issue, we developed a tool analysing all possible permutations of infrastructures to solve the optimisation problem. Since in most cases, only up to 6 infrastructures are present in one trench, computation time is not an issue. For each permutation, the first infrastructure is placed based on its constraints in the upper left corner of the available area (Figure 5-18). Each additional infrastructure is then placed on the lowest cost location of the remaining area. In this model, this is the position where the total volume of the resulting trench is minimal. As can be seen in Figure 5-18, electricity is placed in the upper left corner of the available area. When a fibre network is added to the trench, the constraints for distance between the electricity and fibre infrastructure, and the depth constraints for the fibre infrastructure diminishes the available installation area (gray area in Figure 5-18). The model returns the optimal location of each infrastructure after checking every permutation. After identifying the optimal trench, the costs can be divided between the different utility owners.

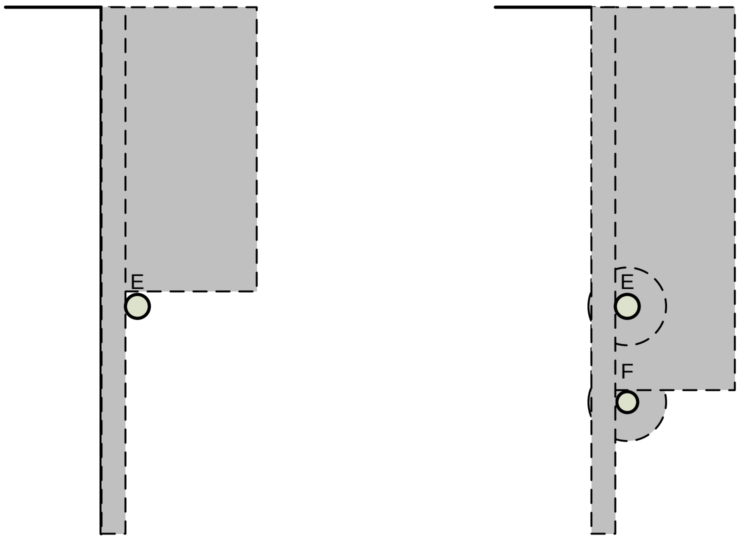

Figure 5-18: Identifying the lowest cost location

5.3.3 Cost allocation model

Before going into detail on the different cost categories taken into account in the cost model, a short introduction on cost allocation theory is given.

5.3.3.a Cost categories and allocation methods

Three distinct cost categories can be identified when cost allocation is concerned, namely direct costs, shared costs and common costs [5.46]. Direct costs are specific for one actor, and are typically borne by one actor and not divided between different actors. In infrastructure rollout projects, the cost of ducts, cables and flexibility points are typical examples of direct costs. Shared and common costs can be divided between the different actors involved, and are thus of interest for the cost sharing model. The difference between both cost categories is in the cost allocation key applicable. Shared costs can be divided based on a cost driver (e.g. time, equipment used, volume, etc.). For infrastructure rollout, the digging costs are shared costs, and can be divided based on the volume each infrastructure requires. In this model, volume is used as cost allocation key for the shared costs, to maintain consistent with the objective function of the trench optimisation model. Common costs are characterised by the absence of a clear allocation key, for example, overhead costs like administration and licensing costs. These costs are divided between all players upon agreed rules, mostly just an equal division between all actors. The different cost allocation methods are described next.

For a fair comparison of an independent rollout and a joint rollout of infrastructures, correct cost allocation methods should be used. The stand alone cost (SAC) is the cost allocation used for the independent rollout. With the SAC method, all direct, shared and common costs are directly allocated to one actor, as if there would be no cooperation between the infrastructure owners (Figure 5-19).

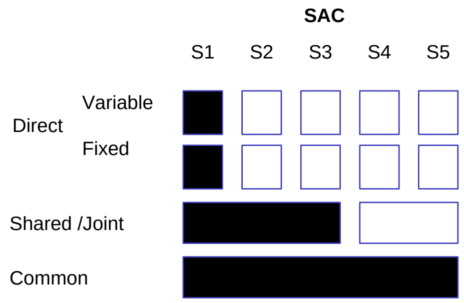

Figure 5-19: Stand alone cost principle

For the joint rollout, the fully allocated cost (FAC) method is used to calculate the rollout cost for each actor under cooperation. All costs are divided between all involved parties based on the allocation schemes selected for each cost category. Direct costs are attributed to each actor, while the shared and common costs are divided based on cost allocation keys (Figure 5-20).

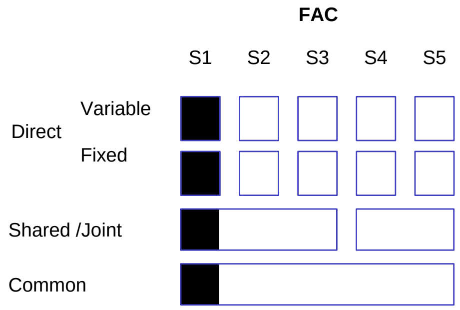

Figure 5-20: Fully allocated cost principle

A third allocation option is the long run incremental cost (LRIC) method (Figure 5-21). Here, every additional actor only bears the additional total cost when he cooperates with the other actors. This might be the case when road works are conducted that require opening the complete street. Any utility network provider who wants to install his network at this moment is accounted for his direct costs, while the actor who commissioned the road works bears all shared and common costs.

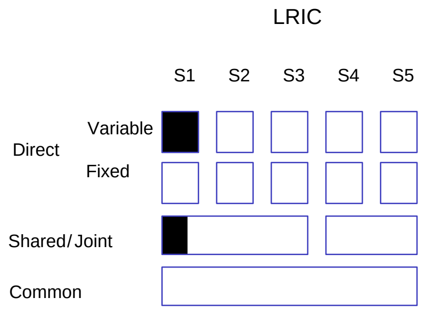

Figure 5-21: Long run incremental cost principle

5.3.4 Cost model – overview of the different impacting factors

In the cost sharing model, focus is on the cost reductions that can be gained from cooperation in the initial deployment phase. Costs linked with the later stages of the network operations are thus not taken into account. It can however be important to check the impact of joined rollout on the operational processes of repair and maintenance in the future, or synergies in the initial household connection phase.

Two important cost categories have been identified within the trenching cost, namely digging and initial installation of the cables or ducts. The digging cost is again driven by two parameters. First, from the trench optimisation model, the total dimensions of the trench can be computed. While a stand-alone rollout might result in a smaller volume of the trench compared with a joint rollout, the incremental cost of the joint trench is spread out over more actors. Secondly, the pavement type also has an influence on the digging costs. A distinction is made between three different types: bank, loose pavement and asphalt. When no pavement is present, this reduces the total cost substantially, since the contractor can immediately start digging and no repair of the pavement after installation is necessary. In the two other cases, loose pavement and asphalt, repair is required and raises the total cost of the rollout.

The dimensions and the pavement type are used to calculate the different components of the digging costs. The largest part of the digging cost is the personnel costs, while material and equipment comprise a smaller portion of the total cost. It is clear that in a joint rollout scenario, these costs can easily be shared between the different utility providers.

Next to the digging cost, installation cost is the second important aspect of the trenching cost. These costs include again personnel costs, now for the deployment of ducts and cables. Additionally, costs for cables, ducts or flexibility points are also taken into account. These costs are actor specific, but cooperation could influence the total installation time, especially for smaller rollouts. Installing several ducts and cables simultaneously in the same trench is impossible. However, for larger installations, a sequenced coordination of work can undo the time losses. An overview of the different costs can be found in Table 5-7.

Table 5-7: Installation and direct costs for trenching [5.43]

Cost type	Cost (€)	Classification
Personnel cost (€/hour)	36.75	Direct / shared
Truck (€/hour)	15.75	Direct / shared
Digging machine (€/hour)	17.85	Shared
Electricity cable (€/m)	3.22	Direct
Fibre cable (€/m)	3.00	Direct
Gas duct (€/m)	3.50	Direct

As introduced in section 5.3.1, this model calculates the possible cost synergies in the initial deployment phase. Making the physical connection to the customer premises is part of the provisioning stage, and thus not included. In case the utility and telecom providers do not cooperate in this stage, this classifies as direct costs, making the extension straightforward. However, in the future cooperation could also apply here.

5.3.4.a Cost allocation key

In the previous paragraphs, it was already indicated that for shared costs, a cost allocation key needs to be decided on to come to a fair distribution of the costs to each individual actor. Since a joint rollout will impact the total volume of the utility trench, and in turn this influences the total digging costs, the cost allocation key is based on these costs. Eq. 5.17 is used to define the cost allocation key for each actor. For the installation costs, a similar allocation key is used.

$$Cost\ allocation\ key_j = \frac{Digging\ cost_i}{\sum_{i=1}^{n} Digging\ cost_i} \tag{5.17}$$

With *Digging cost i* as the digging cost when the utility actor rolls out the network independently.

5.3.5 How cooperation influences the total rollout cost – case examples

The combination of the trench dimensioning optimisation tool and the cost allocation model allows calculating the impact of cooperation on the total rollout cost for each utility network in a fully buried case. Since the main goal is to indicate how cooperation can diminish the costs for fibre networks, thereby speeding up the rollout of these networks in Europe, special attention is given to the impact on fibre rollout cost. However, the impact on other utility networks is also taken into account, as cooperation should obviously benefit all actors cooperating.
Three different scenarios will be described here. First, an independent rollout by all actors will be introduced. It will be indicated that the cost results for the initial trenching are realistic compared to the results from other studies. This scenario will serve as a benchmark for the other scenarios, where a joint rollout with other utility providers will be analysed. In order not to overcomplicate the analysis, these scenarios will look at the rollout of different infrastructure networks in one street, with a trench length of 100 meter. It is assumed that along this road, 20 premises are present, comparable with a rollout in an urban area. Such a geographical model closely resembles a ribbon development case, which is still a typical case in e.g. Belgium. Terminating flexibility points have been foreseen in all scenarios. Current practice is to catalogue these manholes as direct cost, as they are deployed separately by each actor.

5.3.5.a A stand alone rollout by different operators

In case each operator rolls out his network independently, the stand-alone cost allocation is used. every actor has to bear the costs of opening the pavement, digging the trench, installing of the cables or ducts and repairing pavement. Such a situation is presented in Figure 5-22 for electricity, fibre, gas and drinking water networks. In total, an independent rollout requires in the example case a total digging volume of just under 105m^3. The fibre operator would only need to dig 24m^3. Including the costs for flexibility points, the trenching cost per home passed for the fibre network comes down to €470. When comparing this number with costs typically found in research on fibre network rollout in urban areas (€900 - €1200 per home passed), the results of this cost model are found in this region. Indeed, trenching costs consist of around 80% of the deployment costs, which are 60% of the total costs for an all buried installation. Table 5-8 summarises the total costs per home passed (HP) for every utility provider. The impact of trench volume is clearly reflected in the digging costs, with the cost for drinking water 30% higher than for electricity. The extra cost for equipment only has a small impact on the installation cost. This equipment cost also comprises the cost for terminating man- or handholes for each utility at every home passed.

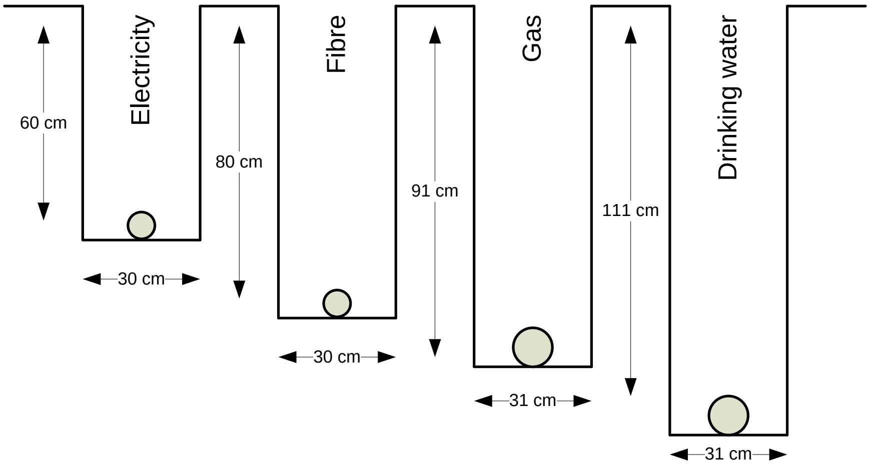

Figure 5-22: Cross section of a stand alone rollout

Table 5-8: Cost allocation results in the stand alone rollout scenario

Cost aspect	Electricity	Fibre	Gas	Drinking water
Digging cost	€82	€91	€98	€107
Installation cost	€113	€114	€117	€118
Equipment cost	€266	€265	€268	€268
Total cost	**€461**	**€470**	**€482**	**€493**

5.3.5.b Brownfield scenario: Joint electricity – fibre rollout

In this first joint rollout scenario, the cooperation between a distribution system operator and a fibre network operator is analysed. This scenario comes close to a Brownfield scenario, where the fibre network is deployed in places where maintenance works are carried out on the electricity network. Since less safety regulations apply for these networks, these types of cables offer the most opportunities for cost reduction in rollout phase. Regulation even allows placing an electricity cable on top of a fibre cable, taking into account a safety distance of minimum 6cm. As a result of this regulation, this type of cooperation in the rollout phase offers large amounts of cost saving opportunities for both actors. Indeed, due to the cooperation in the trenching phase, the shared and common costs can be distributed between the different actors. A fully allocated cost methodology is applied here. The joint rollout only requires one trench, and thus only one time the opening and repair of the pavement, while a stand-alone rollout simply duplicates these operations. Additionally, the total volume of the trench under cooperation equals the volume of the fibre trench under stand-alone rollout, resulting in a substantial reduction of digging time. The results from the trench optimisation model are shown in Figure 5-23.

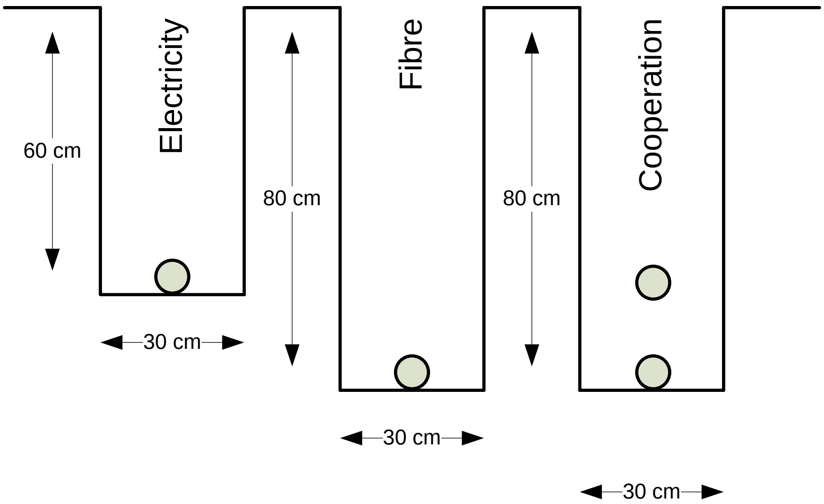

Figure 5-23: Electricity - fibre cooperation cross section

Applying the cost allocation keys derived from eq. 5.17, the following impact on the total cost per HP can be observed (Table 5-9). First, there is a major reduction in the total digging costs of 50% for the fibre network. This reduction, as already indicated, is driven by the large reduction in total digging volume compared with the independent rollout. Secondly, there is also a reduction in installation cost for every utility provider, caused by the reduction in manpower for the opening and repair of the pavement. In total, both infrastructure companies can gain significantly from cooperation, with cost reductions in initial deployment up to 15%. The relative drop in total costs for each actor is lower due to the impact of the direct costs (manholes), where no cost sharing is possible. However, when analysing these numbers closer, the cost reduction resulting from the cooperation is sufficiently large to benefit the business case for each utility provider. Especially for the fibre network operator, a cost reduction of 15% on the initial deployment costs represents a decrease of 7% in the total cost. For a deployment in an area like the city of Ghent, with 106,000 households, the absolute decrease in the total cost would rise to €4.3 million, taking a cost per HP of €500 into account.

Table 5-9: Cost impact of cooperation in electricity and fibre network rollout

Cost aspect	Electricity	Fibre	Cooperation
Digging cost	€43	€48	€91
Installation cost	€86	€87	€173
Equipment cost	€266	€265	€531
Total cost	**€395 (-14%)**	**€400 (-15%)**	**€795 (-15%)**

5.3.5.c Greenfield scenario: Joint infrastructure rollout

While the previous example case introduced a Brownfield scenario where fibre cables were deployed together with an electricity cable during maintenance or repair of the latter, here the Greenfield scenario is studied (Figure 5-24). In case of allotment of new areas, the utility infrastructure needs to be deployed towards all lots. In the trench optimisation model, energy (gas and electricity), drinking water and fibre networks are included. Compared to the independent rollout, the total trench volume is reduced from $105m^3$ to $77.7\ m^3$. From the cost model results, the same trends as in the Brownfield scenario can be observed (Table 5-10). However, the total cost savings are lower, due to the safety restrictions on drinking water and gas networks. The total impact on pavement to be opened and restored is lower since the width of the trench is not impacted as much. However, the synergy gains are still considerable for all network operators, even in the Greenfield scenario.

Table 5-10: Cost results for greenfield rollout

Cost aspect	Electricity	Fibre	Gas	Drinking water	Cooperation
Digging cost	€38	€42	€45	€49	€173
Installation cost	€90	€91	€93	€95	€369
Equipment cost	€266	€265	€268	€268	€1066
Total cost	**€393 (-15%)**	**€398 (-16%)**	**€406 (-15%)**	**€411 (-17%)**	**€1608 (-16%)**

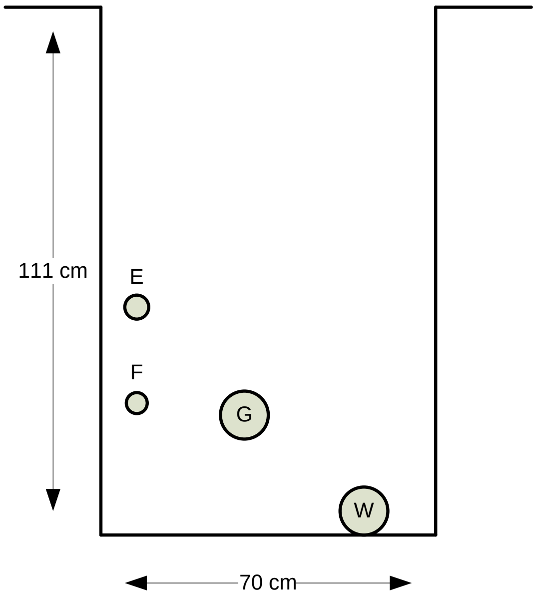

Figure 5-24: Trench cross-section under greenfield rollout with all infrastructures

5.3.5.d Impact of pavement type on the cost gains.

In the previous two paragraphs, the cost reduction was calculated for a deployment under loose pavement. However, while this assumption holds for Brownfield situations, in case of a Greenfield rollout, the installation will most likely be carried out under the bank, since no pavement will be installed yet in the new allotment. In this section, the impact of the pavement type on the cost reduction is indicated. The cost for the fibre rollout is presented in Figure 5-25 under the different pavement types. Since most of the synergy gains come from the reduction of the number of times the pavement has to be opened, the cost for opening and repairing the pavement has a clear impact on the cost gains. Because a deployment under the bank pavement type is the cheapest and easiest, only minor gains (5 to 7%) are achieved, but cooperation in a rollout under asphalt can result in gains up to 21% (between Brownfield and SAC). While cooperation in Greenfield scenarios might be easier to plan and coordinate, this analysis shows that the significant higher cost savings in Brownfield cooperation might incentivise actors to engage in more rollout cooperation in these cases.

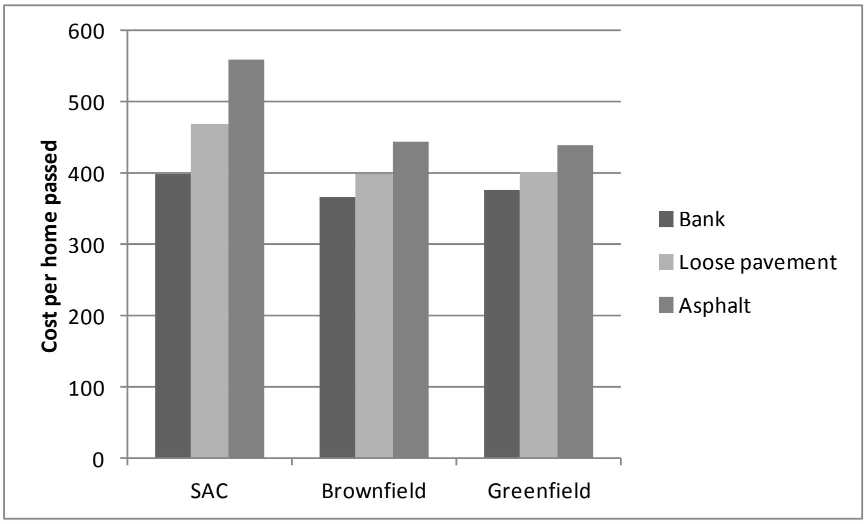

Figure 5-25: Impact of pavement type on cost per HP for fibre rollout

5.3.5.e Impact of manhole deployment on cost gains

In the previous sections, manhole deployment was assessed as a direct cost, to be borne by each actor separately. Two types of man- or handholes exist, intermediate and terminating handholes. While an intermediate flexibility point typically covers equipment covering a larger area, e.g. passive splitters for a fibre network, terminating manholes offer the flexibility point to connect each building to the network.

Current practice is a deployment of manholes in series by the different operators, and is also the approach followed here. As such, the manholes are catalogued as direct costs. The reason for this practice is that the collocation of manholes is expected to result in additional difficulties, and as such an increase in the overhead cost of cooperation. First, the span of intermediate manholes differs between infrastructures, requiring additional planning and cooperation between utility providers to decide on the placement of manholes. For example, passive optical fibre networks require a passive splitter per 4 homes. In the case of copper or electricity networks, the intermediate flexibility point can typically be over 100m away from the house. Secondly, when flexibility points are combined in one structured manhole, this means that technicians of any infrastructure have access to all other infrastructures. Although the same goes for access to ducts, flexibility points are typically more fault sensitive. In such a case, technicians would require additional training in order not to evoke faults to the other infrastructures present in the manhole while performing operations.

However, the algorithm developed in this dissertation can also be applied to evaluate the cost savings in deployment of the manholes, if the correct safety distances between the infrastructures are introduced in the model.

5.3.6 Policy and business implications

The different rollout examples in the previous section have indicated that cooperation in the rollout phase of utility network infrastructures can offer significant cost savings for the actors involved in the deployment phase. However, such a cooperation is not typically observed today, and this raises questions on the impact of this cooperation on the coordination and overhead costs. Indeed, while the cost savings are expected to occur during the deployment phase, the impact of joint infrastructure rollout on the planning phase cannot be neglected.

In fact, a joint infrastructure rollout can be expected to significantly raise the transaction costs [5.47] of the deployment. Transaction costs are defined as costs that are incurred when an exchange happens. They can be subdivided in three categories. The first category, the search and information costs will definitely be impacted, as all actors involved need to be aware of the requirements of the other networks, available infrastructures (e.g. empty ducts), etc. Additionally, since a policy framework for joint rollout is currently missing, the bargaining costs will raise as well. Negotiations on the used cost sharing keys are required, but also permit granting can be an issue. The last category, the enforcement costs are impacted as well by joint deployment. In a standalone rollout, there is only a need to monitor the contractor. In joint rollout, the other parties will need to be monitored as well, again increasing the transaction costs. While the previous examples indicate a raise in the transaction costs of the planning phase, even in the deployment phase, cooperation can increase costs. Joint deployment could require higher skilled workforce, raising the personnel cost.

It is clear that these transaction costs reduce the cost reduction gains from joint infrastructure rollout, and it is here that policy can have a large impact. Already, some countries push towards joint rollout by issuing regulation. Recently, the European Commission organised a public consultation on possible measures to reduce the cost of high speed communication infrastructure. Three main possible policy measures resulted from this consultation [5.41]. Implementing these policy recommendations reduce the transaction costs. This way, the cost gains from joint deployment can be achieved in reality. First, there should be made a better use of existing infrastructure, even across utilities. Here, the search transaction costs can be reduced by using integrated Geographic Information Systems (GIS). It is immediately clear to an actor wanting to do infrastructure works which other infrastructures are present in the area, available infrastructure is visible and the system could automatically warn other interested actors. Examples in Europe are the KLIP project in Flanders, where a full mapping of

the infrastructure is being implemented. In Portugal, the CIS portal indicates spare capacity in the network when an access seeker inspects the network.
Secondly, the transparency and coordination of civil engineering works should be enhanced. Offering possibilities to lay new ducts or infrastructures during public works is recommended. Our model showed that significant cost savings can be gained when infrastructures are rolled out together.
Thirdly, transparent handling of network rollout requests can promote joint rollout. By creating a coordinated permit granting procedure through a one-stop-shop, the transaction costs in the planning phase can be reduced.

5.3.7 Importance of cost sharing through cooperation

One of the reasons the rollout of FTTH networks is lagging in Europe, is the large initial investment costs due to the fully buried installation requirement. However, in order to reach the goals set out in the Digital Agenda for Europe, next generation fixed access networks are the most future proof technology. Several propositions to stimulate the rollout of these networks have already been made. In Sweden, municipal fibre networks have been rolled out by the local governments and opened for competition on the service layer. This way, the investment cost for service providers is sharply decreased, since the network rollout cost is borne by the local government. However, the initial investment outlay is replaced by a recurring cost, the wholesale price for the access to the infrastructure. Other measures to decrease the initial rollout cost is allowing aerial deployment of fibre cables, or promoting cooperation between utility networks.
In this section, we focussed on the latter option, translating the benefits of cooperation through a cost sharing model. To research the impact of cooperation in the deployment phase on the rollout cost, an integrated model was built based on the technical requirements of the underground infrastructure. First, it builds an optimal trench based on the required safety distances between infrastructures in an automated way. For any location in the network topology, this optimal trench is modelled. Secondly, based on this optimal trench, the model allocates the different costs. The model has been applied on two cases, where the cooperative and independent rollout were compared. In the deployment phase, cost savings between 5 and 21% have been found, depending on the pavement type and the number of utility infrastructure providers cooperating.
These results indicate that new policy towards enforcing utility firms to cooperate closer during the rollout phase could not only benefit the inhabitants through a reduced nuisance, both only has a significant positive impact on the rollout cost for the utility firms. Additionally, since a joint rollout between operators requires a coordinated approach, extra insight in the operational and overhead processes should also be gained. This way, the impact of higher

coordination costs of cooperation on the total costs can be integrated with the current deployment cost model.

5.4 Conclusions

When techno-economic decisions are made, the analysis must always take into account the surrounding market environment in which the decision maker is active. In concentrated markets, where only a few players are active, the impact of competitive or cooperative interaction should not be neglected. This interaction impacts the market share of the actor, and directly impacts the costs and revenues linked to the technical design of the techno-economic case.

In case of fibre access network rollout, typical research suggests high take-up potentials for these new networks. However, the impact of existing networks, like cable or DSL networks should be taken into account. Customers choose products based on (perceived) pricing and quality. During our research, we developed a market response model able to capture competitive interaction on the market share of different products and services. This model has been applied throughout various publications, and through the case study presented in this chapter, we show how the model adequately captures market share evolution.

In light of the results from the market model, it is clear that low take-up of FTTH networks is expected to reduce the viability of network rollout. Two approaches to increase this viability exist, either focus on increasing take-up, or focus on cost reduction. Under the first approach, techniques like geomarketing or cherry-picking apply, which fall outside the scope of this dissertation. The second part of this chapter focussed on possible strategies to attain cost reduction through optimal network design in the rollout of access networks.

The most advanced form of cooperation discussed in this chapter is the public private partnership. In such a cooperation model, a public and private player form one entity to serve the market. Such a model has two advantages. First, by cooperating, no duplication of infrastructure is done, so the investment cost of a single infrastructure can be shared between the two partners. Secondly, again since only one entity is active, the customer base is not split between extra operators, thus increasing the customer base of the entity served by the single infrastructure. It is clear how market share is directly reflected in the technical requirements of the techno-economic case study.

However, such a high level of cooperation is not always required. Research has indicated that the majority of the costs in access network rollout are linked to the installation of the outside plant. In case of a buried installation, the costs for trenching can make up to over 50% of the total cost. However, this is also where most synergies can be found with other players, as the processes to rollout physical infrastructure do not differ much between e.g. telecom and electricity

operators. We developed a model quantifying these cost savings, and found a potential of up to 21% cost reduction in outside plant installation.
The tools and models described in this chapter form the basis of the competitive analysis in the following chapter. The quantitative analysis performed there can assess the value of different competitive and cooperative strategies, indicating the optimal strategies for all actors.

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6

Game Theory Methodology to Model Competitive Interaction

"You have to learn the rules of the game. And then you have to play better than anyone else", Albert Einstein

Market interactions play a vital role in the viability of investments in the telecom sector, as was indicated in the previous chapter. When a new offer is entered on an existing market, it will step in competition with the existing offers. While the market model introduced in Chapter 5 allowed predicting the impact of this competition on market shares, and cooperation models offer cost sharing opportunities, these models do not offer insight in the prevailing competitive strategies. When all players have different possible strategies, which one to choose that optimises your utility? This is where game theory comes into play. From a set of players, each with their own strategy set, it offers a methodology to indicate the market equilibrium, taking into account how competitors react on different competitive strategies. In this chapter, we will introduce the basics of game theory from a mathematical point of view. Game theory has been a research topic for over 50 years now, so it offers a broad set of methodologies to analyse competitive interaction. However, its application in techno-economic analysis is only slowly getting accepted. To increase this uptake, a game theory software tool was developed during this research to analyse competition between players with underlying techno-economic models. Again, comparable as in the previous chapters, the insights will be applied to the case study. The results from this case study were published in [6.1].

6.1 An introduction to game theory

Competition is an important aspect in realistic business modelling. Making strategic decisions not only impacts the company itself, but also changes the existing equilibrium on the market and thus the other actors. Price wars are an example of such competitive interaction. When one player decides to lower his price, in order to attract more customers, his competitors can react by lowering their prices as well. No actor will gain extra market share in the long run, but the prices on the market will drop. When price reductions continue to occur, a price war behaviour is observed. As a result, companies start selling at or even below production cost price, and non-efficient companies are driven out the market.

Although price is a straightforward example of competitive interaction, any strategic decision taken by a player impacts the competitive equilibrium. Entering new geographical markets, offering new services or upgrading technology will all have an impact. An example can be found in the fixed broadband access market. If one player decides to increase the access speed it offers, it can be expected that the other operators will follow. Linking back to the real option methodology discussion, any option executed from the 7S framework in Chapter 4 will trigger competitive interaction. However, the options from the 7S framework make abstraction of this competitive interaction. In many cases, such interaction is indeed absent, e.g. when acquiring a mobile licence. The process of the spectrum auction is a competitive process, but once the licence is acquired, the player owning the spectrum licence can operate in absence of competitive interactions within its spectrum.

Therefore, it is important to take competition aspects into account when conducting techno-economic analyses, as each strategy is based upon a different underlying technology model. Two aspects can be identified in such competition modelling.

First, the impact of competitive interaction on the market share and adoption potential needs to be taken into account. Based on price and quality factors, such a model allows estimating the market share of different offers, based on price and cross elasticity concepts. As such, this model also allows indicating the impact of a new entrant in a mature market. The deployment of a fibre network in a region where broadband infrastructure is already present is an example of such an entry. The market model was introduced in Chapter 5.

Secondly, the techno-economic decision process also needs to take into account the possible counter strategies from the competitors. Game theory is the designated tool to model these interactions.

6.1.1 Game theory basics

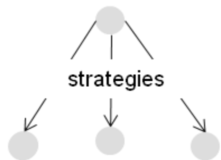
Game theory is "*aimed at modelling situations in which decision makers have to make specific actions that have mutual, possibly conflicting, consequences*" [6.2].

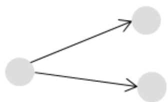
Game theory can be split further down into cooperative and non-cooperative game theory. In the latter, the game is one in which players make decisions independently of each other, cooperation can occur here, but this cooperation must be self-enforcing. All players within the coalition must benefit from the cooperation. The difference with the first is that in cooperative game theory, players can form coalitions which have the power to enforce cooperative behaviour. Within this work, we have focussed on the non-cooperative game theory, as in most techno-economic cases, cooperation will only occur when all players benefit from the coalition. This mutual benefit was also the basic idea from which the cost sharing model in Chapter 5 stems.

In game theory, all players have sufficiently good knowledge of each other's possible strategies and payoffs. Payoffs represent the utility function of the different actors. These assumptions allow representing the game by means of a payoff matrix. This matrix has a payoff (e.g. Net Present Value) for all players for each possible combination of strategies. This is called the strategic form of the game and allows finding an equilibrium in the game (Figure 6-1). An equilibrium is a set of strategies (one for each player) at which players are not inclined to change their strategy. Different equilibrium concepts have been proposed in the field of game theory. The most commonly known equilibrium is the Nash equilibrium (NE), which is defined as a situation in which no player can gain by unilaterally changing its strategy. In such a NE, each player will use a pure strategy [6.2]. It is often assumed that a game with fully rational players (using this equilibrium as criterion) is expected to result in one of the NEs being chosen.

Typically static games (the game has one stage in which the players interact) can also be reduced or solved by removing strictly dominated strategies. These dominated strategies have a strictly lower payoff than another (dominant) strategy for all possible counterstrategies. No fully rational player would play a strictly dominated strategy but would instead play the dominant strategy. As such this strategy can be removed for the considered player. By iteratively using this approach for the different players, the matrix of the game can be simplified and can in some cases be solved to a unique strategic choice for each player. In these cases, this strictly dominant strategy set is the only NE of the game.

In Figure 6-1, a strategic form of a toy example is shown, with two players. Each cell represents a payoff tuple, where the first number represents the payoff of player B, while the second is the payoff of player A. Applied to the example strategic form, it is clear that strategy A3 is dominated by A2. With this strategy removed, the strategy B2 is no longer interesting for player B, since he gains a larger payoff in all cases for strategy B1. Now only the strategic combinations (B1, A1) and (B1, A2) remain, and player A will always choose A2.





	A1	A2	A3
B1	1,0	1,2	0,1
B2	0,3	0,1	2,0

Figure 6-1: Strategic form of a game and Nash equilibrium (highlighted)

Pareto optimality is a second equilibrium concept. It is based on the Pareto improvement concept. Given an initial set of strategies, a change to a different allocation making at least one player better off without making another actor worse off is called a Pareto improvement. When no Pareto improvements can be made from a given strategy set, the set is Pareto optimal or efficient. An economic system that is not Pareto efficient implies that changing the strategy set would make some players better off without reducing the payoff for the other individuals. From an efficiency point of view, it is clear that non-Pareto optimal points should be avoided. When looking at the example given in Figure 6-2, which plots the matrix from Figure 6-1 on a payoff chart, strategy set (B1, A1) is not Pareto optimal, since player A can improve its payoff from 0 to 2 without reducing the payoff off Player B if it chooses action A2. Extra analysis shows that the Pareto optimal points are in this small example (B2, A1), (B1, A2) and (B2, A3). Another way to identify Pareto optimal points is using the Pareto frontier concept. The Pareto frontier is the set op Pareto optimal solutions and can be graphically presented (Figure 6-2).

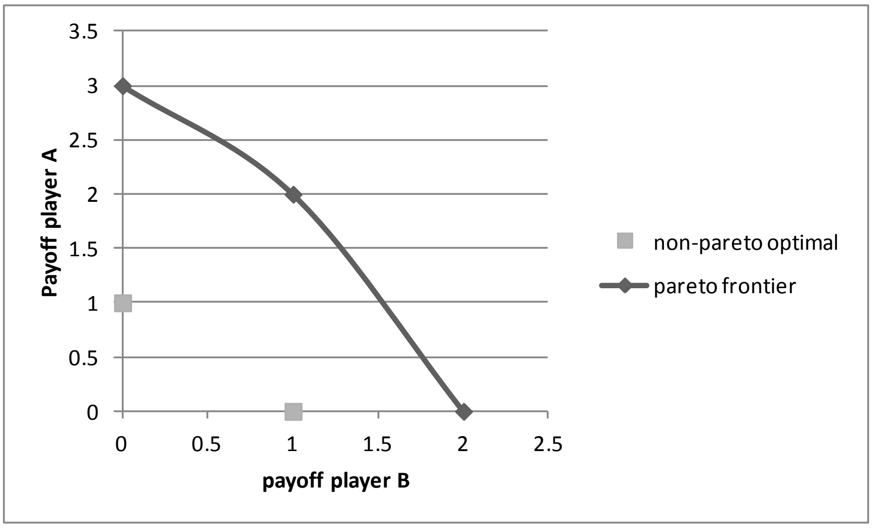


Figure 6-2: Pareto optimal strategy sets for the example game

6.1.2 Game theory in telecom

Game theory has already been widely applied in telecom research. However, the main application of this theory is in networking games for flow and congestion control, network routing, load balancing and quality of service (QoS) provisioning. We refer to [6.3] for a complete literature overview of these networking games in wireless networks.

Nevertheless, techno-economic telecom research can also greatly benefit from the concepts of game theory. Investment projects in new fixed and wireless networks never occur in a monopolistic environment. Typically, for both the fixed and mobile market, customers have the possibility to choose between different vendors, operators and service providers. When launching a new product, network or service, the actor has to take into account the effect of its decision on the competitive equilibrium in the market. Techno-economic oriented game theory offers important methods and concepts to assess this competitive interplay in the economic assessment. To use the concepts of game theory, it is important to model the impact of the competition between all players on their respective business cases. Most likely, the chosen strategies will have an impact on the division of the market between all players and on the technical design.

Competition modelling by means of game theory between different operators is a more recent field in techno-economics. Typically, a mathematical model is built to analyse the game and the resulting equilibria. For example, [6.4] studied the competition equilibrium in the Chinese triple-play market. Another example is

[6.5], where the optimal pricing strategy for new telecom services in developing countries is assessed using mathematical game theory models.
However, while such mathematical models can prove useful for general reflections on competitive interplay, they lack the possibility to model competition between different players with an underlying numerical techno-economic model. Such research has already been used in several techno-economic publications. In [6.6], the viability of a municipal Fibre To The Home (FTTH) network rollout was assessed. It introduced a first mover advantage to divide the potential market between a cable operator and an FTTH network. Being the first to offer services to consumers resulted in a faster adoption and larger initial market share. This allows for an analysis of the business case of the FTTH deployment under more realistic assumptions, especially since the viability of such a deployment largely depends on the take rate and thus the competition with other operators. If the FTTH network is rolled out in regions where existing communication infrastructures, like copper and/or cable broadband access networks, are present, this could drastically impact the economic assessment. Applied to the specific case of a municipality rolling out an FTTH network where an existing cable operator upgrades its network to DOCSIS 3.0, game theory offers insight in the most profitable rollout scenarios under competition. Since an FTTH rollout suffers from high upfront installation costs, it is advantageous to start with a slower rollout compared to the cable operator and focus first on the largest industrial sites. In residential areas, FTTH should focus on the densest regions, since this reduces the digging costs per connection. On the other hand, the cable operator has less digging constraints and focuses on the larger residential areas.
In another case, using game theory to model the competition between different wireless operators, price competition was introduced to divide the market between the different operators [6.1]. Based on this market division, the viability of different business models offering wireless broadband access was studied. A municipal WiFi network was found to be economically interesting, even in competition with several mobile operators offering 3G femtocell access. However, when other players are interested in rolling out a commercial WiFi network, a public-private partnership (PPP) between these players is designated. We discuss this case in more detail in Section 6.4.1.

6.2 Mathematical game theory

The main approach used to apply game theory in techno-economics is the mathematical approach. In this section, we will shortly describe the mathematical approach through a simple example, and indicate why techno-economics require a more hands-on approach.

There exists a broad mathematical foundation of game theory. Names like Nash, Cournot, Bertrand and Von Neumann laid these foundations, on which the researchers today are still building further.
Here, the basics of mathematical game theory in duopoly will be introduced. In duopoly, competition is characterised by competition between two firms. To analyse duopoly, a clear view on the influence of each firm on the other is required. Game theory offers the toolkit to analyse this influence. Several models exist to study duopoly, of which the Cournot quantity and Bertrand price competition model are the most well known. Both models can be used to indicate how competitive advantage can result from a better cost position. These models were already introduced shortly in the previous chapter. Here, we present a more in-depth description of the mathematical background.

6.2.1 Cournot and Bertrand duopoly – background

The quantity competition model was introduced by Cournot in 1838 [6.7]. As it was developed more than a century before Nash introduced his equilibrium concepts, it obviously does not rely on them. However, Cournot roughly anticipated these concepts. The basic assumption of the Cournot model is that two firms decide on output quantity. From the aggregated output, the market decides on the market-clearing price level, as a representative auctioneer. In this case, price is exogenously determined. The main criticism, resulting in the Bertrand model [6.8], is that in reality, firms do not compete on quantity, but on price. Currently, both models are used as cornerstones in industrial organisation. Due to their differences in approach, the Bertrand model is viewed as a short-run, tactical approach, while Cournot quantity competition explains long-term capacity commitments. In the next section, we will introduce the Bertrand model for heterogeneous goods.

6.2.1.a Bertrand duopoly – mathematical foundation

The mathematical derivation of the equilibrium in Bertrand duopoly is based on profit maximisation. When competing with another company, both firms will try to maximise their profit, given the market price and demand resulting from their aggregate outputs. Take an iso-elastic demand curve, depicted in eq. 6.1. An iso-elastic demand curve has a constant elasticity coefficient. This elasticity is the ratio of percentage change in the dependent variable to the percentage change in the independent variable. The demand curve reflects the price in function of the quantities sold by both companies. Parameter s indicates the substitution degree of both products. The higher s, the more both goods are substitutes of each other. If s equals zero, player i operates in monopoly. Indeed, in that case, the price of product i (p_i) is only function of the amount of i produced (q_i).

$$p_i = \frac{1}{q_i + sq_j} \tag{6.1}$$

With: p_i = price of good or service *i*
q_i = amount of good of service *i* sold.
q_j = amount of good or service *j* sold
s = substitution factor $\in [0,1]$

Both players face the same constant variable cost *c*, resulting in the following profit function.

$$\prod_i = p_i q_i - cq_i \tag{6.2}$$

To calculate this profit function, the inverse demand function is required. This inverse demand function returns quantity in function of the price of the two products. The inverse demand function for player *i* equals:

$$q_i = \frac{p_j - sp_i}{p_i p_j (1 - s^2)} \tag{6.3}$$

This results in the following profit function for player *i*.

$$\prod_i = p_i \left(\frac{p_j - sp_i}{p_i p_j (1 - s^2)} \right) - c \left(\frac{p_j - sp_i}{p_i p_j (1 - s^2)} \right) \tag{6.4}$$

The functions for player *j* can be derived symmetrically. As both players strive for profit maximisation, the first order profit maximisation condition must be met.

$$\frac{\partial \Pi_\mathrm{i}}{\partial p_i} = 0 \tag{6.5}$$

Or, when applied to the profit function of player *i*, resulting in the reaction curve for player *i*:

$$p_i^2 = \frac{cp_j}{s} \tag{6.6}$$

Again, the reaction curve for player *j* is obtained symmetrically.

$$p_j^2 = \frac{cp_i}{s} \tag{6.7}$$

As both players try to maximise profit, the equilibrium price is obtained where these two curves intersect.

$$p_i = p_j = \frac{c}{s} \tag{6.8}$$

6.2.1.b Bertrand competition – numerical example

To indicate the application of the Bertrand duopoly model in practice, a toy example is included. Two players are offering mobile and wireless access in a city environment. Player *i* offers this access through its 3G network, while player *j* deploys a WiFi network. Both products offer the same functionality, so they are (partial) substitutes. However, as the 3G provider also offers connectivity outside the city, the products are not assumed to be full substitutes. Parameter *s* from the demand function (eq. 6.1) is chosen at 0.50.

The two players are confronted with an iso-elastic demand curve, and have symmetrical variable costs of 10. Inserting these parameters in eq. 6.8, results in an equilibrium price of 20. A graphical representation of the reaction curves can be found in Figure 6-3.

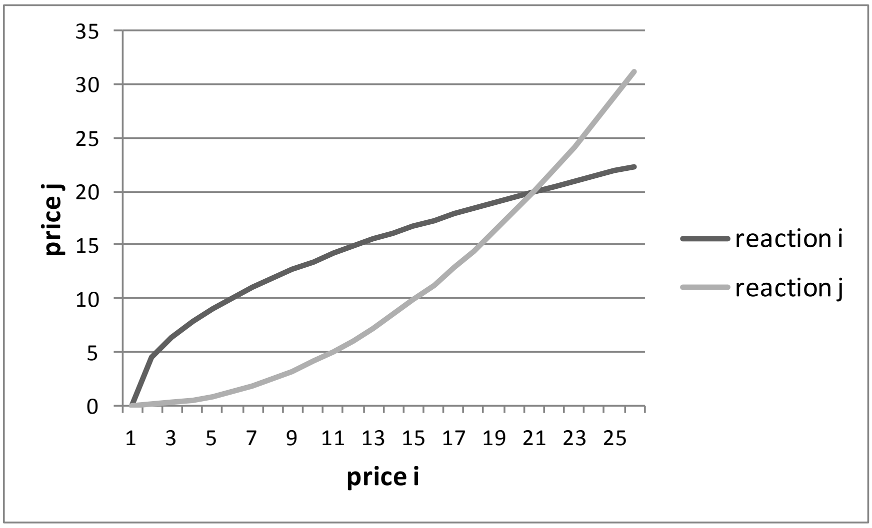


Figure 6-3: Reaction curves and equilibrium determination for toy example

6.2.1.c Advantages and drawbacks of mathematical game theory

Applying mathematical game theory to techno-economic investment problems has several advantages. First, as it is an established field, it offers a broad toolkit to solve such problems. Secondly, as was indicated in the numerical example, it can be applied in a straightforward manner.

However, it also has numerous drawbacks. The Bertrand model, and in extension the other models, are based on strict assumptions. The profit function must be derivable. While performing this might still be feasible for simple cases, for more complex cases, this can no longer be performed ‘on the back of an envelope’. Especially when profit functions are based on a detailed techno-economic model, this increases the difficulty of the exercise. In addition, the example above only takes in account variable costs. In realistic cases, fixed costs cannot be neglected. For example, when a WiFi network is rolled out, this comes with considerable fixed costs, depending on the technical specifications used in the techno-economic model. Extensions exists for the basic Cournot and Bertrand models incorporating these costs, but this again impacts the computability. Finally, mathematical game theory as applied above requires knowledge of the demand curve. For emerging markets, this is no straightforward exercise.

While the mathematical approach can be extended to include these additions, it decreases the readability of the models used, making it less suited for applied techno-economics. Professionals are used of working with more detailed models. As a result, a more hands-on game theory approach is required for techno-economic cases.

6.3 A hands on Game Theory approach

Resulting from the drawbacks described for mathematical game theory, techno-economic telecom investment problems require a more hands-on approach, useable by decision makers who typically do not have the background for the mathematical modelling. Actors make decisions based on more complex utility functions than the profit function used in the Bertrand example above. As was introduced in Chapter 3, private players base their decisions on value creation metrics, like the NPV. And for public players, the broadband performance index can be used as utility function.

In this research, software was developed to allow for the game theoretic modelling of competitive aspects in telecom infrastructure projects. The approach is built around the strategic form of the game (Figure 6-4). A game is determined by players and their action set. These action sets contain the different strategies the players in the game have. In addition to these two aspects, every game contains a calculation engine. It is in this engine that the main intelligence of the game lies. Based on the different actions, it returns the payoff for each player. As such, the calculation engine allows to calculate every cell in the strategic form of the game. If a game is provided, with players, actions and a calculation engine, different solution concepts offered by game theory can be applied. Nash equilibrium and Pareto optimality are two of these concepts which were already introduced above. The implementation of these solution concepts is based on the formal definition of these concepts. In the following sections, more detail on the different classes is given.

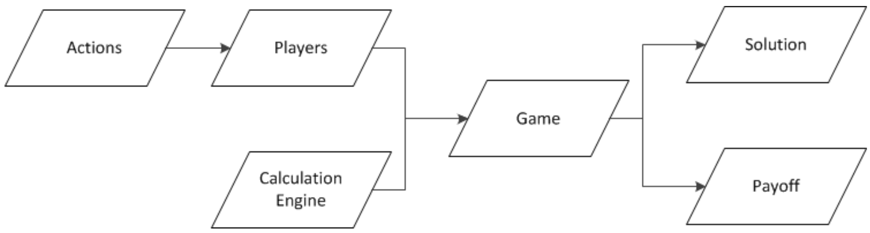


Figure 6-4: A hands-on game theoretic approach

6.3.1 Actions modelling strategies

In the hands-on game theory approach developed, an action serves as a placeholder for a player to react upon and for any calculation engine to trigger the right calculations.

Several of specific action types can be modelled, depending on the specific requirements of the techno-economic case. The most basic action contains only a name. Based on this name, it is possible to compare two actions. Actions are considered equal if they have the same name. Building further on this basic action, several other actions are possible, extending the name of the action with a strategic variable. This variable can represent an array of values, with each value referring to a specific time. As a result, it is possible to model more specific actions, based on e.g. price or investment behaviour. Such an action defines the price or investment strategy of a player over a certain course of time. Considering a price strategy, this can be a constant price over time, but more complex cases, like exponentially decreasing prices are also possible. With changing actions over time, more disruptive action changes are also possible.

Combining different actions together is also possible. With this approach, the model allows to include actions consisting of combined strategies. Such strategies can for example consist of a combination of a price and an investment strategy. In the end, it is the calculation engine that will use the input from the actions to determine the payoff of a certain strategic combination based on the actions defined in the game.

6.3.2 Players engaging in the game

A player represents one of the actors engaging in the competitive game. Players are solely defined by their name, if two players have the same name, they are considered the same player. Comparable to actions, different sorts of players are possible. The most basic player consists only of a name, but more detailed players, based on initial market shares are also possible. We have found that a combination of a name and an initial market share suffices to tackle all competition problems tackled during our research.

The list of actions contains the strategy set of the player in the game. If two or more players have been modelled, the strategic form of the game can be built based on these strategy sets.

6.3.3 The calculation engine as central intelligence in the game

As already indicated above, the calculation engine contains the required intelligence to calculate the payoffs of all players under a given strategic combination. The calculation engine returns the payoff of all players for one combination of actions.

Every game requires its own calculation engine, as the underlying specifics of each game are different. For example, the interaction between different price strategies by different players can be included in this engine through the market model introduced in Chapter 5. In addition, the calculation engine contains the links to the underlying techno-economic models of the different players. In these models, the dimensioning of infrastructure, equipment and operational processes is performed, based on expected adoption from the market model. Calculation engines have been built for different problems, e.g. to study how competition between different wireless access providers influences the business case [6.1], how open access in an FTTH network impacts the different players, and even on mobile base station sharing to reduce energy consumption.

6.3.4 Game: bringing everything together

In order for a game to be solved, it requires a list of players and a calculation engine. As every player in the list contains the strategy set of the player, and the calculation engine the intelligence to calculate the payoff of each player, the game has everything required to calculate the strategic form.

6.3.5 Solution concepts

With the game modelled, different solution concepts can be applied to solve the game. Two main concepts have been included, namely the Nash equilibrium and the Pareto optimality concept. The first is typically used to identify the outcome of the game under competition, with players solely acting in their own interest. The second concept aims at identifying the so-called social optima, where no player can improve its payoff without decreasing the payoff of another player. By including these two concepts, extra insight is gained in the dynamics of each game. In fact, if both solutions are identified, they either coincide, or they do not. In the first case, it can be stated that competition without intervention will result in the social optimal situation. In the latter case, the deviation of the two solutions offers an indication to which action might be required to reach the social optimum.

6.3.6 Advantages of a hands-on approach

The software developed during this research to solve strategic games offers several advantages compared to the mathematical game theory approach. The first main advantage is that it allows to use detailed techno-economic models as utility function for different players. As this is more closely linked to the world of decision makers, it is more clear how the different strategies interact, compared to a mathematical model, especially since visualising the strategic form is possible. A second main advantage is that the approach allows to include the impact of uncertainty on the analysis. The game can be run repeatedly with a changing input parameter. This parameter can be linked to the revenue side of the different underlying techno-economic models, e.g. price sensitivity or market potential, but also to cost-related aspects like operational costs or mean time between failure. By calculating the strategic form for these different cases, changes in outcome can be identified. If the outcome of the game remains the same, no matter what the uncertain parameter is, competition will result in the same solution. However, if the parameter has a large impact on the chosen equilibrium, such a sensitivity analysis can indicate to decision makers how they can impact the game and steer it into a desired direction.

It should be noted that in our hands-on approach, only non-cooperative game theory is considered. However, the simulation framework developed can be extended straightforward to contain cooperative game theory. Indeed, Nash himself proposed two different options for cooperative game theory [6.9]. The first is based on an axiomatic approach, while the second consists of including the cooperative strategy in the non-cooperative game. This second approach can be applied in our framework. This will be indicated through two case study examples, described in more detail below.

6.4 Competition in access network rollout

When making strategic decisions, be it long term investments or regulatory decisions, it must be taken into account that these happen in the existing market environment. Typically, an actor deploying a new access network in Western

Europe, will have to compete with existing operators. A regulator changing the local loop unbundling price will notice a shift in take-up of these services, but maybe also an impact on the investment behaviour of the incumbent.

Including this competitive impact on your objectives is key into making a correct valuation of the strategic decision. Game theory is the designated approach to take this into account. To indicate how game theory and the framework developed during this research can be applied to realistic cases, two examples are elaborated on in this section.

The first example applies a game theoretic approach to the rollout of competing wireless networks in a municipality [6.1]. However, as cooperation between different players through a public private partnership is a possible ‘competitive’ strategy, this strategic option is to be included in the model. In the second example, the same approach is applied to the rollout of a municipal fibre network. In this case, the network is introduced in the existing broadband market, and must compete for market share with the existing infrastructures. Again, a cooperative strategy is available within the game. Operators can engage in a joint rollout (cfr. Chapter 5), or existing operators can migrate to the new infrastructure. The choice of strategy thus clearly impacts the network and equipment model.

In both examples, a municipal player is included in the model. This player has, next to its financial objective, other social objectives. In the first example, the social objectives are monetised through the concept of indirect revenues. For the second example, the game is repeated with the broadband performance index described in Chapter 3 to indicate how other utility functions can be used in the hands-on game theoretic approach.

6.4.1 Competition or cooperation in wireless network rollout

In this first case under study, competition between multiple wireless access providers will be discussed. Next generation access networks are expected to bring ubiquitous broadband access and have attracted the interest of municipal governments. Using a game theoretic approach, the different investment options of the municipal player are investigated.

To investigate the different partnership and competition scenarios for the introduction of a city-wide wireless access network, a general model was developed, focusing on the rollout in the city of Ghent. Ghent is the third largest city in Belgium, with over 240.000 inhabitants. The city also houses 65.000 students and attracts almost 400.000 tourists a year. Based on the work of Van Ooteghem [6.10], we focussed on the city centre as most interesting rollout area. Previous research has already been conducted in this topic. In Lannoo et al. [6.11], a municipal WiFi player and a 3G mobile virtual network operator (MVNO) were already brought into competition. However, several questions remain to be addressed in this topic. Will the municipality be interested in a PPP with a commercial WiFi provider? Or is it more interesting for both partners to deploy their own network and compete instead of cooperate? By choosing for competition, problems with state aid rules and hidden subsidisation will be avoided. In order to answer these questions, we developed two techno-economic models, based on the wireless technology used by the actor. The first model is a 3G model, while the second models a WiFi network deployment. Building further upon the WiFi model, three different players can be modelled, depending on the player rolling out the network and the cooperation strategy. As such, a public and private operator is possible, together with a public private partnership (PPP) model. First, a techno-economic analysis is conducted for the techno-economic models of the 3G operator and the WiFi operator in absence of competition. Next, the competitive interplay will be discussed and how it impacts the results from the standard techno-economic analysis.

6.4.1.a Viability of a WiFi deployment

Technical info

WiFi is a certification label for wireless local area network (WLAN) devices that comply with the international IEEE 802.11 standards and sub-standards. Those labels are distributed by the WiFi Alliance, and interoperability between different products is ensured. Different flavours of the IEEE 802.11 standard exist, where 802.11a, 802.11b, 802.11g and 802.11n are presently the most wide spread variants. WiFi devices were primarily intended to be installed and managed by the customer. However, some telecom operators are nowadays exploiting WiFi access points (AP) at public places to offer their clients a fast wireless Internet connection, as an extension to their main telecom services.

In this case, the recent 802.11n standard (released in October 2009) is used, because of the higher throughput, compared to the older standards. The 802.11n standard can be considered as the successor of 802.11g and it is backwards compatible with the latter. Two non-licensed radio frequency bands are defined for WiFi, i.e. 2.4 and 5 GHz, and there is opted for a 20 MHz channel bandwidth. The wireless municipality network is expected to work within the 2.4 GHz frequency band, for which three low-interfering 20 MHz channels are available. A maximum achievable physical layer data rate of 65 Mbps per 20 MHz-channel can be attained. The 802.11n standard also supports multiple antenna techniques like Multiple-Input Multiple-Output (MIMO), which can extend either the data rate or the range of the WiFi signals. For outdoor APs, MIMO is better used to extend the wireless range while keeping a 65 Mbps channel, than to increase the data rate.

Access point deployment model

An import aspect of developing a full techno-economic model of a wireless access network is the calculation of the number of WiFi APs that need to be deployed in order to assure both coverage and sufficient available bandwidth to serve all users. Four important input factors to assess the needed number of APs can be distilled: covered area, number of users, required bandwidth and physical parameters of the technology. As the number of users directly impacts the number of APs, it is already clear here how market share impacts technical design. The physical parameters define the signal power, gains, losses, receiver sensitivity and margins (fade, shadow, interference …) for calculating the maximum range of the technology at a given data rate. Together with the three other input factors, the amount of needed APs can be defined.
In [6.10], the best technical scenario from a techno-economic point of view was selected for the deployment of a wireless network. It considered two main access technologies: WiFi and WiMAX. The backhaul solutions were varied as follows: all APs individually connected to a fixed backhaul network (e.g. digital subscriber line (DSL) or fibre); meshed networks of a single wireless technology, reducing the number of fixed backhaul connections; or a combination between WiFi (as access) and WiMAX (as wireless backhaul) technology. The best choice was a meshed WiFi network. The main deployment details can be found in Table 6-1.

Table 6-1: WiFi deployment scenario

Wireless connection	Technology	Antenna heights (m)
AP to user	WiFi	1.5 to 6
Backhaul	WiFi	6

Cost model

The deployment of a wireless access network requires a large upfront investment, mainly driven by the need to install both WiFi APs and the wireless backhauling. The APs will be subject to failure, caused by external factors like weather conditions and vandalism, so a replacement investment is assumed every five years. Next to the APs, an investment in central infrastructure is also necessary. This can be subdivided in core equipment, such as routers, servers, and general Network Operating Centre (NOC) infrastructure like power supply and cooling. All costs are based on [6.10].
Next to the upfront investment, operational expenditures will also play an important role. WiFi APs are deployed on either public or private sites. Site rental will thus be a major aspect of the yearly OpEx. Access to public sites is typically cheaper than access to private sites. This is modelled by halving the cost for site rental when it concerns a public site. To model the difference between a public or a private player, differences in the amount of public and

private sites were introduced. In absence of a public player in the project, only 10% of all sites are assumed to be public. When a municipality steps into the partnership, this rate shifts completely, with 90% public sites. These numbers are based on discussions with operators. The dimensioning provides the number of necessary sites.

The backhauling APs will be connected to a fixed backhaul connection. A volume-dependent connection price per connected AP per year is included. Operations, administration and maintenance (OA&M) are mainly driven by the number of APs and their equipment. Personnel costs for planning and maintenance of the APs are included [6.12]**.**

The cost for Customer Relationship Management (CRM) is fully driven by the number of customers. Offering a new service raises for example the need for a helpdesk department. In [6.13], a method is proposed to calculate the helpdesk cost. Cost of sales, marketing and advertising complete the CRM cost and are based on [6.10]. An overview of the different cost aspects can be found in Figure 6-5.

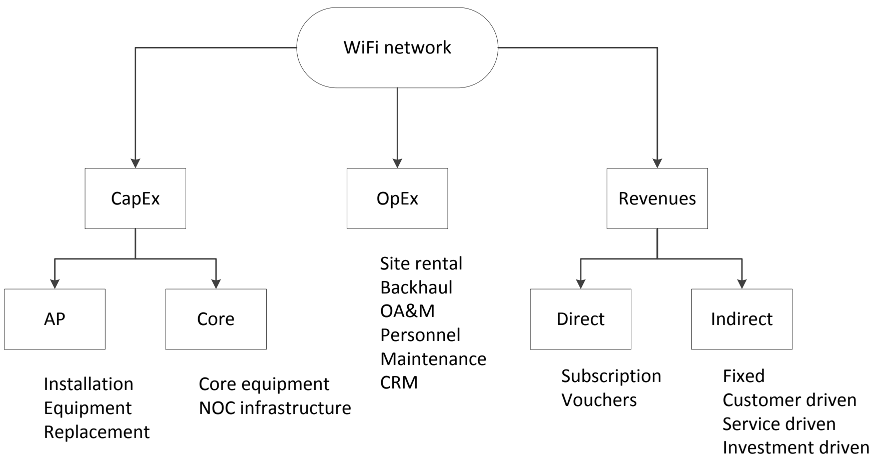


Figure 6-5: Cost and revenue breakdown for WiFi network deployment

Revenue model

Revenues fall apart in two categories. There are the direct revenues, driven by the number of customers. For indirect revenues, the link between the revenues and the main activity, here the sale of wireless access, is indirect. It is however the existence of indirect revenues that makes network infrastructure projects so important for public players.

Direct revenues

Direct revenues can be derived from the forecasted number of customers. A distinction between different service offers is made, based on [6.10]. Table 6-2 gives an overview of the monthly revenue per user for the different service categories for the considered network. The monthly revenues are based on prices for similar services offered by two commercial players in Belgium: namely the WiFi operator ZapFi and the WiMAX operator Clearwire. ZapFi will offer a WiFi service with prices starting from €10 per month in a nearby city [6.14], while Clearwire currently offers WiMAX subscriptions ranging between €30 for 1Mbps and €45 for 3Mbps per month at the time of the study**.** The prices used are thus a reasonable compromise between these two different offers. To be able to offer a free service, other parties can buy advertising space which will be displayed to customers using the free subscription possibilities.

Table 6-2: Monthly revenue per WiFi service

Service	Price	Data rates	
		Downstream	Upstream
Free	€ 5 (advertising)	512 kbps	128 kbps
Low-bandwidth	€ 12	1 Mbps	256 kbps
High-bandwidth	€ 20	3 Mbps	512 kbps
Vouchers (per card)	€ 9	1 Mbps	256 kbps

To allow for customer segmentation, four different customer classes are taken into account. Each class has a different interest in each of the service offerings, as shown in Table 6-3. Inhabitants will be interested in using the free service, in addition to their existing fixed broadband connection. Students on the other hand will use the two monthly subscription possibilities as primary connection. The better bandwidth offer of these services will be more in line with their interests than the free service that only offers 512 kbps. Tourists and business users will mainly buy vouchers. While tourists are only interested in the vouchers and the free service, business users can, depending on their usage time, choose for a monthly subscription.

Table 6-3: Customer class and interest in WiFi services

Service	Inhabitants	Students	Tourists	Business
Free	60%	5%	20%	10%
Low-bandwidth	25%	60%	0%	10%
High-bandwidth	15%	35%	0%	20%
Vouchers	0%	0%	80%	60%

Indirect revenues

While direct revenues are the main focus for private players, indirect revenues form a major driver for public authorities to invest in NGANs. Indirect revenues are additional advantages caused by the main activity. Efficiency gains in public services are one of the drivers for indirect revenues. The wireless network helps the municipality in promoting several eServices. Next to these gains, this project can attract new businesses, extra employment and tax revenues. Due to the broad spectrum of possible indirect advantages, it is hard to estimate the total indirect revenues a project generates. A distinction is made between four different drivers to evaluate the indirect revenues, namely fixed, customer, service and investment.

Fixed indirect revenues have no specific driver, but setting up a wireless platform allows deploying new applications, which can lead to efficiency gains and cost reductions. Customers drive the second part of indirect revenues, as the impact of for example an eGovernment application or social network is assessed by the amount of users. A third part is service based: an increased wireless coverage and bandwidth might benefit several new applications like e-health and video services. The last component of indirect revenues is investment driven. The municipality can expect to attract companies and high educated inhabitants due to such an investment. A part of the invested money will flow back in the regional economy, and taxation will generate a money flow to the local government. The calculation of the indirect revenues is based on [6.10], [6.15].

Investment analysis

From the cost and revenue models discussed above, a detailed investment analysis is carried out for the rollout of a municipal WiFi network. All customer classes are considered, and they can choose from the different services offered. Figure 6-6 shows the evolution of the cumulative NPV over the lifetime of the project. The combination of a high initial investment and slow user adoption gives a negative NPV in the first years. The payback period is over 6 years. After 10 years, an NPV of almost €3.2 million is obtained. Based on these numbers, this investment is a viable project, when indirect revenues are taken into account. However, it should be noted that no competition is taken into account here. A symmetrical player entering the same market would half the uptake, and thus largely decrease the return on investment.

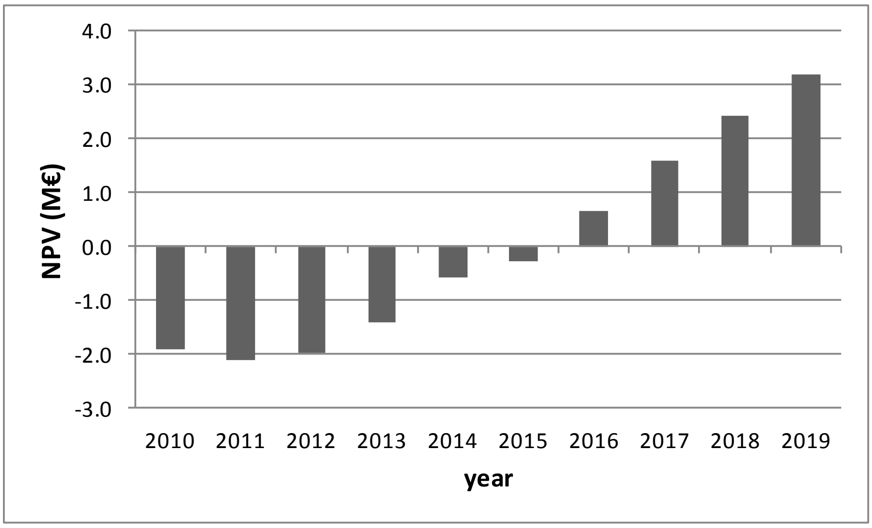


Figure 6-6: NPV evolution of the WiFi network case

6.4.1.b Viability of a 3G femtocell deployment

Technical info

3G coverage can be extended by installing femtocells at the customers' house. The technical aspects of both 3G and femtocells are described in the following subsections.

3G technology

The third generation of mobile telephony (3G, like UMTS) refers to the transformation of the digital mobile telephony technology (2G, like GSM) to a full mobile Internet access technology. The third generation partnership project (3GPP) tries to provide uniform standardisations for these and other 3G flavours. Release 99 was the original UMTS version. A user typically gets up to 384 kbps downlink for R99 handsets. Other releases (R4 - originally Release 2000, R5, R6, R7, R8 and R9) are already specified to further improve the UMTS technology. The UMTS successor is HSDPA, introduced in Release 5. It improves the downlink data rate for UMTS by using shared channels for different users. As this is an improvement of the 3G UMTS standard technology, it is called a 3.5G technology. 3GPP standards beyond Release 5 further improve the data rate. Release 6 introduces High Speed Uplink Packet Access (HSUPA), new antenna array technologies (beam forming and MIMO) and a new uplink transport channel. It targets 28.8 Mbps downlink and 5.8 Mbps uplink. HSUPA clearly improves the uplink, and is sometimes referred to as 3.75G technology. Release 7 introduces evolved High Speed Packet Access (HSPA) or HSPA+. The target is 42 Mbps downlink and 22 Mbps uplink. Release 8 and 9 introduce

Long Term Evolution (LTE) and the Evolved Packet Core (EPC). LTE promises peak rates up to 100 Mbps in downlink and 50 Mbps in uplink.

Femtocells

A femtocell is a small cellular base station designed for indoor use. It connects to the service provider's network via the customer's broadband connection instead of connecting via the local mast. So no additional costs for site deployment occur. A femtocell typically supports two to five mobile devices in a residential setting [6.16].

Femtocells are able to provide exceptional cellular service with a typical coverage range of tens of meters. For a mobile network operator (MNO), femtocells are attractive, since they can significantly increase the achievable data rates on its mobile network at the customer's property. This is very interesting since delivering high-quality mobile services inside buildings is on one hand a tough challenge for 3G because it uses higher frequency bands where radio signals attenuate more rapidly. On the other hand fast data rates are only possible with a strong signal. Individual connections to the femtocell offload traffic from the macrocellular network, thereby improving network quality for the remaining users [6.17].

We consider the extension of the macrocell 3G (or 3.5G / 3.75G) network of an MNO with femtocells installed by a fixed network operator at the customer side. The fixed network operator then provides access to its customers through both femto- and macrocells (having agreements with the MNO for the latter), and is acting as an MVNO. The used release of the 3G technology will depend on the network of the MNO.

Cost model

For the introduction of 3G femtocells, four scenarios were developed. In each scenario, the MVNO chooses a different subsidisation rate of the femtocells. Typically, an operator can choose to either charge the customer for the femtocell, or it can buy the femtocell itself, and charge the customer an extra subscription cost. A summary of the different scenarios can be found in Table 6-4. The operator will need to finance all or a percentage of the femtocell costs, depending on the chosen scenario. After five years, these femtocells are replaced by new ones.

For the deployment of a 3G femtocell network, there are also important network investments required in core equipment. A femtocell gateway needs installation and integration with the existing back office systems. An operator will typically opt for a nationwide rollout of closed access 3G femtocells. To assure comparability with the municipal WiFi rollout, these costs are scaled down to the municipal level. All costs are based on [6.11]. A detailed cost revenue breakdown can be found in Figure 6-7.

Table 6-4: Different 3G subsidisation scenarios

Service	Subsidisation	Monthly subscription fee
1) Full subsidisation scenario	100%	€ 20
2) 50% subsidisation scenario	50%	€ 18
3) No subsidisation scenario	0%	€ 16
4) Combinatory scenario	Combination	Weighted average

Again, OpEx needs to be considered too. Next to the recurring maintenance, a cost for the additional usage of the fixed line connection of the customer is included based on [6.18]. For the maintenance cost of the core equipment, a fractional approach of the total CapEx is used, as done by [6.19].
Unlike the WiFi network case, a mobile licence is necessary for the 3G network. The cost is influenced by the channel bandwidth, population and the number of BSs. A fixed annual cost per customer per year is included [6.11].
To assure comparability with the WiFi case, the same model for the promotion and helpdesk costs is used. The marketing cost is put lower. Since the 3G operator deploys a nationwide network, it can benefit from economies of scale.

Revenues

As this player is considered to be a private player, only direct revenues are taken into account here. The first three subsidisation scenarios are straightforward. Scenario 4 offers flexibility to the customer. In the first years, with high prices for femtocells, customers will opt for leasing the femtocell. For example, in the first year, 80% of customers will choose for a lease agreement. With femtocell prices dropping fast, customers will become aware of cost benefits when buying their own femtocell. In 2019, it is expected that only 20% of the customers will choose for the femtocell leasing model.
The operator offers closed access femtocells. This opens up possibilities to offer enhanced services, like virtual home numbers or SMS alerts. Not all users will show the same interest in these services. Mostly families with teenagers will be interested in additional services. Therefore, additional revenues for extra services of €5.20 are only added for families with three or more members [6.20]. This comes down to about 40% of all households in Belgium.
In contrast with the WiFi case, one femtocell per household is needed. The number of adopting inhabitants is divided by the average household size in Ghent, being 2,10. For business users, a distinction between small and medium enterprises (SMEs) and large enterprises is made. For SMEs, which account for 85% of all businesses, two femtocells per business suffice. Large enterprises, with over 100 employees, are covered with 20 3G femtocells.

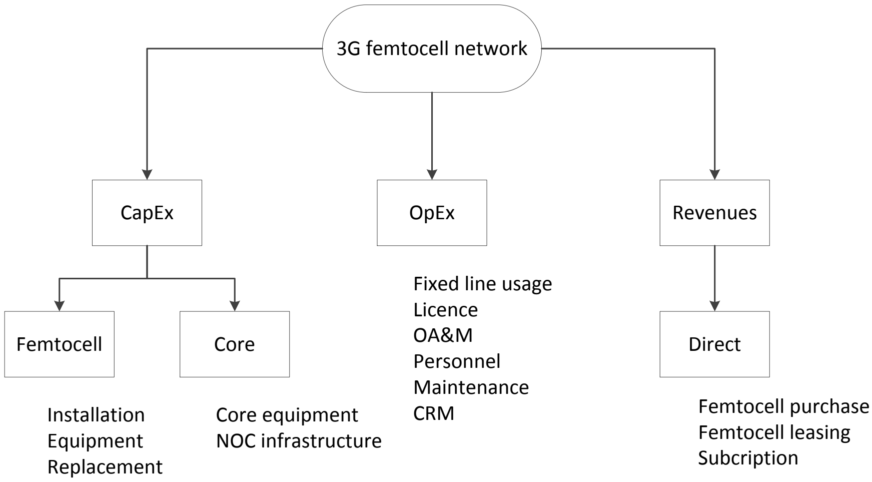


Figure 6-7: Cost and revenue breakdown for 3G femtocell network deployment

Investment analysis

The investment analysis is carried out the same way as for the WiFi operator. The NPV evolution of all four scenarios can be found in Figure 6-8. All scenarios have a positive payoff, with a payback time around two years. This is considerably shorter than the payback period for the WiFi network deployment. The case where the operator subsidises 100% is clearly the most profitable, with an NPV of almost €6 million after 10 years.

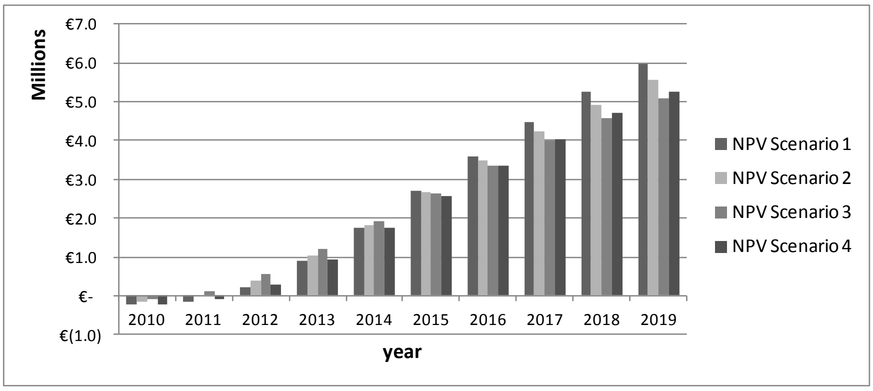


Figure 6-8: NPV evolution for a 3G femtocell deployment under different subsidisation scenarios

6.4.1.c Available strategies under competition

Up to now, the business cases for both actors were considered in the absence of competitive interaction between these players. However, when such networks are deployed together in the municipal environment, such interaction must be taken into account. When players compete, they can consider several competitive strategies. In addition, it should be clearly assessed what the objectives of the different actors are. This is where the game theoretic analysis proves very useful.

In the game, we consider three players, a 3G MVNO, a private WiFi network operator and a municipal WiFi network operator, each with several possible strategies (Table 6-5).

The main strategy studied here to attract customers is price change. The WiFi player has price schemes based on the offered service. Its strategy will therefore be changing its premium subscription price, either up or down. The other services are also offered, and their price scales up or down based on the change of the high bandwidth service price. For the 3G femtocell player, an extra strategic option emerges. Next to changing its premium subscription price, this player can choose between different subsidisation rates. In [6.11] the price setting strategy was chosen. This work is complemented with the subsidisation strategic choice.

Both WiFi players are offered an extra strategic choice, namely cooperation through a PPP. Under this strategy, the four WiFi services are offered by a single operator, the PPP. Costs and revenues are adequately shared between both players. For the municipality, since it does not have profit, but public welfare as its main driver, the non-profit behaviour was added to the business case via the indirect revenues concept. As such, as the municipality acts in the best interest for its inhabitants, the strategic decision variable for the municipality in this game will be the maximisation of the sum of its payoff and the discounted indirect revenues.

Some additional potential problems need to be tackled before modelling this game. State aid is not allowed, so the municipality must invest according to the market economy investor principle. Similar to the Amsterdam case, the municipality in this model invests 30% of the necessary funds, and reaps 30% of the benefits, if any. Similarly, the losses are spread between both partners on a 30 – 70 basis. This way, state aid issues are avoided.

The municipality can also choose to rollout an independent network. In this situation, its strategies concur with the price strategies of the commercial WiFi player. Table 6-5 summarises the different strategies for each player.

Table 6-5: Strategic choices for each player in the wireless network rollout game

Player		Strategy	Strategic choices
1	Commercial WiFi	Price strategy	€ 18 - € 21
2	Municipal WiFi	Partnership & price strategy	Independent vs. PPP € 18 - € 21
3	3G player	Price strategy	Subsidisation percentage

These strategies result in an asymmetric matrix. Player 1 and 3 both have four different options, while Player 2 has five. The resulting payoff matrix can be found in Table 6-6. It can be concluded that the municipality will choose for a PPP with the commercial player. This strategy is strictly dominant for the independent strategic choice. Using strict dominance, the Nash equilibrium [0.05;1.56;1.10] can be derived. It is indicated in negative in Table 6-6. The municipality should always choose to partner with a commercial player. The impact of other adoption choices on the NE was also checked. Both a lower and a higher adoption resulted in the same equilibrium being chosen, even with adoption curves not only differing by a multiplicative factor. Therefore it can be concluded that the results are not impacted by the adoption choices made.

When the NE is analysed for the other players, it is clear that it is also in the best interest for the commercial WiFi player to engage in this PPP. Direct competition with the municipality would result in a negative business case, while the PPP offers a slightly positive payoff for the commercial player. Due to this minimal result, the reasons for the commercial player to engage in this PPP could be questioned. Non profit related incentives for the commercial player would be brand image, customer satisfaction or reduced churn. The municipality could also offer extra advantages to the private player, like free site access or backhaul, so both players benefit from the partnership. However, it should be checked if these advantages offered comply with state aid regulation.

The 3G player will, in contradiction with the results of the static business case analysis, not choose for the full subsidisation scenario. When this player lowers its monthly subscription prices, it gains extra market share that compensates the lower profit margins.

From these results, it is clear that a game theoretic analysis offers more detailed insight in the price setting game played by all players. A naive player would choose to fully subsidise the 3G femtocells, while it is clear that this strategy does not result in the highest payoff.

A price war behaviour was also noticed in the game theoretic analysis. The equilibrium consists of the lowest price for the premium service. The WiFi players have an intention to keep lowering their prices, to capture extra market share. Continuously lowering prices would result in negative profit margins, which is forbidden by national and European legislation. Too low prices compared with other, mainly fixed services, offered by the commercial player, could result in an increase churn from fixed towards mobile access, shifting part of the resources to the mobile market.

6.4.1.d Case conclusions

A lot of attention is going to city-wide wireless access networks, since they promise to bring ubiquitous broadband access together with a broad range of advantages, like a stimulus for economic growth and extra employment. However, the rollout of these networks is only taking off slowly. By investigating the prevailing cooperation and competition models between WiFi and 3G players in a realistic competitive environment, we show how the application of game theory on a realistic case fits these observations.

The strategic behaviour of a public authority and commercial operators when they choose to invest in a wireless next generation access network (NGAN) is researched. Detailed numerical techno-economic models for the different players were developed, which all showed to be profitable when a standard techno-economic investment analysis was performed. However, this analysis cannot capture the impact of competition on the different business cases. Using a game theoretic approach to model this competitive environment, the cooperation and competition between the different players was studied. The model clearly showed that when the WiFi players roll out the network simultaneously and independently in this environment, their business cases are not profitable. Duplication of infrastructure while only attracting half of the customer base impacts the viability. Using the Nash equilibrium concept from game theory, it was proven that a public private partnership (PPP) is the only possible cooperation model for public and commercial WiFi players to roll out a city-wide wireless access network. An additional result from this analysis is the different strategy chosen by the 3G MVNO. The best scenario found in the static analysis proves to be the least interesting choice in the competitive setting. While the static analysis suggest to choose for the highest monthly subscription price, the game theoretic analysis shows that the higher market share gained by a lower subscription price offsets the lower revenues per customer. It is clear that game theory offers valuable insight to decision makers for investment analysis compared to the static NPV analysis.

Table 6-6: Strategic form for partnership scenario, dominant strategies in negative (NPV in M€, lifetime of 10 years)

		2. Municipality														
		enabler			independent			independent			independent			independent		
1. Commercial Wifi	3. 3G				18			19			20			21		
18	Scenario 1	0.33	1.81	0.52	-1.75	0.23	-0.17	-1.73	0.12	-0.10	-1.67	-0.04	0.07	-1.61	-0.26	0.23
	Scenario 2	0.18	1.68	0.87	-2.19	-0.15	0.40	-2.14	-0.26	0.43	-2.06	-0.44	0.55	-2.00	-0.70	0.69
	Scenario 3	**0.05**	**1.56**	**1.10**	-2.57	-0.51	0.80	-2.52	-0.62	0.85	-2.43	-0.82	0.96	-2.35	-1.10	1.05
	Scenario 4	0.21	1.70	0.74	-2.16	-0.10	0.26	-2.10	-0.21	0.30	-2.02	-0.40	0.41	-1.95	-0.64	0.52
19	Scenario 1	0.26	1.71	0.57	-1.77	0.36	-0.10	-1.74	0.26	-0.04	-1.67	0.08	0.13	-1.60	-0.13	0.29
	Scenario 2	0.12	1.59	0.91	-2.19	0.00	0.43	-2.14	-0.12	0.48	-2.06	-0.29	0.60	-1.98	-0.55	0.73
	Scenario 3	0.00	1.48	1.13	-2.61	-0.35	0.84	-2.54	-0.44	0.89	-2.44	-0.67	1.00	-2.36	-0.92	1.07
	Scenario 4	0.16	1.62	0.78	-2.13	0.03	0.30	-2.07	-0.07	0.34	-2.00	-0.24	0.46	-1.92	-0.49	0.57
20	Scenario 1	0.20	1.64	0.76	-1.83	0.58	0.07	-1.78	0.47	0.14	-1.69	0.30	0.30	-1.62	0.10	0.45
	Scenario 2	0.07	1.53	1.08	-2.28	0.22	0.57	-2.25	0.10	0.62	-2.15	-0.06	0.75	-2.06	-0.30	0.86
	Scenario 3	-0.05	1.42	1.27	-2.67	-0.12	0.98	-2.63	-0.22	1.02	-2.53	-0.44	1.08	-2.44	-0.68	1.17
	Scenario 4	0.11	1.57	0.93	-2.22	0.25	0.42	-2.18	0.15	0.47	-2.08	-0.02	0.58	-1.99	-0.26	0.71
21	Scenario 1	0.13	1.57	0.93	-1.94	0.79	0.25	-1.90	0.70	0.31	-1.80	0.53	0.47	-1.73	0.35	0.55
	Scenario 2	0.00	1.45	1.21	-2.40	0.44	0.72	-2.33	0.34	0.77	-2.22	0.16	0.88	-2.15	-0.07	1.01
	Scenario 3	-0.12	1.34	1.40	-2.82	0.13	1.07	-2.77	0.00	1.11	-2.65	-0.19	1.20	-2.53	-0.43	1.29
	Scenario 4	0.04	1.49	1.05	-2.32	0.48	0.55	-2.28	0.39	0.60	-2.18	0.22	0.73	-2.08	-0.01	0.84

In [6.1], the impact on the strategic behaviour of the different players when extra competition enters the market was also studied. While a PPP was shown to be the only prevailing strategy for the WiFi operators, the market reaction when extra 3G players enter the market were investigated. The extra competition poses problems for the WiFi partnership, since its market share is reduced further. Building further on the game theoretic model, a new strategic game was developed with extra 3G players competing for the market share with the PPP. Although the payoff in equilibrium state for the entire PPP remained positive, it was shown that the return for the commercial player in the PPP becomes negative, thereby completely removing its incentive to participate in the partnership. No intention to either rollout an independent or a joined WiFi network remains. These findings fit the overall observation that the rollout of municipal wireless networks remains slow.

6.4.2 FTTH rollout in a competitive environment

In the first case, competition between wireless broadband access providers were studied. As a public player, a municipality, was included, it was required to correctly capture its objectives. Its objective function consisted of the costs related to network deployment and operations, and both direct and indirect revenues were monetised and included in the NPV analysis. However, in Chapter 3, we introduced the broadband performance index as a ranking tool for comparing different outcomes when measuring social objectives. In the second case example, we will show how a game theoretic analysis can also be performed for regulatory problems, applied to the rollout of a municipal FTTH access network. Due to the presence of state aid rules, a municipality is not allowed to invest in fibre infrastructures, unless it can prove to have a viable business case. Both objectives should thus be checked in the analysis.

6.4.2.a The municipal competitive environment

In an urban environment, fixed broadband infrastructures are already present. In typical European cities, there is both a cable and DSL network installed. The rollout of fibre networks in existing broadband market is thus expected to have an impact on the existing market shares and the competitive equilibrium in this market, as was shown in Chapter 5. In case the newly deployed fibre network is rolled out by a third party, it will compete for retail customers with the legacy copper and cable networks. On the other hand, when an incumbent is rolling out the network, it will cannibalise on its existing network. As a result, the fibre business case is expected to be put under pressure, since lower uptake (and thus lower revenues) due to competition can significantly reduce the economic viability. We have indicated the effect of competition on uptake in Chapter 5. This is being observed in Europe, where the rollout of FTTH networks is only occurring slowly, compared with other regions [6.21]. In addition, the actors deploying the infrastructure are mostly not private ones. Typically, public actors engage in fibre network rollout. In Sweden, most physical fibre infrastructures have been deployed by municipalities (e.g. Stockholm), in the Netherlands, the city of Amsterdam has a share of 30% in the fibre deployment company, etc [6.22], [6.23]. Their main rationale is that a fibre network has a strong public policy case, as it is expected to attract companies, to close the digital divide, increase tax income, etc [6.24]. These indirect benefits can justify investment of public money in the fibre network deployment.

However, the investment of public money is bound to regulation. White, grey and black areas have been indicated by the European Union, and the investment of public money is only allowed in the white areas, where no broadband infrastructure is currently available, or planned by private players to be deployed within the next three years [6.25]. In the other zones, public money can only be invested according to the market economy investor principle. The public player invests money, but on the same conditions a private player would. As a result, municipal infrastructure providers (MIP) that wish to deploy next generation access networks should prove that a viable business case can be obtained for the deployment in the municipality. But as was already indicated, competition with the existing broadband networks can have a large impact on this viability. It should thus be checked how competition impacts both the equipment modelling, the financial viability and the social objectives.

In this case study, it is assumed that an MIP rolls out an FTTH infrastructure, and has the possibility to make the policy decision to choose between an open or closed network. An open access network allows multiple operators to use the network to provide connectivity and services, next to the public network operator (NP), while a closed network allows no intra-platform competition, meaning that only the public NP is allowed on the network. By choosing for an open access model, the municipality can attract the existing players as network providers on its newly deployed fibre infrastructure. In case of a closed network, the MIP is the only network provider on the fibre infrastructure, attracting more customers and their associated revenues. Both choices have their advantages and disadvantages. As the MIP can determine the playing field, its strategy can steer the outcome of the competitive game. We refer to Chapter 3 for a more in-depth description of these different FTTH value network configurations.

6.4.2.b Players and their available strategies

The presence of a new, future proof FTTH network offers a range of new strategic possibilities to the existing operators, which will in turn impact the profitability of the MIP (Table 6-7). With such a dynamic interaction between the different strategies, a game theoretic analysis is well suited. Next to allowing finding the prevailing competitive equilibrium, the game theoretic analysis will also allow to assess the profitability of the MIP under competition. Competition with other infrastructures will negatively impact the adoption. However, competition on top of the new fibre infrastructure, so-called intra-platform competition, could increase total uptake. Typically, this competitive effect on adoption is left out. Some studies have indicated that the adoption of fibre can reach 50% within the first five years [6.26].

If a passive FTTH infrastructure is rolled out in urban environment in Western Europe, three different infrastructures (copper, cable and fibre) are typically available to offer broadband access to consumers. However, these three infrastructures each offer different possibilities concerning access speeds. Without going into more detail on the technical aspects, it can be stated that the upgrade possibilities of the copper network towards higher speeds are more limited compared to the cable network, whereas the fibre network has almost unlimited speed upgrade possibilities, together with the option to offer symmetrical speeds [6.27]. Current copper networks could upgrade towards higher download speeds (up to 100Mbps) using advanced techniques like vectoring and shadowing. However, these download speeds are very dependent on the quality of the copper cables, and the distances between the street cabinets and the households. The deployment of an FTTH network could thus put large pressure on the market shares of the operators offering broadband through the copper network.

Table 6-7: Players and their possible strategies in a competitive fixed access network environment

Player		Strategic choices
1	Incumbent	Stay on copper infrastructure Migrate as ANP to fibre infrastructure Deploy own fibre network
2	MIP (PIP + NP)	Open access network Closed access network
3	Copper ANPs	Stay on copper infrastructure Migrate to fibre infrastructure

Taking this into account, the incumbent has various possible strategies to react to the presence of a fibre infrastructure. The first strategy is continuing to use its legacy copper network, and compete with the other operators through more aggressive pricing. Additionally, as the copper incumbent has a significant market share on the retail market, lock-in effects could assure that their market share only decreases slowly. However, in case the newly deployed fibre network is an open access network, nothing withholds the copper incumbent to formulate a fibre broadband offer. In this case, they can buy wholesale access from the

MIP, and offer broadband access to customers using these leased fibres as alternative network provider (ANP). This way, the operator can even formulate a differentiated offer, by continuing to offer broadband access through the copper network. As a third strategy, the incumbent operator can also choose to deploy its own fibre network. Here, it needs to be taken into account that when deploying its own fibre network, the operator can engage in a joint infrastructure rollout with the MIP, as was described in Chapter 5 [6.28]. The total cost of the deployment will be decreased for both the incumbent and the MIP, thereby improving their business case.

Existing ANPs do not have their own passive network infrastructure and depend on leasing offers. For these ANPs, the emergence of an open access fibre infrastructure offers them the opportunity to switch to this offer to provide retail services to consumers. This gives them the possibility to offer higher speeds to their customers. On the other hand, continuing to buy wholesale access from the incumbent’s copper network remains a strategic option. This offer will typically be cheaper than the fibre offer, and no customer migration and related equipment installation would be required.

Up to now, the municipal fibre network was assumed to be an open access network. Although this might be the preferred choice for the municipality, an open access network comes with additional cost during the deployment phase. In order to increase profitability, the MIP could decide to allow only no additional ANPs on its network. In this case, the copper incumbent and ANPs will not be able to buy wholesale access on this network.

Since the cable operator has a strong presence in Belgium, this player was also taken into account. In order not to overcomplicate the game theoretic analysis, the cable operator was modelled as a passive player in the market model from Chapter 5.

6.4.2.c Business models for competitors

To conduct the game theoretic analysis, several quantitative models are required for each strategy of all players. For the incumbent, a techno-economic model is developed for when he stays on the legacy copper network, switches to the MIP fibre network as ANP and as infrastructure owner when he rolls out his own fibre network. In the last case, he can profit from cost reductions if he engages in a joint rollout with the MIP. For the existing ANPs, a model for copper ANP and fibre ANP is built. Finally, for the MIP, there is a model for an open and closed fibre access infrastructure, covering a PIP and NP player. In the following sections, these models will be described in more detail. For the quantitative analysis, input information for the city of Ghent was used.

Fibre based models

For a description of the MIP and ANP models, we refer to Van der Wee et al. [6.29]. This model consists of an equipment dimensioning for the entire network, driven by customer uptake. This model was introduced in Chapter 2, Figure 2-7 and Figure 2-8. Additionally, the total required trenching, ducts and fibre length was calculated using GIS based models. A comparable model was built for the synergetic rollout, taking the cost savings in the rollout phase into account. This synergetic rollout occurs in case both the incumbent and MIP roll out a fibre network. Our research has indicated cost savings up to 15% for the initial trenching [6.28].

Incumbent models

The copper incumbent model is based on two different submodels, namely a wholesale model and a retail model. In the wholesale model, the costs and revenues the incumbent incurs from offering access to ANPs are calculated. However, since these regulated wholesale access prices are based on a Long Run Incremental Cost calculation, the revenues the incumbent gains from the ANPs should cover the costs.

For the retail model, the cost is based on the bitstream access prices, supplemented with a cost for service provisioning. Additionally, an extra cost to connect a new customer is included. The revenue model is based on the monthly subscription price per customer.

In case the incumbent decides to roll out its own fibre network, the used model is comparable to the MIP model.

ANP copper access model

Comparable to the incumbent copper model, the ANP copper access model is based on a simplified cost-benefit model, starting from the existing regulated access prices. Per customer, the ANP pays a monthly price to the incumbent. Again, extra costs were taken into account for service provisioning and customer connection. The revenue model simply multiplies the number of customers with the yearly income.

6.4.2.d Game theoretic analysis of inter-platform competition

The different strategies for all players were introduced above. However, not all strategic combinations are possible. For example, in case the municipal operator opts for a closed network, neither the ANPs, nor the incumbent can migrate to this fibre network. In the analysis, this was modelled by reducing the adoption of these offers to zero in these specific cases. As a result, the business case analysis of the players resulted in a minus infinity payoff. This ensures the specific strategy is not chosen in equilibrium.

To model the market shares of the different offers, the market model based on general economic parameters like price elasticity of demand and cross-price elasticity is used. Feeding the service offer prices into the model results in a market share evolution for all offers over time, which in turn drives consumer driven equipment installation. The monthly retail prices for the different offers can be found in Table 6-8. The prices for the different offers were based on the current market prices in Belgium, and the prices for fibre based broadband in Europe [6.26].

The impact of inter-platform competition on the business cases of the different players is checked, if customers are willing to pay a premium for higher speed (Table 6-9).

An example of the market division can be found in Figure 6-9. The strategic combination played by the different players in this market model is the following. The copper incumbent deployed his own fibre network, and the ANPs migrated to the municipal fibre network, which is an open access type network. Different conclusions can be drawn from this figure. First, due to the extra infrastructure in place, the market share of the existing operators (both cable operator and incumbent legacy) decreases significantly. Additionally, due to the switch off of the ANPs legacy buying copper wholesale access, this market share is decreasing gradually. Finally, three new offers attract broadband services, namely the municipal fibre offer (MIP), the ANPs fibre on top of the municipal physical infrastructure, and the incumbent offering fibre based access on its own network (Incumbent fibre). Due to the small difference in price between these last three offers, the impact on their total market share is negligible. Of course, this is mainly caused by the low price sensitivity of customers for broadband, which was set at -0.05 per euro difference [6.30]. As such, an offer that is priced €1 per month more expensive attracts 5% less market.

Table 6-8: Monthly retail prices for the different broadband offers

Offer	Monthly ARPU (€)
Incumbent copper	30
ANP copper	29
Cable	32
Incumbent fibre	55
Municipality fibre	52
ANP fibre	52

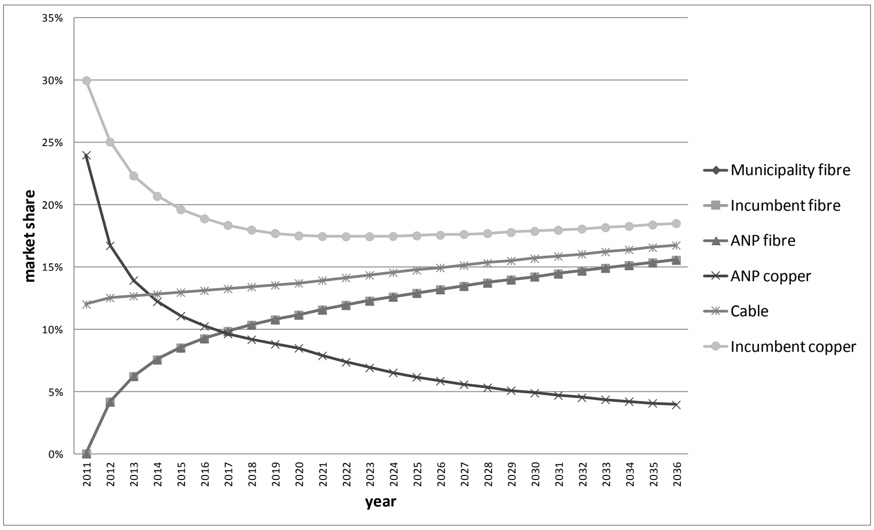


Figure 6-9: Market division on the broadband market under competition

Table 6-9: Perceived broadband quality measured in download speed

Offer	Speed (Mbps)
Incumbent copper	20
ANP copper	20
Cable	30
Incumbent fibre	60
Municipality fibre	60
ANP fibre	60

6.4.2.e Impact of competition on the business cases

The main question that rises from the market division figure is about the profitability of an FTTH deployment. The network needs to be deployed towards all households and comes with a significant investment cost. With uptake only reaching 16% after 20 years (see Figure 6-9), it is to be expected that this will not be an economical viable project. It has been shown that for a MIP, an uptake of 30% after 5 years was required to result in a close to break-even business case after 20 years [6.26]. The same holds for the FTTH roll out by the incumbent operator. Two competing fibre infrastructures would each attract about 16%

market share, which is insufficient to result in a positive business case, even with cost savings in the rollout phase taken into account.
We performed a techno-economic analysis for the case of Ghent. The graphical representation of the game can be found in Figure 6-10. The results show the NPV for each player after 25 years in million € in the form [Payoff incumbent, Payoff Public MIP, Payoff ANPs]. It is immediately clear that under the given circumstances, an FTTH rollout is unprofitable in case the municipality chooses for a closed network. Even with an open access network, it is required that all operators move towards this network to result in sufficient uptake for the MIP to have a positive business case. When looking at the rollout of two fibre infrastructures, it is clear that this is uninteresting for both infrastructure owners. While the municipality might have a strong public policy case justifying the rollout, the incumbent operator will not engage in a rollout. The high payoff for the incumbent under the two other strategies that can be observed in Figure 6-10 is driven by its current high market share on the broadband market through its copper network.

		Public MIP (PIP + NP)							
		CLOSED			OPEN				
Incumbent	STAY	4.84	-23.00	4.50	4.84	-30.00	4.50	COPPER	ANPs
		-∞	-∞	-∞	4.75	-0.91	4.86	FIBRE	
	MIGRATE	-∞	-∞	-∞	6.77	-9.90	3.82	COPPER	
		-∞	-∞	-∞	6.54	12.20	4.21	FIBRE	
	OWN	-24.00	-21.50	3.82	-24.00	-28.20	3.82	COPPER	
		-0.25	-23.40	4.50	-26.00	-4.30	4.21	FIBRE	

Figure 6-10: Results from inter-platform competition under different strategies (in million €)

When analysing the game in more detail, the following conclusions can be drawn. The first Nash equilibrium, where no player can unilaterally change his strategy to improve his payoff is [STAY – CLOSED - COPPER] (grey negative equilibrium in Figure 6-10). In case the municipality chooses for a closed network, the incumbent can only choose between two strategies, namely deploying his own network, or compete through the legacy copper network. However, the latter strategy clearly dominates the fibre deployment option. Also, in this case the ANPs can only choose to continue buying access from the incumbent. Although this is clearly negative for the business case of the municipal fibre network, it is one of the prevailing competitive equilibria.
The second Nash equilibrium is [MIGRATE – OPEN - FIBRE] (negative equilibrium in Figure 6-10). In case of an open access network, the ANPs will definitely migrate to the more profitable municipal fibre network. In order to retain his market share in the broadband market, the incumbent will also choose to migrate towards this municipal fibre network. While this second competitive

equilibrium could also result from the free competition between the different players, it is also one of the Pareto optimal strategic combinations. In these points, no player can change his strategy to improve his payoff, without hurting another player. The second Pareto optimal point is depicted in light gray.

From the techno-economic analysis based on financial objectives for the MIP, it may be clear that the municipality can only present the required positive business case when he deploys an open access network infrastructure. Even then, it is still necessary that the other players on the broadband market formulate an offer on this infrastructure to come to this positive business case. However, as the MIP is the actor engaging in the network infrastructure rollout, it has the advantage to be able to define the playing field. As the game theoretic analysis indicated, by choosing for an open access network, the physical network will attract the ANPs as well as the incumbent.

6.4.2.f Including non-financial objectives

As a municipality, and in extension any public player, typically does not invest in large infrastructure projects from a profit maximisation viewpoint, the analysis should not be limited to financial objectives. Their objectives comprise more social welfare related aspects, like broadband penetration, acceptable price levels or sufficient competition. As was indicate in Section 6.4.1, indirect revenues can be applied to measure these social welfare gains. Another approach to model these gains was introduced in Chapter 3. By clustering the different objectives in a composite broadband performance index, a ranking of several strategic situations is possible.

In order to analyse the impact of competition on these social goals, we repeat the game from section 6.4.2.d, but the utility function of the municipality is now represented by the composite broadband performance index introduced in Chapter 3. The resulting strategic form is presented in (Figure 6-11).

		Public MIP (PIP + NP)							
		CLOSED			OPEN				
Incumbent	STAY	4.84	0.69	4.50	4.84	0.69	4.50	COPPER	ANPs
		-∞	-∞	-∞	4.75	0.90	4.86	FIBRE	
	MIGRATE	-∞	-∞	-∞	6.77	0.84	3.82	COPPER	
		-∞	-∞	-∞	6.54	1.00	4.21	FIBRE	
	OWN	-24.00	0.63	3.82	-24.00	0.63	3.82	COPPER	
		-0.25	0.80	4.50	-26.00	0.80	4.21	FIBRE	

Figure 6-11: Strategic form of broadband market competition including non-financial objectives

It is clear that using a different utility function impacts the competitive outcome. Now, three Nash equilibria prevail. Two remain the same compared to the financial goal game, the third is located in the strategic combination [OWN –

CLOSED – MIGRATE]. In this case, the NGAN oriented BPI increases due to the availability of two fibre infrastructures. However, it should be noted that the Pareto optimal points are again located under the open access strategy by the municipality, with [MIGRATE – OPEN – FIBRE] again being both a Nash equilibrium and a Pareto optimal solution. As a result, the MIP can decide from the beginning to open its network, steering the competitive outcome in its socially desired solution.

6.4.2.g FTTH case conclusions

Rolling out a fibre infrastructure as municipality will happen in the existing competitive broadband market. As a result, the new fibre based offers will have to compete for market share with existing legacy copper networks and cable networks. Additionally, when multiple ANPs are allowed on top of the physical infrastructure, intra-platform competition will most likely also impact the business case of the fibre infrastructure.

By modelling a realistic market environment, the previous section indicated how market shares of different offers change under the influence of price and quality preferences by end consumers. In addition, the strategies from existing and new actors on the market will also influence the market division, which in turn influence the equipment dimensioning step in the techno-economic analysis. Using a game theoretic analysis, this section modelled the dynamic interaction between different operators and indicated the prevailing competitive equilibrium.

In the case study, two equilibria existed in this competitive environment. Either the fibre infrastructure was a closed infrastructure, forcing the existing operators to stay on the legacy networks. Additionally, in this case the business case for the fibre network (MIP+ANP) was unviable. However, the second equilibrium, where the MIP opted for an open access infrastructure, resulted in existing players migrating to this infrastructure. Now, the total fibre adoption rose from 20% to 36%, spread out over three ANPs (MIP, ANP fibre and Incumbent fibre). As a result, the business case for the infrastructure provider improved significantly. This equilibrium is a Nash equilibrium, and could be reached under competitive interaction. However, since the municipality not only focuses on profitability of the fibre network, but also on social welfare, it should be checked if the equilibrium reached using a financial utility function coincides with the equilibrium reached using a utility function capturing its social objectives.

In fact, the equilibrium where all players migrate towards the fibre network is reached with both utility function, and is also Pareto optimal, and should thus be preferred.

The municipality can define the playing field when deploying its infrastructure. By opening up the physical infrastructure, the municipality can push the other actors towards the social optimal situation. In this situation, the payoff for the newly deployed fibre infrastructure is positive, while the other operators also

have a positive business case. No player is inclined to move from this situation, as he cannot improve his own result.
This analysis indicates the importance of conducting a game theoretic analysis when investment decisions and policy decisions are considered. Here, the analysis was particularly helpful in identifying different problems in the fibre business case. First, it showed which strategic combinations resulted in a positive payoff for the MIP. This is of high importance, as regulation forbids state aid and intervening in areas where broadband infrastructures are already present. Secondly, by indicating the different Nash equilibria, one can estimate which states could be reached under competition, while Pareto optimality indicates the optimal solutions. Thirdly, it offers guidelines for the different players in how to optimise their result. Two equilibria could be reached, but only one resulted in a positive payoff for the MIP. As this decision maker will typically move first in a sequential game, controlling the playing field, the MIP can steer the equilibrium in the desired direction.

6.5 Conclusions

In this chapter, the importance of including competitive interactions in the techno-economic evaluation is described. Game theory analysis in telecom typically uses a mathematical approach. However, once realistic techno-economic problems are considered, the increasing complexity of this mathematical approach decreases the applicability for these problems. Therefore, we developed a hands-on game theoretic approach, suited for the analysis of realistic telecom investment problems. Once more detailed numerical techno-economic models are used, the hands-on approach is more suited, especially since it allows to visualise the game in the strategic form.
Applying the existing solution concepts, like the Nash equilibrium and Pareto optimality to this strategic form allows to identify the impact of competitive interaction on the decision making process. This was shown through two case studies. The first case researches the deployment of wireless broadband access networks in a municipal environment. First, a standard analysis is conducted, without taking competition into account. The conclusions derived from this standard analysis were proven wrong when competition was added to the analysis. Other strategies are followed, and cooperation through a partnership with a private player was the most designated strategy. In addition, social objectives were monetised with the indirect revenues concept.
In the second case, social objectives play a major role. The deployment of a fibre access infrastructure in the existing fixed broadband market is studied. When a municipality rolls out the network, both financial and social objectives are measured. Financial objectives are important since regulation prohibits state aid. The public investor must present a viable business case. However, social

objectives are the main reason for investing in such broadband infrastructures, and were measured with the broadband performance index developed in Chapter 3. When the equilibria are identified with both objectives taken into account, the municipality identifies the open network as the most designated, as this optimises both financial viability and the social goals.

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7 Flexibility and Competition in Access Network Rollout

"Risk comes from not knowing what you're doing", *Warren Buffett*

In this dissertation, both flexibility and competitive interactions and their impact on the techno-economic decision process were assessed. Flexibility in the upgrade path towards higher speeds in the fixed access network or the impact of market share on the equipment dimensioning are just two examples. However, up to now, these aspects were investigated separately. The final question remaining is: How do these concepts interact and influence the techno-economic decision making process? How is the access network flexibly upgraded towards higher bandwidth, taking into account competitive interaction with other infrastructures.

This is a very important issue, especially since the concepts handed throughout this book have sometimes conflicting outcomes. For example, under uncertainty and flexibility, the real option theory discussed in Chapter 4 will always push towards waiting as long as possible. Waiting decreases the uncertainty, reflecting in a better assessment and payoff. On the other hand, one of the concepts of game theory is the first mover advantage. Under competition, it is interesting to move first to gain a competitive advantage, resulting in a higher utility. Waiting with upgrading the access network towards higher speeds will prove valuable under option theory, but when competitors make this upgrade before you, you might lose market share. Here, using a different theory will clearly result in a diverging decision. The main reason for this diverging result is that both frameworks model a different aspect of the techno-economic decision. Real options focus on modelling the impact of stochastic uncertainty on the own business case, while game theory aims at incorporating strategic interactions on the case.

In this chapter, we will introduce the foundations of an integrated flexibility-competition framework. By indicating the limitations of this existing framework, we will be uncovering future work opportunities in the field of extended techno-economic evaluation.

7.1 Is it a strategy or an option?

One of the questions arising when looking for an integrated options and games framework is what the difference between both approaches is. So far, standard game theory has not dealt with stochastic dynamics. By their very nature, static games do not involve such a problem, while dynamic games are defined in a deterministic environment. On the other hand, real option analysis makes abstraction of the effect of strategic interaction while taking stochastic uncertainty into account. As both approaches tackle a different problem, decision makers can benefit from explicitly incorporating flexibility and commitment together. Real options identify flexibility options in the future course of the project, while game theory is built around the different strategies. However, the difference between an option and a strategy is not that clear. When is an action classified as an option, when as a strategy? Is the migration towards a Fibre to the Home (FTTH) network lifting an option, or a strategy to attract more customers? The answer to this question can offer an indication to which framework should be used to analyse the case. However, the answer is not straightforward and very case dependent. Some guidelines can be handed to identify the designated approach, as both approaches model different aspects.

When the decision is likely to impact the competitive interaction, it is a strategy, and game theory should be used. On the other hand, if there is no such or only limited interaction and the decision does not need to be taken today, it should be handled as an option.

For example, the rollout of a new access network infrastructure as described in the previous chapter has a clear impact on the market. The new infrastructure installed will churn on the market share of the existing operators, and the competitive impact is the major aspect in the case. On the other hand, when the operator already has an infrastructure, and if a gradual upgrade of the network is not expected to influence the market that much, the possible different follow-up investments are worth investigating through a real option analysis. This especially holds when the decision can be postponed into the future, linking it back to the timing condition for a real option analysis.

However, the difference is not always that clear, and dependent on the gut feeling of the decision maker. Or the problem is a combination of two aspects. In case a mobile network operator acquires a licence, he has to take into account both aspects when making the techno-economic analysis. There exists uncertainty surrounding customer uptake and technological performance, in combination with strategic interaction with other operators. An integrated framework can offer more insight in the interaction between options and games. In the following sections, we will indicate two approaches combining options and games.

7.2 Option games – integrating option and game theory

Option games have been introduced a few years ago as a framework for an integrated real option-game theory approach [7.1], [7.2], [7.3], [7.4]. This framework can provide valuable insight in problems like optimal investment timing and the trade-off between flexibility and commitment. In practice, these problems are analogue, as investment timing is closely linked with commitment.

7.2.1 Option games background

As the name states, option games combine the concepts of real options, based on uncertain future evolutions, and game theory, which relies on strategic interaction. As such, it is a hybrid model, overlaying the traditional payoff matrix with real option binomial trees. The binomial tree is used to represent the uncertain evolution of the project value, while two-by-two matrices are modelled at the end nodes of this tree to capture the competitive interactions between the two players. As the option games concept is more difficult to grasp from a theoretical description, we indicate how they work through an illustrative example case.

Consider a duopoly with two firms, each having an option to invest. Linking back to the case studies described in the previous chapters, these two firms can be the DSL incumbent and the cable operator, each having the option to invest in an FTTH network. Both firms share the option to invest, and for simplicity, it is considered that the option expires within two years. This expiration can for example be linked with the expiration of the right of way of the operator. However, while such a precondition might not typically exist and is artificially introduced in this case on the fixed broadband access market, the expiration of the option is more frequent in the mobile market. The example case study in Chapter 6 introduced competition between wireless operators. Here, we consider

two operators operating their network in the licensed spectrum. Operators can obtain a wireless licence, under the precondition that they start with the rollout of a network operating this licence within the next two years. However, the evolution of the monthly retail prices is uncertain. It may be clear that examples of investment decisions where option games can prove valuable do exist on the telecom market. We will name the two firms in our case Champion and Challenger.
On the mobile broadband market, the uncertainty identified by both firms is the future price evolution, or thus the average revenue per user (ARPU) the company can gain. The binomial tree in Figure 7-1 depicts this expected price evolution. The price is expected to go up or down with a multiple of 10%. However, the probability of an up or down move is not equal. The probability of the price going up is 40%, and there is a 60% chance of prices going down. After two years, we expect the price level to stabilise (Figure 7-2). The investment project considered has an expected lifetime of 10 years. Again, this can be closely linked to the lifetime of the wireless licence. Both firms thus face the same question: To Invest or Not to Invest in the deployment of a wireless network?

		726	726
	660		
600		600	600
	545		
		496	496
Y0	Y1	Y2	Y3

Figure 7-1: Expected price evolution

		16%	16%
	40%		
100%		48%	48%
	60%		
		36%	36%
Y0	Y1	Y2	Y3

Figure 7-2: Probability of price evolution

Consider the case from the viewpoint of Champion. Champion has plans to invest in a new nationwide mobile network, and thus faces two main uncertainties. The first is the future price evolution, the second is if Challenger will enter the market with a similar network. We assume that in the region considered, the mobile market is saturated, with one million subscribers. To install its new network, Champion requires an initial investment outlay of €500 million in the year it decides to invest. Additionally, a variable cost of €480 per customer is expected. The project of Challenger is quite similar. For this project, the initial investment outlay is only €350 million, but it faces higher variable costs of €520. These differences can be driven by different factors. The initial investment can be lower due to government stimulus to increase competition on the mobile market. Easy site access for new entrants, or regulated access to the sites of Champion or just two possibilities. The higher variable cost can be driven by the need for higher customer acquisition costs, or the absence of synergies with other products on the market.

When the investment decision is considered, different scenarios exist (Figure 7-3). Indeed, both firms have different possibilities as they can invest now, wait and invest within two years, or even completely abandon the project and let the option expire. In case a player decided to wait, they can still decide to invest at maturity, after two years. However, this results in a cost of waiting, namely lost revenues for the first two time periods. As such, four distinct scenarios can be distinguished at start date. In the first scenario, both firms invest today. In scenario two and three, only one firm invests now, while the other waits and can still decide to invest at maturity. In scenario four, both actors wait and postpone the decision to invest for two years. We will go into detail on all scenarios.

<table>
<tr><td colspan="3" rowspan="4"></td><td colspan="3">Champion</td></tr>
<tr><td colspan="3">Y0</td></tr>
<tr><td>Invest</td><td colspan="2">Wait</td></tr>
<tr><td colspan="3">Y2</td></tr>
<tr><td rowspan="4">Challenger</td><td>Y0</td><td>Y2</td><td>/</td><td>INVEST</td><td>ABANDON</td></tr>
<tr><td>INVEST</td><td>/</td><td>Scenario 1</td><td colspan="2">Scenario 3</td></tr>
<tr><td rowspan="2">WAIT</td><td>INVEST</td><td rowspan="2">Scenario 2</td><td colspan="2" rowspan="2">Scenario 4</td></tr>
<tr><td>ABANDON</td></tr>
</table>

Figure 7-3: Investment scenarios in mobile network rollout

7.2.1.a Scenario 1: Both players invest today

When both firms decide to enter the market in Y0, they will both face their initial investment outlay during the start year. Starting from Y1, their investment will start generating positive cash flows. However, as both are present on the market, no player will serve the entire market. For simplicity reasons, we assume that each player captures 50% of the market if both are present. In reality, a more advanced market modelling should be used, e.g. the market response model from Chapter 5. Per customer, the company gains the ARPU at the specific node, minus the variable costs. In case of a mobile network, this can be energy consumption to serve connections, operational processes like billing, etc. For example, in the upper node at Y3 in Figure 7-1, Champion will gain €246, while Challenger only gets €206 per customer. The same rationale can be followed for each node. As a result, Champion gains €123 million in Y3 if this node is reached. However, remember that the project had a lifetime of 10 years. In Y4 to Y10, the same payoff will be gained. As such, these payoffs should be added to the calculation. This is performed through the terminal value (TV) concept. The payoffs are discounted with the risk-free interest rate of 5% and summed up. The resulting payoff tree for Champion and Challenger can be found in Figure 7-4 and Figure 7-5, with the TV included in the payoff of the nodes of Y3.

To calculate the final payoff for both firms, the annual cash flows must be weighted with the probabilities from Figure 7-2 and discounted with the discount rate. When adding up all numbers, we get the final expected payoff in Y0 for both firms when they invest today.

		123,000,000	834,723,928
	90,000,000		
-500,000,000		60,000,000	407,182,404
	32,727,273		
		7,933,884	53,842,301
Y0	Y1	Y2	Y3

Figure 7-4: Cash flow evolution prediction for Champion if both invest

		103,000,000	698,996,460
	70,000,000		
-350,000,000		40,000,000	271,454,936
	12,727,273		
		-12,066,116	-81,885,167
Y0	Y1	Y2	Y3

Figure 7-5: Cash flow evolution prediction for Challenger if both invest

When this analysis is conducted, a final payoff of €-99.5 million for Champion and €-104 million for Challenger is obtained. In case both firms invest today, both end up losing money.

7.2.1.b Scenario 2: Champion invest and Challenger waits

In the second scenario, the case when only Champion invests is analysed. As Champion is the only investor in Y0, it is the sole player active on the market during the first two years. In the second year, Challenger decides if he invests, based on the node reached at this year. As such, it can be expected that Challenger will only invest if the price evolved favourably.

In the first step, we start by calculating the expected payoff for Challenger in the end nodes. In Y2, Challenger makes the initial investment outlay of €350 million. From Y3 on, the company claims 50% of the market, with an ARPU depending on the price evolution from Figure 7-1. The resulting cash flows are depicted in Figure 7-6. Only in case the upper price node is reached will Challenger gain a positive payoff for its project (€286 million). In the two other nodes, the project is not economically interesting for Challenger, and it will not invest. As such, it's payoff in those nodes is €0. Combining these payoffs with the probabilities from Figure 7-2 results in an expected payoff for Challenger of €46 million.

		-350,000,000	698,996,460
	0		
0		-350,000,000	271,454,936
	0		
		-350,000,000	-81,885,167
Y0	Y1	Y2	Y3

Figure 7-6: Expected cash flows of Challenger when investing in Y2

Having in mind that Challenger will only invest in Y2 if the upper price node is reached, Champion can make its investment analysis for its investment today. As it is the sole player in Y1 and Y2, and from Y3 to Y10 in the two lower price nodes, it attains 100% market share in these scenarios. Only in the upper node, it has 50% market share, as Challenger decides to invest if that node is reached. The market shares of Champion can be found in Figure 7-7**.**

		100%	50%
	100%		
100%		100%	100%
	100%		
		100%	100%
Y0	Y1	Y2	Y3

Figure 7-7: Market share evolution of Champion in scenario 2

Obviously, the decision of Challenger not to invest has a large impact on the investment viability of Champion. This is clearly reflected in the cash flows estimates (Figure 7-8). Weighing these cash flows with the price evolution probabilities results in an expected payoff for Champion of €186 million. In this scenario, Champion is thus better off to invest today, in contrast with the previous scenario.

		246,000,000	834,723,928
	180,000,000		
-500,000,000		120,000,000	814,364,808
	65,454,545		
		15,867,769	107,684,603
Y0	Y1	Y2	Y3

Figure 7-8: Expected cash flows for Champion in scenario 2

7.2.1.c Scenario 3: Challenger invests, Champion waits.

The analysis of this scenario is comparable to the description in the previous paragraph. Now, it is first assessed in which price nodes Champion will decide to invest in Y2. Like Challenger in the previous scenario, Champion only reaches a positive payoff under high price, resulting in an expected payoff of €42.8 million.

Next, the impact of Champion's decision on the case for Challenger is assessed. The market share evolution for Challenger is equal to the one of Champion in the previous section (Figure 7-7). The expected payoff for Challenger is €46 million.

7.2.1.d Scenario 4: Both firms wait

This fourth scenario, where both firms postpone their investment decision, is the most interesting one from an analysis point of view. For each price node, it needs to be assessed what decision the firms will make: investing or abandoning the project. Four subscenarios exist in the price nodes. Either both companies invest,

		16%
	40%	
100%		48%
	60%	
		36%
Y0	Y1	Y2

Champion

Challenger

	INVEST		ABANDON	
INVEST	**301**	**281**	935	0
ABANDON	0	1,038	0	0

	INVEST		ABANDON	
INVEST	-83	-101	**152**	**0**
ABANDON	**0**	**250**	0	0

	INVEST		ABANDON	
INVEST	-407	-427	-482	0
ABANDON	0	-379	**0**	**0**

Expected payoff in Y0 (€ million)	
Equilibrium outcome	
Champion	281
Challenger	301
Mixed outcome	
Champion	125
Challenger	76
Equilibrium outcome	
Champion	0
Challenger	0

Figure 7-9: Expected payoffs for all nodes in scenario 4

no-one invests or only one company invests, while the other abandons the project. We will elaborate the upper price node for these four subscenarios.
In the first subscenario, both firms invest in Y2. The investment analysis can be conducted in a similar way as in section 7.2.1.a. This results in an expected payoff of €281 million for Champion and €301 million for Challenger. In the three other subscenarios, when a player abandons, its payoff is €0. If the other firm does invest, its payoff is calculated as above. As a result, for the upper price node, a strategic form is obtained (Figure 7-9). Using the Nash equilibrium concept, the equilibrium is reached when both firms invest. In the upper node, the expected payoff for the firms is thus €281 million for Champion and €301 million for Challenger. For the two other price nodes, a comparable analysis is made. Again, a strategic form is obtained at these nodes, where the Nash equilibria obtained represent the expected payoff for each player. A special case occurs in the middle price node. Here, two equilibria are obtained. There exist theories on how to determine the favoured equilibrium, but for the purpose of simplicity, we assume two roughly symmetrical firms, resulting in an equal chance that either equilibrium will prevail. This results in a payoff of €125 million for Champion (= 50% * 250 + 50% * 0).
To obtain the expected payoff for each player in the fourth scenario, where both players wait to decide until Y2, the outcomes from Figure 7-9 are weighed with the probabilities, resulting in a result of €105 million for Champion and €84 million for Challenger.

7.2.1.e Bringing the results together

Recall that four scenarios were identified in the investment case. Both players had two strategies, investing or waiting. As such, the results for the four scenarios can again be combined in a strategic form (Figure 7-10). When solving this game for the Nash equilibrium, we obtain the strategies each player will play at Y0. The equilibrium is highlighted. According to the solution, the Champion should move now and pre-empt the Challenger, while the Challenger is better off postponing its investment. By waiting, Challenger can gain extra insight in the price evolution and only enter when this evolution is favourable.

		Champion			
		INVEST		WAIT	
Challenger	INVEST	-104	-100	46	43
	WAIT	**46**	**186**	84	105

Figure 7-10: Time-zero strategic form for the investment decision

7.2.2 Advantages and drawbacks of option games

The application of option games provides very valuable insight, as it manages to combine real option insight with the tools from game theory. When a traditional NPV analysis would have been conducted in the example above, assuming that the company invests and the other company never enters the market, the calculation results a positive payoff for both players (if both made the analysis independently). Performing this analysis would suggest that both players invest now. As is clear from the option games analysis, this strategic combination would lead to high losses for both players in reality. When comparing option games to the traditional real options, as real option analysis typically attributes value to waiting, performing this analysis would push both players towards postponing their investment, which again is contradicted by the option games analysis performed above. As the option games framework takes the impact of competition into account, and the probabilistic evolution of an uncertain parameter, it manages to make the trade-off between commitment and flexibility for both players.

The example above is based on option games in discrete time. Extensions have been proposed to allow for an application of option games in continuous time, but these result in an increase of complexity of the analysis [7.4]. In addition, as these continuous time models have a broad mathematical basis, the readability of the models decreases significantly.

In addition, as a binomial tree is used to model the uncertainty aspect of the option game, similar drawbacks as those introduced in Chapter 4 for traditional real options emerge. In reality, actors are confronted with continuous uncertainty of multiple parameters. The combination of these drawbacks, high complexity for realistic cases and the limitations of the binomial tree method make option games in our opinion less suited for everyday application in techno-economic problems. As such, we propose another extension to options and game theory, which we believe can offer new insights and increase the application of a combined option-game thinking in techno-economics.

7.3 Bringing uncertainty into game theory through sensitivity games

The approach we propose to combine options and game theory thinking builds further on the hands-on approach introduced in Chapter 6. By extending the game theory framework with an integration of the three conditions for a real option analysis (see Chapter 4), an integrated framework can be built.
This extension has already been developed for the uncertainty condition, and will be discussed in the next section. The two other conditions, flexibility and timing, will be discussed qualitatively and form the basis of future work.

7.3.1 Incorporating uncertainty

In Chapter 4, uncertainty was identified as the first condition to allow for a real option analysis. Thus, incorporating uncertainty in the underlying techno-economic models of the players in the game theoretic analysis is the first step towards an integrated flexibility-competition framework.
Capturing uncertainty is a straightforward exercise using the hands-on approach described in the previous chapter. As the model is built around the strategic form of the game, with the underlying techno-economic models integrated in the calculation engine, adding uncertainty within these models allows for an assessment of the impact of this uncertainty on the analysis. In a sensitivity games approach, by repeatedly calculating the game with the changed underlying techno-economic models and solving for the Nash equilibrium and Pareto optimal points offers an indication of the impact of uncertainty on the game. Sensitivity games have already been applied previously to an FTTH access network rollout case [7.5].

7.3.2 Uncertainty and flexibility in fibre access rollout

In the previous chapter, we discussed the viability of a fibre access network rollout. The rollout of a such a network in an urban environment was assessed to be economically viable, even under competitive interaction. More specifically, competition even steered the outcome towards the social optimal solution. The game theoretic analysis indicated that this is only the case under the assumption that the physical infrastructure provider opens the infrastructure for other operators. In this case, the existing operators, the DSL incumbent and the alternative network providers (ANP) on this DSL network will migrate to this fibre infrastructure.
However, opening the infrastructure for ANPs is not a zero-cost operation. We already indicated that providing an open access network requires additional equipment. While the decision to open the network may be partially driven by regulatory and policy decisions, the impact of this choice on the business case

cannot be neglected. Indeed, offering an open access network comes with an upfront cost and an additional provisioning cost when a customer connects to the fibre network. Linking this back to the real option concepts, the infrastructure provider buys the option to offer open access to the end users during the deployment phase. Later on, he can offer open access to other players and lift this option.

The effect of this option can already be observed in the game theoretic analysis in Chapter 6. We repeat the strategic form here (Figure 7-11). The strategic combination [STAY – CLOSED – COPPER] indicates a situation where the public MIP did not buy the option for an open access network. Comparing this situation with [STAY – OPEN – COPPER], all underlying assumptions are the same, apart from the public MIP buying the option to offer open access. As a result, its business case payoff decreases significantly, since the MIP bought the option, but no other player migrates to its fibre network. Since the option is not lifted, due to strategic choices by the other market players, no extra revenues are gained. The same result can be seen between the combinations [OWN – CLOSED – COPPER] and [OWN – OPEN – COPPER]. Again, the option is not exercised, resulting in a significant deterioration of the payoff for the public MIP.

		Public MIP (PIP + NP)							
		CLOSED			OPEN				
Incumbent	STAY	4.84	-23.00	4.50	4.84	-30.00	4.50	COPPER	ANPs
		-∞	-∞	-∞	4.75	-0.91	4.86	FIBRE	
	MIGRATE	-∞	-∞	-∞	6.77	-9.90	3.82	COPPER	
		-∞	-∞	-∞	6.54	12.20	4.21	FIBRE	
	OWN	-24.00	-21.50	3.82	-24.00	-28.20	3.82	COPPER	
		-0.25	-23.40	4.50	-26.00	-4.30	4.21	FIBRE	

Figure 7-11: Strategic form of broadband market competition

However, in cases when the option is lifted, a significant improvement of the public MIP business case can be observed. In the base scenario, shown in Figure 7-11, exercising the option, by offering the open access network, clearly pushed the other players towards a migration to the fibre network. A twofold reason for this behaviour can be given. First, when the option is not exercised, the public MIP reduces the possible strategies for the other players. Neither the Telco's nor the ANPs can migrate to a closed network. Secondly, if the option is exercised, the uptake of the fibre network is increased, thereby increasing the viability of the MIP business case. This can be seen by comparing the COPPER and FIBRE strategies in case of an open network.

It can thus be concluded that in this case, the public MIP profits from buying the open access option in the planning phase. By effectively opening its network and exercising the option, the existing players migrate to its network and improve the viability of the public MIP's business case.

7.3.2.a Cost implications of providing open access

However, an important remark must be made. Up to now, the impact of transaction costs for the public MIP was not taken into account. Transaction costs were already introduced in Section 5.2. These have been estimated between 10 and 20% of the yearly revenue for the MIP, and can thus significantly impact the viability of the business case. These transaction costs represent the exercise price of the option.

In case no transaction costs are present, the results from Chapter 6 hold. In order to check for the impact of transaction cost, an extreme case was modelled, with a transaction cost of 30% for the public MIP. For every customer connecting to the physical infrastructure via the Telco fibre or ANP fibre, the monthly revenue of the public MIP is reduced with 30%. The results of this analysis are shown in Figure 7-12. First, it is important that the transaction costs only have an impact on the public MIP. The payoff for the other players remains the same. Indeed, since these costs are limited to the public MIP, and are not reflected in the retail prices, the market division does not change.

Secondly, the prevailing equilibriums do not change under transaction cost uncertainty. In this sequential game, where the public MIP can make the first choice (open or closed network), it remains in its best interest to exercise the option of the open access network. Although his viability decreases significantly in [MIGRATE – OPEN – FIBRE] due to the transaction costs, it remains the most profitable strategic combination from its point of view.

		Public MIP (PIP + NP)							
		CLOSED			OPEN				
Incumbent	STAY	4.84	-23.00	4.50	4.84	-30.00	4.50	COPPER	ANPs
		-∞	-∞	-∞	4.75	-22.80	4.86	FIBRE	
	MIGRATE	-∞	-∞	-∞	6.77	-28.80	3.82	COPPER	
		-∞	-∞	-∞	6.54	-14.40	4.21	FIBRE	
	OWN	-24.00	-21.50	3.82	-24.00	-28.20	3.82	COPPER	
		-0.25	-23.40	4.50	-26.00	-22.00	4.21	FIBRE	

Figure 7-12: Impact of transaction costs on infrastructure competition in the broadband market

In Figure 7-11 and Figure 7-12, the two extreme cases for the game theoretic analysis are shown, but there is a large degree of uncertainty on the height of transaction costs for the public MIP.

This is where the sensitivity game analysis can offer important insights. A scanning was performed between the two transaction cost extremes for the payoff of the public MIP in the strategic combination [MIGRATE – OPEN –

FIBRE] (Figure 7-13). It is clear that the transaction costs have a significant impact on the viability of the public MIP business case. Once these costs rise to about 13.5% of the monthly revenue per customer, the public MIP business case turns negative (Figure 7-14). Again, the transaction costs have no impact on the prevailing Nash equilibrium and Pareto optimum. Due to the modelling of the transaction costs, the relation between the public MIP payoff and the transaction costs is linear.

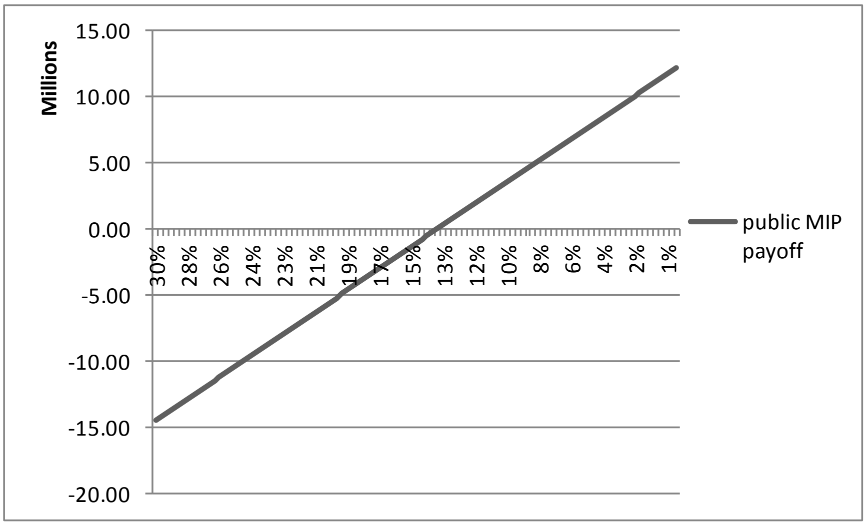

Figure 7-13: Impact of transaction costs on the public MIP business case

		Public MIP (PIP + NP)							
		CLOSED			OPEN				
Incumbent	STAY	4.84	-23.00	4.50	4.84	-30.00	4.50	COPPER	ANPs
		-∞	-∞	-∞	4.75	-10.70	4.86	FIBRE	
	MIGRATE	-∞	-∞	-∞	6.77	-18.40	3.82	COPPER	
		-∞	-∞	-∞	6.54	0.20	4.21	FIBRE	
	OWN	-24.00	-21.50	3.82	-24.00	-28.20	3.82	COPPER	
		-0.25	-23.40	4.50	-26.00	-12.20	4.21	FIBRE	

Figure 7-14: Infrastructure competition with 13.5% transaction cost

7.3.3 Impact of uncertainty on competition

Uncertainty about future evolutions of different parameters has a major impact on the techno-economic analysis. When this uncertainty is present in a competitive environment, sensitivity games offer an easy-to-use approach to incorporate the impact of both factors on the analysis. Sensitivity games consist of a repeatedly calculation of the strategic form and equilibrium selection with different parameters. For each calculation, the underlying techno-economic model, together with the required equipment dimensioning is performed. Through this approach, two important aspects of uncertainty impact can be identified. The first aspect covers the impact of uncertainty on equilibrium selection. In the case presented above, the preferred equilibrium was robust for uncertainty on transaction cost. However, this will not always be the case. Uncertainty on e.g. customer take-up can push the equilibrium towards a wait-and-see strategy. This behaviour was observed in [7.5], where uncertainty impacted the equilibrium.

The case study in [7.5] focused on the rollout of an FTTH network in a municipal environment. As take rate, and thus competition between operators impacts the viability of the business case, the strategic interactions between an FTTH network operator and a cable operator was investigated. The rollout of the new FTTH network pushes the existing operator towards a more aggressive strategy concerning network upgrades. The FTTH operator initially focuses on smaller areas and industrial areas. Applying a sensitivity games approach, it was indicated that there exists a variation in the prevailing equilibrium under uncertainty, although the variation is low.

The second important insight sensitivity games offer is the impact of uncertainty on the individual payoffs of the different competitors. The infrastructure competition case in a municipal environment offers a clear indication of this impact. Due to uncertainty on certain cost aspects, the payoff in the different strategic combinations is impacted differently. This allows for a risk analysis of the techno-economic case under uncertainty.

7.4 Incorporating timing and flexibility in game theory

Flexibility and timing are the two other conditions in order to be able to conduct a real option analysis. The hands-on game theory approach from Chapter 6 analyses the competitive interaction at a given point in time. In order to incorporate timing and flexibility, the approach should be extended towards a time-dependent game theory approach. We describe this extension here.

7.4.1 Continuous time games

Continuous time games describe a game theory analysis of a certain techno-economic problem over a certain time period. Up to now, the strategic form of the game only represents the utility reached at a predefined point in time. For example, in the option games section above, the analysis was performed based on the payoff gained after ten years. In the sensitivity games example, the result at year 25 was used as basis for equilibrium selection.

However, in techno-economic problems, these payoffs represent an evolving utility over time. At each point in time after choosing a certain strategy, a certain payoff will be gained. At the start of the project, this payoff is typically negative, but it increases continuously as more customers start buying the product or service. Each payoff in fact represents a time function of the utility function used.

When determining the equilibrium in traditional game theory, the selected equilibrium is thus dependent on the time horizon selected. In continuous time games, an equilibrium should be selected independently of the chosen time horizon. A first extension to traditional game theory towards continuous time games should thus focus on the evaluation of the competitive interaction on different points in time, and how the prevailing equilibrium changes over time.

We will indicate this with a simple example. Imagine two operators willing to invest in a new broadband access network. Basically, both operators have two strategies, namely investing or not investing. The payoff function of each player when investing is time-dependent and shown in eq. 7.1 and 7.2.

Player 1: $$U_1 = t - 3 \tag{7.1}$$

Player 2: $$U_2 = 3t - 5 \tag{7.2}$$

At t = 0, the resulting strategic form is the following (Figure 7-15). As only the initial investment outlay has been paid and no incoming cash flows are gained. The abandon strategy is dominant for both players, resulting in an NE at [ABANDON , ABANDON]. In the hypothetical case the game theoretic analysis would be performed with a very short time horizon, both players would refrain from investing.

		Player 2			
		INVEST		ABANDON	
Player 1	INVEST	-3	-5	-3	0
	ABANDON	0	-5	**0**	**0**

Figure 7-15: Strategic form of toy example at t = 0

However, with an increasing time horizon, the prevailing equilibrium shifts. At t = 2, the resulting strategic form looks like Figure 7-16. Apparently, for a somewhat longer time horizon, player 2 is better off investing in the project, while player 1 still decides that the project is not economically viable.

		Player 2			
		INVEST		ABANDON	
Player 1	INVEST	-1	1	-1	0
	ABANDON	**0**	**1**	0	0

Figure 7-16: Strategic form of toy example at t = 2

If t increases even more, the equilibrium will shift towards [INVEST , INVEST], as depicted in Figure 7-17 for t = 4. This simple toy example already indicates the time dependency of game theory, and why a continuous time game approach would offer valuable insight in the dynamics of the decision making process.
However, the analysis becomes even more interesting when flexibility is added to the process.

		Player 2			
		INVEST		ABANDON	
Player 1	INVEST	**1**	**7**	1	0
	ABANDON	0	7	0	0

Figure 7-17: Strategic form of toy example at t = 4

7.4.2 Options in sensitivity games

With timing and uncertainty incorporated, players still choose a strategy at t = 0 and stick with it. Incorporating the impact of the third condition for a real option analysis, flexibility, is thus required to come to a hands-on option-games approach. At each point in time, the game theoretic analysis should thus allow to shift strategy towards the one with the highest additional utility over the following time period, taking into account the switching costs. Extending the existing game theory toolset with this approach is certainly an interesting topic for future work.

7.5 Conclusions

The concepts for extended techno-economic analysis introduced in this dissertation, real options and game theory, can sometimes have a conflicting impact on the outcome, as they model different aspects. Real options model stochastic uncertainty and its impact on the techno-economic decision, while game theory incorporates strategic interaction with other players. An integrated approach combining option and games thinking can resolve this conflict.
Two approaches were identified to combine flexibility and competition in the techno-economic analysis. While option games have been around longer and

have a broader theoretical background, this approach seems less fit to analyse more advanced numerical techno-economic cases. However, they can offer a first indication of the impact of both aspects.

To assess such detailed numerical techno-economic cases, the sensitivity games approach is more suited, especially since the hands-on approach can simply integrate uncertainty. Extending the sensitivity games approach towards a complete option integration, by incorporating both the timing and flexibility condition, is an important topic of future work, to build a hands-on approach for extended techno-economic analysis under uncertainty and competition.

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8
Conclusions and Recommendations

"A conclusion is the place where you got tired thinking", Martin Henry Fischer

Today telecommunication companies act in an increasingly uncertain and competitive environment. The introduction of new services, the shortening life cycle of telecom solutions, advances in access network technology, changing customer taste, increasing bandwidth demand and concentrated markets are all aspects of this environment. Within this environment, decision makers constantly need to adapt in order to stay in the game.

Extended techno-economic analysis aims at supporting the decision making process for these companies. As a result, flexibility to handle uncertain future evolutions and competitive or cooperative interaction have a major impact on this analysis.

The very basis of techno-economic analysis is a clear view on the underlying technological requirements of the case under study. The deployment of a fixed access network requires a detailed model of the required equipment, fibre, duct and trench length. Introducing a mobile network requires insight in base station equipment, impact of cell load and line of sight on the cell coverage. Uncertainty on user uptake, influenced by competitive interaction or other factors and uncertainty on the performance of the new equipment already have their impact here.

Next, the assessment of the viability of the new service or product needs to be made. However, before the viability can be assessed, it should be made clear what the objectives of the project are. Not all actors have financial motives, and non-financial goals should be taken into account if these are the main objective of the actor. For example, the impact of new regulation does not aim at monetary value creation, but rather at increasing social welfare. With the objectives clearly delineated, the quantitative techno-economic analysis can be conducted. Here again, the impact of uncertainty and competition cannot be neglected. User uptake drives both revenues and variable costs, and this uptake is uncertain by nature. Competitors try to optimally behave in light of your strategy.

This dissertation explores the additions to the standard techno-economic analysis to capture flexibility and competitive interaction, taking into account both financial and non-financial objectives. First, the standard approach to techno-economic analysis is introduced, together with a clear indication of the limitations of this approach. In the subsequent chapters, more detail on these limitations was provided, together with an approach to overcome the drawbacks. We introduced value network analysis as methodology to identify the required components for the value proposition, which offers at the same time a clear view on the possible competition and cooperation strategies. In addition, we discussed a composite indicator to capture policy goals related to the broadband market. Next, the impact of uncertainty and flexibility on the techno-economic analysis was tackled. We introduced real options as an approach capable of quantifying managerial flexibility. To incorporate interactions between different actors, we developed a market response model based on elasticity parameters, churn and price, together with an overview of possible cooperation strategies and their possible synergies. Making the best decision under competition was performed using a hands-on game theoretic approach. In the final chapter, we propose an integrated framework for capturing both competition and flexibility. Throughout the entire dissertation, the different frameworks introduced are applied to a case study, the rollout of a broadband access network in a city environment. We looked at both Greenfield and Brownfield rollout of a fixed fibre access network, thereby referring to the underlying technical models.

In the remainder of this chapter, we summarise the most important work and the main results obtained during our research. We also give a general conclusion and offer some directions for future work.

Measuring non-financial objectives

The telecom market has been liberalised two decades ago. The main objective was to increase competition on the market. On the broadband access market, regulation aimed at offering a connection to everyone. Today, focus has shifted from having broadband to what is broadband? The European Commission, through its Digital Agenda, hopes to achieve by 2020 that everyone has access to a 30Mbps connection, with 50% of customers having a connection of minimum 100Mbps. When policy makers or regulators make decisions, they clearly not aim at maximising their own monetary payoff, but at achieving non-financial goals. The Digital Agenda aims at high speeds, large coverage, high uptake of services, etc.

In order to capture these policy goals and assess different regulatory strategies on their impact on these objectives, we developed a composite next generation access network oriented broadband performance index. We applied this index in a variety of cases, to rank different countries on broadband performance, but also to assess different policy strategies on their performance.

Keeping the different factors of such an index up to date is very important. What is defined as broadband in the current edition of the index may no longer catalogue as broadband within a few years, so the definitions should be constantly adapted to reflect the current state of technology and of the market.

Applying real options in practice

Real options have been developed almost half a decade ago to capture the value of flexibility in economic analysis. But up to now, they are only slowly getting accepted within the telecom world. However, real options offer valuable insight, not only to the financial department, but also to network planners. The 7S framework offers insight in possible flexibilities, and different calculation methods can quantify the value of these flexibilities. During our research, we have classified techno-economic problems and the flexibility technology offers into the real option framework. We have applied real options to different techno-economic cases, showing their applicability to realistic problems. We applied them to sensor network rollout, core network migration and fibre access network installation. Resulting from these different case studies, we developed a tutorial on how to apply real options to telecom investment problems.

Modelling customer uptake under competition

The impact of competitive interaction on techno-economic cases cannot be overestimated. Each new network, product or service is introduced in an existing market, and will thus notice competition from the existing market players. As uptake is an important driver for the viability of techno-economic cases, we developed a market response model to estimate market share evolution under competition. With this model, based on general accepted parameters like elasticity and churn, we were able to adequately model the observed uptake of fibre access in the Netherlands. We also applied this model in other cases. In the case of a fibre access network rollout, we showed how competition clearly reduces expected uptake.

A hands-on game theory framework

A second aspect of competitive impact is answering the following question: What is my best strategy in light of possible competitive strategies? Game theory can be used to model this question. Much like real options, game theory has been around for a long time, but it has not found its way into mainstream techno-economic modelling. To increase the uptake of game theory in techno-economic decision making, we developed a hands-on game theoretic approach which can be applied on detailed techno-economic models. This framework offers the possibility to evaluate techno-economic models of different players with different strategies and select the prevailing equilibrium. This equilibrium is either socially optimal (Pareto) or optimal under competition (Nash).
This hands-on approach was applied to both wireless and fixed broadband access rollout in a city environment. In case of the wireless network, we incorporated the cooperative strategy through a public private partnership into the strategy set, which is a straightforward exercise using the developed framework. The selected equilibrium returned the partnership strategy as being designated, explained by the reduction of infrastructure duplication. When a fixed fibre access network rollout in a competitive environment was considered, the impact of choosing between a closed and open access network was analysed. Here, results showed that an open access network is the most interesting strategy, both from financial and non-financial perspective.

Overall conclusion

Before the introduction of technology breakthroughs, new applications, products or services is performed, the viability of this introduction needs to be assessed. Typically, a techno-economic analysis is conducted for this assessment. However, two impacting factors are to be taken into account in this analysis. Increasing uncertainty and competitive interaction in the environment makes decision making more difficult. It is therefore important that decision makers have the appropriate evaluation tools at their disposal to perform a correct techno-economic analysis.
In this work, we have described and developed different tools to be used in an extended techno-economic analysis. We developed a composite indicator to measure social objectives of broadband policy makers and regulators, indicated how real options can capture managerial flexibility, developed cost sharing models for synergetic infrastructure rollout, a market response model to estimate uptake under competition and a hands-on game theory framework to evaluate detailed numerical techno-economic models. Finally, we described two approaches to integrate options and games thinking.

Future work

This work has offered tools to improve the techno-economic analysis on various aspects. Within the scope of this research, it is impossible to cover all aspects of extended techno-economics. In this section, we will broaden the scope of our research towards possible extensions. Some of these extensions were already introduced in this dissertation, and form the logical next step.

A practical integrated options and games framework

Throughout this dissertation, we introduced real options and game theory to incorporate flexibility and competitive and cooperative interaction. However, as both frameworks model a different aspect of the techno-economic problem, techno-economics can greatly benefit from an integrated framework.

We described two recent approaches towards an integrated framework. Option games overlay the game theory approach with a binomial tree, but it has only been applied to toy examples up to now. As a binomial tree overlay is used, we believe that research towards incorporating continuous uncertainty into more detailed techno-economic models should be performed in the field of option games.

The second approach consists of sensitivity games. These consists of a repeated sampling of the same game with different input factors for the underlying techno-economic models. The game theory framework we developed during this research can offer the basis for the application of sensitivity games, but also for an extension towards "sensitive continuous flexible" games. In these type of games, each player can at each point in time flexibly change strategies to optimise his payoff. Moving towards these games can offer interesting results, both from a theoretical and practical point of view.

Quantifying public policy goals

To quantify public policy goals, two distinct approaches exist. In this dissertation, we applied composite indices to measure and rank the outcome of different strategies on these policy goals. However, we already indicated that using such indices will always be limited by the definitions used in the index, and that an evolving definition of the underlying parameters is required. In addition, indices like the broadband performance index developed here are bound to subjectivity. The weight factor of the different dimensions need to be decided upon, and these weights are very dependent on the actor using the index.

The second approach consists of monetising the indirect revenues of the project. Indirect revenues following an investment can be reduced nuisance, an increase in inhabitants, improved quality of life, etc. We touched upon this subject in the analysis of the wireless access network rollout by a municipality. There, a fractional approach to indirect revenues was used. However, research into a more realistic modelling of these indirect revenues can offer increased detail of the analysis.

Multi-objective analysis

Multi-objective analysis is the final aspect we would like to introduce as possible future work of this dissertation. In this dissertation, two approaches were used to analyse multi-objective in the different analyses. The first is a straightforward approach, repeating the analysis multiple times, thereby evaluating another objective. But which decision needs to be taken when the indicators used have conflicting results? For example, fixing copper local loop unbundling prices to a lower level will increase the uptake of these services, but might reduce the willingness to invest in fibre access networks, as more uptake on copper results in lower uptake on fibre. When an actor aims for both objectives, the decision is no longer straightforward.

In a second approach, we integrated the different objectives into a composite index. This removes the problem with conflicting outcomes, but as already indicated, subjectivity of such indices can pose a problem.

In a third approach, we could move towards a real multi-objective analysis, in which objectives are combined into tuples. Different strategies will form different tuples of outcome, and can thus be analysed using the Pareto front concept.